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Compressive Strength Optimization of Cassava Peel Ash and Waste Paper Ash Blended M25 Concrete: A Statistical Analysis of Variance Approach

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Abstract: Cement production imposes major environmental and economic burdens in Nigeria. This study evaluated locally sourced cassava peel ash and waste paper ash as partial replacements for ordinary portland cement in concrete of nominal M25 grade. The ashes were produced by controlled incineration and sieved to 75µm, and their chemical oxide composition was determined. Concrete cubes were cast at 0, 5, 10, 15 and 20% replacement levels for each ash and tested for slump and compressive strength at 7, 14, 21 and 28 days. The cassava-derived ash satisfied the ASTM C618 threshold for a Class N natural pozzolan, with a combined silica, alumina and iron oxide content of 70.04%, whereas the paper-derived ash did not, at 44.9%, despite a high calcium oxide content of 36.4% suggesting mild hydraulic activity. Slump fell progressively from 75mm at 0% replacement to 36mm and 41mm, respectively, at 20% replacement. The control mix attained a 28-day compressive strength of 26.2N/mm²; the best-performing mixes, at 5% replacement of each ash, attained 24.7N/mm² and 24.4N/mm², or about 94% and 93% of the control value. No replacement mix fully met the M25 specification, though two-way analysis of variance confirmed that only 5% replacement was statistically indistinguishable from the control at 28 days, supporting 5% as the optimal level for concrete approaching M25 strength. Strength-activity-index analysis confirmed pozzolanic activity up to 15% replacement, and an indicative embodied-carbon assessment estimated a 5% emissions reduction for every 5% of cement replaced.

Keywords: *Cassava Peel Ash; Waste Paper Ash; Ordinary Portland Cement; Supplementary Cementitious Material; Compressive Strength; Pozzolan; Sustainable Concrete.*

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I. INTRODUCTION

Concrete is the most widely used building material in the world, and its role in infrastructural development in developing economies such as Nigeria cannot be overemphasized. Ordinary Portland Cement (OPC) is the principal binder in conventional concrete production; however, OPC manufacture is one of the most energy-intensive industrial processes, is responsible for approximately 8–10% of anthropogenic CO_2 emissions worldwide (Habert et al., 2020; Mavroulidou & Feruku, 2022), and is widely regarded as both expensive and environmentally unfriendly (Ighalo & Adeniyi, 2020; Mehta & Monteiro, 2014). Cement also imposes a significant economic burden on Nigerians, representing a major constraint on the affordability of housing and civil

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infrastructural projects for low- and middle-income segments of the population. These combined environmental and economic pressures have generated considerable research interest in supplementary cementitious materials (SCMs) that can partially replace OPC without compromising the structural performance of concrete.

Pozzolanic materials react with the calcium hydroxide liberated during OPC hydration to produce additional calcium silicate hydrate (C-S-H) gel, the compound principally responsible for concrete strength and microstructural densification (Neville, 2011). A wide range of supplementary materials has been investigated as partial cement replacements, including pumice (Arun Kumar et al., 2020), sugarcane bagasse ash (Moretti et al., 2018), ceramic waste (Pacheco-Torgal & Jalali, 2010), egg shells (Ofuyatan et al., 2020), and fly ash, silica fume and ground granulated blast-furnace slag (Azimi-Pour et al., 2020; Guo et al., 2020; Ofuyatan et al., 2021), the last three being the most widely adopted globally. Waste-derived materials such as recycled brick powder are also being actively evaluated as alternative SCMs in response to the environmental concerns of the cement industry (Sallı Bideci et al., 2024). Conventional industrial SCMs, however, are not available everywhere, notably in many developing countries, which necessitates the identification and validation of alternative, locally derivable pozzolanic sources, and agricultural solid waste has demonstrated potential as such a source (Paul et al., 2019).

Nigeria's agricultural economy generates vast quantities of biomass waste that are presently managed through open burning or uncontrolled disposal, constituting a source of both environmental pollution and unexploited material value. Nigeria is the world's largest producer of cassava, Manihot esculenta (Food and Agriculture Organization of the United Nations, 2022), and the processing of cassava tubers into garri, flour and starch generates cassava peel as a by-product in vast quantities annually. When subjected to controlled incineration, cassava peel yields a light-colored ash with appreciable concentrations of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3); prior characterization work has confirmed that the combined content of these three oxides in Cassava Peel Ash (CPA) can meet the minimum threshold prescribed by ASTM C618 for classification as a natural pozzolan (ASTM International, 2023; Iro et al., 2024).

Cassava processing is itself a source of environmental pollution: according to Ubalua (2007), waste materials from cassava processing fall into four categories, namely peels from initial processing, fibrous by-products from crushing and sieving, starch residues left after settling, and waste water (effluent). Several Nigerian studies have evaluated the compressive strength of CPA-blended concrete. Osuide et al. (2021) assessed concrete in which cement was partially replaced with CPA at levels ranging from 0% to 50%, and found that although compressive strength increased with curing age, it generally decreased as the CPA replacement level increased, with the tested mixtures remaining within the authors' stated acceptable strength range indicating the potential suitability of CPA as a partial cement replacement. Olubunmi et al. (2022), comparing CPA and wood ash at replacement levels up to 25%, recorded a 28-day control strength of 27.11N/mm² decreasing to 15.93N/mm² at 25% CPA, with only the 5–15% replacement mixes remaining within the 20N/mm² plain-concrete specification.

More recently, Iro et al. (2024) applied a central composite design (CCD) approach to optimise CPA concrete mix proportions. They identified an optimal cement:CPA:fine:coarse aggregate ratio that produced a maximum compressive strength of 28.51N/mm², and reported combined SiO_2+Al_2O_3+Fe_2O_3 oxide contents as high as 81.83% in controlled-combustion CPA. CPA has also been shown to retain good mechanical and microstructural performance when combined with natural fibre reinforcement in kenaf-fibrous concrete composites (Ogunbode et al., 2023). Oladipo et al. (2013) likewise presented the use of cassava peelings in concrete as a waste-to-wealth route for lowering concrete input costs in southwestern Nigeria, reinforcing the economic case for its adoption.

In addition to the agricultural waste stream, significant quantities of waste paper are generated from offices, educational institutions, printing facilities, and commercial establishments across Nigeria. Waste paper, when incinerated, yields a pale ash composed mainly of calcium oxide (CaO) and silicon dioxide (SiO_2), in which the CaO fraction confers latent hydraulic activity and pozzolanic reactivity. Meko and Ighalo (2021) studied the use of Waste Paper Ash (WPA) as a cement replacement in M25 concrete at 0–20% replacement and found that the chemical composition of WPA did not meet the requirements for classification as a pozzolanic material, unlike CPA; they also observed extended setting times and improved paste consistency with increasing WPA content, a finding of direct relevance to the present study.

Mavroulidou and Feruku (2022) reported that wastepaper sludge ash at about 15% replacement gave the best overall strength and durability (water absorption and carbonation resistance) in structural concrete, while Mitikie and Waldtsadik (2022) similarly found 5% waste paper pulp ash to give the highest strength among the replacement levels tested. The classical two-stage model of strength development in blended-cement concrete, an early phase dominated by OPC hydration up to 14 days, followed by a phase increasingly governed by the secondary pozzolanic reaction of the SCM (Neville, 2011), has direct implications for the strength development of CPA- and WPA-blended concrete.

The studies reviewed above establish general strength trends for CPA- and WPA-blended concrete individually, but were carried out using materials sourced and mix designs formulated outside the Niger Delta region, and none directly compares CPA and WPA side by side under an identical M25 mix design, aggregate source, and curing regime. The present study addresses this gap by evaluating both ashes, sourced from the same locality in Delta State, within a single experimental protocol, providing a locally verified, directly

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comparable strength dataset for CPA and WPA blended concrete in the region.

The aim of this study is therefore to assess and compare the physicochemical properties and the fresh and hardened performance of concrete produced with domestically derived CPA and WPA as partial OPC replacements at five levels (0, 5, 10, 15 and 20%), and to identify, through statistical analysis of variance and an independent pozzolanic activity criterion, the replacement level that best approaches the strength requirements of M25-grade concrete while also estimating the associated reduction in embodied carbon.

II. MATERIALS AND METHODS

➢ *Materials*

The materials used in this study are described below:

- *Cement:*

Dangote OPC Grade 42.5N (Figure 1a), conforming to NIS 444-1:2003 (Standards Organisation of Nigeria, 2003) and BS EN 197-1:2000 (British Standards Institution, 2000), was used throughout the study and procured from a single batch to ensure consistency of properties across all test series.



Fig 1a: A Sample of Ordinary Portland Cement (OPC)

- *Cassava Peel Ash:*

Fresh cassava peels, obtained as a by-product of processing cassava tubers into garri at small-scale garri-processing units in Orhomuru-Orogun, Ughelli North Local Government Area, Delta State, were washed to remove adhering residue and soil, sun-dried for four days (Figure 1b), and incinerated in a muffle furnace at 750°C ± 15°C for two hours and incinerated in a muffle furnace at 750°C ± 15°C for two hours, ensuring complete combustion while limiting uncontrolled emissions. The resulting ash (Figure 1c) was ball-milled for 45 minutes and sieved to 75µm, adapting the controlled-incineration and sieving approach reported for CPA by Iro et al. (2024).



Fig 1b: A Sample of Dried Cassava Peel ash



Fig 1c: A Sample of Grinded Cassava Peel Ash

- *Waste Paper Ash:*

Waste paper (uncoated newsprint, office A4 paper, cardboard and continuous stationery) was sourced from offices and institutions within the same locality, sun-dried for 48 hours, incinerated at 600°C ± 15°C for two hours, then ground and sieved to 75µm by the same procedure applied to CPA. The high temperature used for WPA was adopted to ensure complete combustion of the cellulose fibre and to minimize residual unburnt carbon in the ash. Figure 1d shows the waste paper before incineration, and Figure 1e shows the resulting waste paper ash.



Fig 1d: A Sample of Waste Paper

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Fig 1e: A Sample of Grinded WPA

- *Fine Aggregate:*

Naturally occurring river sand, screened to 4.75mm and retained on a 75µm sieve, served as fine aggregate (Figure 1f).


Fig 1f: A Sample of the Fine Aggregate (River Sand)

- *Coarse Aggregate:*

Crushed granite of 20mm nominal maximum size, graded per BS EN 933-1:2012 (British Standards Institution, 2012) and BS EN 12620:2002 (British Standards Institution, 2002a), served as coarse aggregate (Figure 1g).


Fig 1g: A Sample of Coarse Aggregate (Crushed Granite)

- *Water:*

Potable water conforming to BS EN 1008:2002 (British Standards Institution, 2002b) was used for mixing and curing.

➢ *Mix Design and Treatment Matrix*

The target concrete grade was M25 (characteristic cube strength 25N/mm² at 28 days). Adopting the characteristic-strength margin k = 1.64 with an assumed standard deviation of 5.2N/mm², consistent with a 'good' standard of control assumed for laboratory trial batching in the absence of long-term production records (Teychenné et al., 1997), gave a target mean strength of 33.5N/mm² (25 + 1.64×5.2). This target mean strength was then used, together with the standard strength-versus-free-water/cement-ratio relationship of the same DOE method for the OPC grade used, to obtain a free water-to-binder ratio (w/b) of 0.50; fixing this ratio across all nine mixes held the effective water content constant, isolating the effect of ash replacement from variation in mixing water. The binder-to-aggregate proportion was fixed at 1:2:4 (binder:fine aggregate:coarse aggregate) by mass, an established nominal mix proportion conventionally associated with lower nominal-mix strength grades in several regional concrete codes, rather than independently derived from the DOE absolute-volume procedure for the specific aggregates used here. Holding this aggregate proportion constant across all nine formulations ensured that observed differences in fresh and hardened properties could be attributed to the ash replacement level rather than to variation in the mix design basis; its adequacy for the M25 target was confirmed empirically through the achieved control strength (Section 3.4) rather than assumed a priori, with the higher-grade cement used (Dangote OPC 42.5N) and the comparatively lean w/b of 0.50, relative to the water content conventionally assumed for a 1:2:4 mix, offered as the likely explanation for the control mix exceeding the strength typically associated with this nominal proportion. Nine mix formulations were cast in triplicate: a control (100% OPC) and four replacement levels (5, 10, 15 and 20%) for CPA and WPA independently, as summarized in Table 1. The achieved 28-day control strength (26.2N/mm², reported in Section 3.4) exceeded the M25 characteristic strength requirement of 25N/mm² but fell short of the 33.5N/mm² target mean strength used in the mix design; because the mix design basis (w/b ratio and aggregate proportion) was held constant across all nine formulations, the comparison of replacement levels against one another and against the control remains valid irrespective of this shortfall, though the shortfall itself and its widening with increasing replacement level, as shown in Section 3.4 is addressed further as a limitation in Section 2.6.

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Table 1 Mix Designations and Binder Proportions

Mix ID	Description	OPC (%)	CPA (%)	WPA (%)	w/c ratio
M0	Control (100% OPC)	100	0	0	0.50
C5	5% CPA replacement	95	5	0	0.50
C10	10% CPA replacement	90	10	0	0.50
C15	15% CPA replacement	85	15	0	0.50
C20	20% CPA replacement	80	20	0	0.50
P5	5% WPA replacement	95	0	5	0.50
P10	10% WPA replacement	90	0	10	0.50
P15	15% WPA replacement	85	0	15	0.50
P20	20% WPA replacement	80	0	20	0.50

➢ *Specimen Preparation, Casting and Curing*

Materials were batched by mass using a calibrated digital balance and mixed in accordance with BS EN 206:2013 (British Standards Institution, 2013): dry aggregates were combined and rotated for 60s, the binder blend was added and dry-mixed for a further 60s, and water was introduced gradually over 30s before a final 3-minute mixing period. Concrete was cast into 150mm × 150mm × 150mm steel cube moulds, demoulded after 24 hours, and water-cured until testing at 7, 14, 21 and 28 days.

➢ *Testing Procedures*

Chemical oxide composition of the OPC, CPA and WPA was determined by X-ray fluorescence (XRF) spectrometry on pressed-pellet samples, with results reported as oxide mass percentages (Section 3.1).

Slump was measured immediately after mixing per BS EN 12350-2:2019 (British Standards Institution, 2019a), with the observed consistency class assigned per BS EN 206:2013 (S1–S5).

Compressive strength was determined on three 150mm cubes per mix at each age (7, 14, 21 and 28 days of water curing) per BS EN 12390-3:2019 (British Standards Institution, 2019b), using a 2,000kN compression testing machine at a loading rate of 0.6N/mm²/s. Compressive strength was computed as:

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

Where P is the failure load, and A is the cross-sectional area; the mean of three cube specimens is reported for each mix at each age.

➢ *Statistical Analysis*

The individual triplicate cube compressive-strength results underlying each reported mean were analysed statistically using Python (SciPy v.1.x and statsmodels v.0.14). Analysis of variance (ANOVA) was used to evaluate the effects of cement replacement level, curing age, and ash type, as appropriate to the experimental design (Montgomery, 2019). For each ash series, a two-way ANOVA was performed with replacement level and curing age as fixed factors. Tukey's honestly significant difference (HSD) post hoc test was subsequently applied to the 28-day compressive-strength results to identify significant differences among the individual mixes, including comparisons with the control (Tukey, 1949). Additionally, a three-way ANOVA incorporating ash type, replacement level, and curing age was performed on the eight ash-blended mixes, excluding the control because ash type was not applicable at 0% replacement. This analysis assessed whether compressive strength differed significantly between cassava peel ash (CPA) and waste paper ash (WPA) mixes across the experimental conditions. Welch's independent-samples *t*-tests were also conducted to compare corresponding CPA and WPA mixes at matching replacement levels and curing ages. Statistical significance was assessed at $\alpha = .05$, with Bonferroni correction applied where multiple pairwise comparisons were conducted within the same family of tests. Statistical assumptions were considered when interpreting the results, and findings were reported using the relevant test statistics, degrees of freedom, and *p*-values, in accordance with established statistical guidance (Field, 2018).

The coefficient of variation (CoV) was computed for each mix at each age as the ratio of the sample standard deviation to the mean, and the 28-day characteristic strength of each mix was estimated per BS EN 206:2021 (British Standards Institution, 2021) as fck = fm − 1.64s, where (fm) is the mean compressive strength and (s) is the sample standard deviation.

➢ *Scope and Limitations of the Study*

The nominal 1:2:4 binder-to-aggregate proportion adopted in this study (Section 2.2) was held constant across all nine mixes to isolate the effect of ash replacement, but was not independently re-optimized for the specific aggregates and target strength used here; the achieved 28-day control strength consequently fell short of the 33.5N/mm² target mean strength by a margin that widened with increasing replacement level (Section 3.4). This does not affect the internal validity of the comparisons between replacement levels, which share the same mix design basis, but it does mean the absolute strengths reported should be treated as conservative relative to what an aggregate-specific, fully re-optimised mix design might achieve at each replacement level. This study also assessed compressive strength only; flexural and tensile strength, and durability indicators such as water absorption, chloride penetration and carbonation resistance, were not tested. These properties are recommended as priorities for future work before CPA- and WPA-blended concretes are specified for structural use. Statistical comparisons between mixes (Section 3.4.1) were based on triplicate (n = 3) cube results per condition; while

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sufficient to detect the large, consistent effects of replacement level and curing age, this sample size limits the statistical power available to resolve smaller pairwise differences between individual CPA and WPA mixes, and a larger replicate count is recommended in future work for more definitive discrimination between the two ash types.

III. RESULTS AND DISCUSSIONS

➢ *Chemical Composition of Cassava Peel Ash and Waste Paper Ash*

The oxide composition of OPC, CPA, and WPA, obtained by XRF analysis (Section 2.4), is presented in Table 2. For CPA, the combined SiO_2+Al_2O_3+Fe_2O_3 content of 70.04% slightly exceeds the 70% minimum stipulated by ASTM International (2023) for classification as a Class N natural pozzolan, confirming that CPA is a genuine pozzolanic material and is broadly consistent with the higher combined oxide content of up to 81.83% reported for controlled-combustion CPA by Iro et al. (2024). The loss on ignition (2.61%) lies well within the 10% ceiling, suggesting efficient combustion and low residual unburnt carbon. By contrast, WPA showed a combined oxide content of 44.9%, below the ASTM C618 limit, but a relatively high CaO content of 36.4%, indicating that WPA is not a conventional pozzolan but a weakly hydraulic, slightly pozzolanic material. This agrees with the cementitious, calcium-rich character reported for waste paper sludge ash by Mavroulidou and Feruku (2022) and with the non-pozzolanic chemical classification of WPA reported by Meko and Ighalo (2021).

Table 2 Oxide Composition of OPC, CPA and WPA (% by Mass)

Oxide	OPC (%)	CPA (%)	WPA (%)
SiO_2	18.50	53.27	22.6
Al_2O_3	4.5	11.42	14.7
Fe_2O_3	3.00	5.35	6.7
SiO_2+Al_2O_3+Fe_2O_3	26.00	70.04	44.9
CaO	67.52	10.37	36.4
K_2O	0.5	11.17	2.8
SO_3	2.67	1.81	2.8
MgO	1.46	3.01	5.1
LOI	0.85	2.61	7.3

➢ *Physical Properties: Specific Gravity*

Figure 2 shows the average specific gravity of granite, river sand, OPC, CPA, and WPA, obtained by the pycnometer method. The highest specific gravity value of 3.01 was found in OPC, consistent with its crystalline clinker mineralogy, while the lowest value of 2.35 was found in WPA, reflecting its higher organic residue and more porous particle structure. The lower specific gravities of both ashes relative to OPC indicate that, on an equal-mass replacement basis, they occupy a relatively larger volume in the paste, consistent with the workability reduction discussed in Section 3.3.

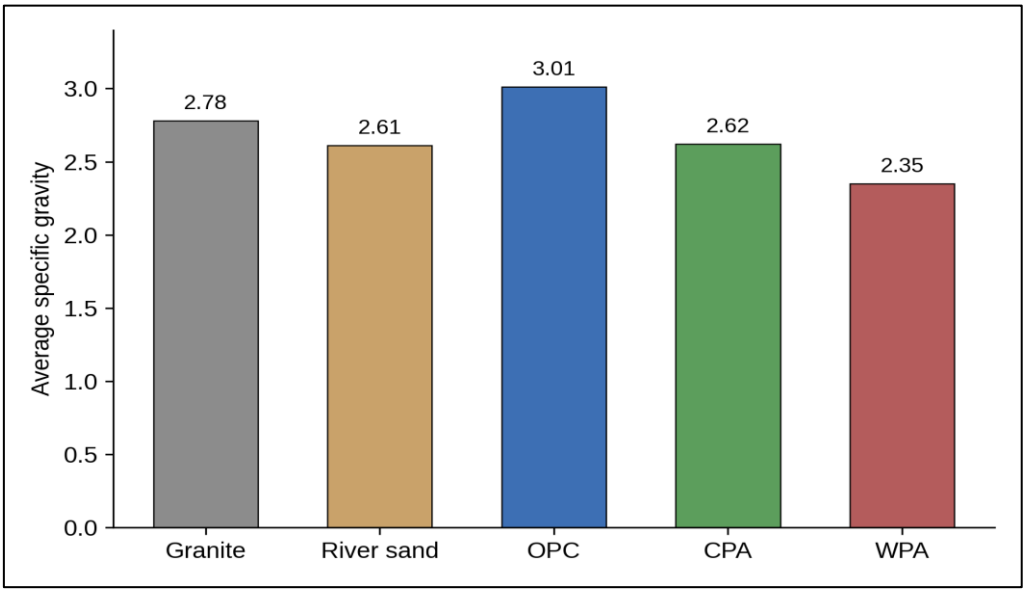


Fig 2 Average Specific Gravity of Granite, River Sand, OPC, CPA and WPA

➢ *Fresh Concrete Properties: Workability (Slump)*

Figure 3 presents the slump results. The control mix (M0) achieved a slump of 75mm, classified as medium workability (S2) per BS EN 206:2013. Slump decreased progressively and consistently with increasing ash content in both series, falling at 20% replacement to reductions of approximately 52% (CPA) and 45% (WPA) relative to the control. This progressive loss of workability is attributed to

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the higher specific surface area, and consequent water demand, of the finely ground ash particles relative to OPC. All mixes up to 10% replacement retained medium (S2) workability; at 15% and 20%, workability fell to the low (S1) class, indicating that a water-reducing admixture would be required to restore workability at these higher replacement levels.

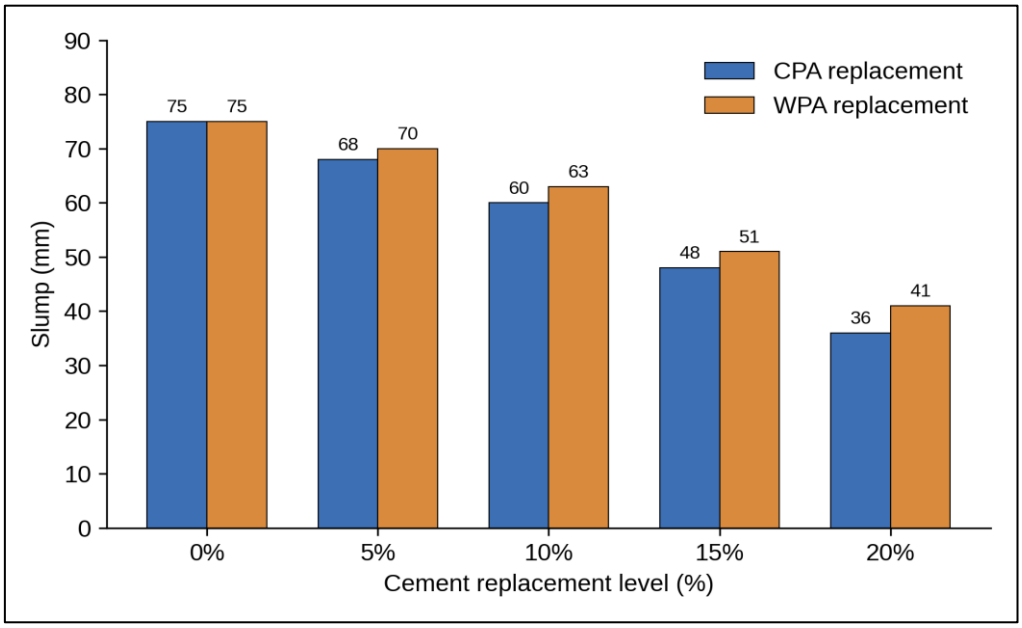


Fig 3 Effect of CPA and WPA Replacement Level on Slump of Fresh Concrete

➢ *Compressive Strength of Hardened Concrete*

Figure 4 shows that the control mix achieved a compressive strength higher than the M25 design target at 28 days. The highest strength among the replacement mixes was obtained for C5, at 94.3% of the control value, decreasing progressively with further CPA replacement. C20 did not exceed 20N/mm² (the M20 characteristic strength), whereas all CPA mixes up to 15% replacement exceeded this value. The progressive reduction in compressive strength with increasing replacement is consistent with the findings of Agbenyeku and Okonta (2014) for CPA-blended laterised concrete, and with the general trend reported by Osuide et al. (2021), who likewise observed a reduction in compressive strength with increasing CPA replacement. A related trend has also been reported by Nwa-David et al. (2023) for concrete containing a nanosized form of cassava peel ash, although their study focused on this processed material rather than the coarser, sieved ash used here. However, the magnitude of the decline observed in the present study is less severe than that reported by Olubunmi et al. (2022), who observed a reduction from 27.11N/mm² for the control mix to 15.93N/mm² at 25% CPA replacement. The strength obtained here falls within the range identified by Iro et al. (2024) as achievable through optimized CPA concrete mix proportioning, who reported a maximum compressive strength of 28.51N/mm² at an optimized, statistically derived binder-aggregate ratio. The nominal 1:2:4 mix design adopted in the present study, though adequate for comparative assessment, therefore has scope for further strength gains through mix optimization.

A similar pattern was observed for the WPA series. P5 achieved the highest 28-day strength among the WPA mixes, at 93.1% of the control, followed by P10 and P15, both remaining above the M20 threshold, while P20 fell below it. Across both series, 7-day strengths of all ash-blended mixes were 8–32% lower than the control, reflecting the delayed nature of pozzolanic reactions relative to the rapid early hydration of OPC a trend consistent with the delayed pozzolanic reaction of ash-blended systems (Neville, 2011). The finding that the 5% level performed best among the WPA mixes also agrees with the 5% optimum reported for waste paper ash by Meko and Ighalo (2021) and for waste paper pulp ash by Mitikie and Waldtsadik (2022), although in those studies the 5% mixes exceeded the control strength, whereas here P5 reached 93.1% of the control. The non-pozzolanic chemical classification of WPA established in Section 3.1 is consistent with the finding of Meko and Ighalo (2021), who likewise reported that WPA did not meet the chemical requirements for classification as a pozzolanic material, while noting a lengthening of setting time and increased water demand with increasing WPA content — both effects that plausibly contribute to the workability reduction and delayed early-age strength gain observed for the WPA series in the present study.

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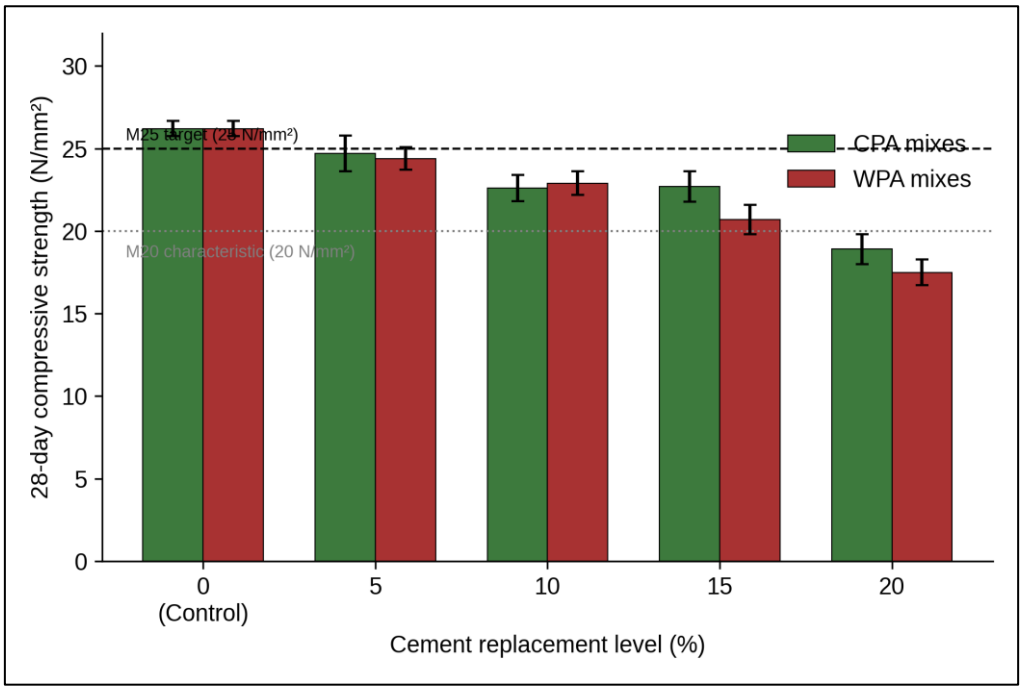


Fig 4 28-Day Compressive Strength of CPA and WPA Concrete Mixes Compared with the M25 and M20 Design Thresholds (Error Bars Show ±1 Standard Deviation, n=3)

Figure 5 compares the strength development of the control mix with the best-performing ash mixes (C5, C10, P5, P10) across curing ages. The ash-blended mixes begin at a lower base at 7 days but show a steeper rate of strength gain between 14 and 28 days, so that the gap with the control narrows with curing, typical of pozzolanic systems, in which early strength depends on OPC hydration while later-age gain depends increasingly on the secondary pozzolanic reaction (Mehta & Monteiro, 2014; Neville, 2011). None of the replacement mixes in either series reached the M25 design strength at 28 days; however, replacement levels up to 15% retained more than 80% of the M25 target in both series. The 5% level in each series was closest to the target (C5: 94.3% of control; P5: 93.1% of control), indicating that 5% replacement is the optimal level for concrete approaching M25 requirements. This finding agrees with the low-replacement optimum reported for CPA concrete by Iro et al. (2024), whose best performance corresponded to roughly 11% cement replacement by CPA. In view of the ASTM International (2022) recommendations on durability-related transport properties of blended concretes, further durability characterization of these optimal mixes is warranted before formal specification.

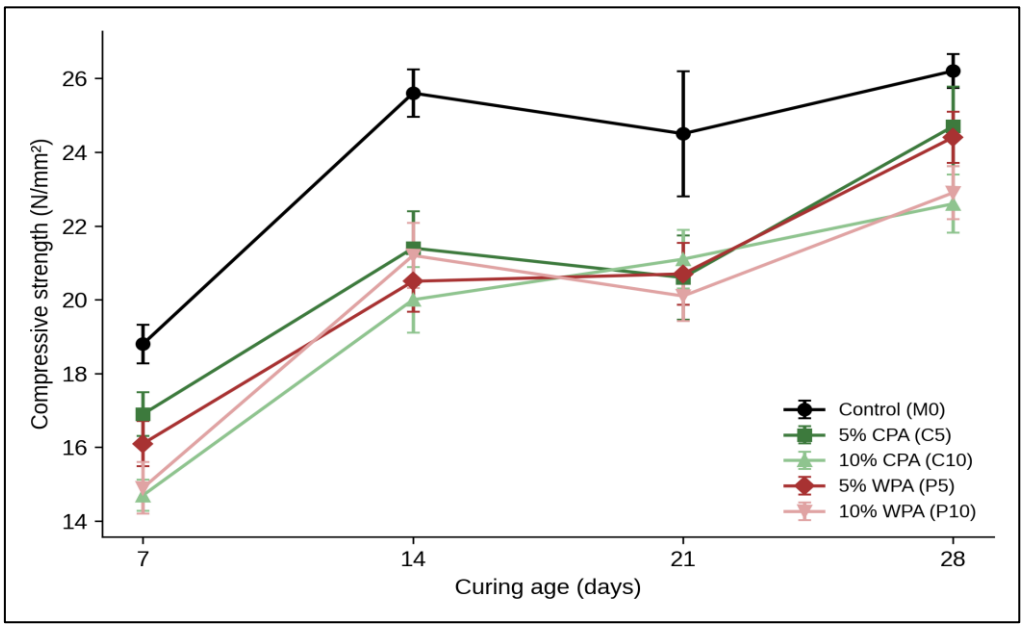


Fig 5 Compressive Strength Development of the Control Mix and the 5% and 10% CPA and WPA Mixes with Curing Age (7–28 Days), Error Bars ±1 Standard Deviation

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- *Statistical Analysis of Compressive Strength Results*

Before conducting ANOVA, the residuals of each fitted model were checked against the normality and homogeneity-of-variance assumptions underlying the F-test. A Shapiro-Wilk test on the CPA-series model residuals found no significant departure from normality ($W = 0.974$, $p = 0.222$); the WPA-series residuals showed a marginally significant departure ($W = 0.944$, $p = 0.0085$), as did the pooled three-way model residuals ($W = 0.938$, $p < 0.001$), though ANOVA is generally considered robust to moderate non-normality of this kind at these sample sizes. Levene's test found no evidence of unequal variances across cells in either series (CPA: $p = 0.977$; WPA: $p = 0.995$) or in the pooled model ($p > 0.999$), supporting the assumption of homogeneity of variance underlying the ANOVA presented below.

Following the statistical procedure described in Section 2.5, two-way ANOVA, three-way ANOVA, Tukey HSD and Welch's t-tests were applied to the triplicate cube results. Table 3 presents the two-way ANOVA summary for each series.

Table 3 Two-Way ANOVA Summary for Compressive Strength (Replacement Level × Curing Age)

Series	Source of variation	df	Sum of Sq.	Mean Sq.	F	p-value
CPA (incl. control)	Replacement level	4	375.09	93.77	132.61	< 0.001
	Curing age	3	491.77	163.92	231.81	< 0.001
	Replacement × Age	12	48.48	4.04	5.71	< 0.001
	Residual (error)	40	28.29	0.71		
	Total	59	943.62			
WPA (incl. control)	Replacement level	4	463.40	115.85	184.77	< 0.001
	Curing age	3	444.04	148.01	236.06	< 0.001
	Replacement × Age	12	15.50	1.29	2.06	0.044
	Residual (error)	40	25.08	0.63		
	Total	59	948.02			

In both series, replacement level and curing age each had a highly significant effect on compressive strength ($p < 0.001$), confirming that the strength reductions described above are not attributable to chance. The replacement × age interaction was also significant in both series, indicating that the rate of strength gain with curing age itself depends on replacement level, consistent with the delayed, pozzolanically-driven strength development described above and illustrated in Figure 5.

Table 4 Three-Way ANOVA Summary for Compressive Strength — Ash Type × Replacement Level × Age (CPA and WPA Mixes Only, Control Excluded)

Source of variation	df	Sum of Sq.	Mean Sq.	F	p-value
Ash type	1	6.31	6.31	10.56	0.002
Replacement level	3	325.90	108.63	181.63	< 0.001
Curing age	3	732.93	244.31	408.46	< 0.001
Ash × Replacement	3	4.61	1.54	2.57	0.062
Ash × Age	3	13.28	4.43	7.40	< 0.001
Replacement × Age	9	30.35	3.37	5.64	< 0.001
Ash × Replacement × Age	9	16.29	1.81	3.03	0.005
Residual (error)	64	38.28	0.60		
Total	95	1167.96			

Pooled across all replacement levels and curing ages, ash type had a statistically significant effect on compressive strength ($F(1,64) = 10.56$, $p = 0.002$), confirming that CPA mixes achieved significantly higher strength than the corresponding WPA mixes overall. However, this significant pooled effect should be distinguished from the pairwise, mix-by-mix comparisons discussed below: Welch's independent-samples t-tests comparing each CPA mix against its corresponding WPA mix at the same replacement level and 28-day age did not reach significance in any case (5%: $p = 0.709$; 10%: $p = 0.651$; 15%: $p = 0.056$; 20%: $p = 0.114$), reflecting the limited statistical power available from triplicate ($n = 3$) sampling at any single test condition. Repeating these comparisons across all four curing ages (16 tests in total) produced only one nominally significant result: 15% replacement at 21 days ($p = 0.005$), which does not survive a Bonferroni correction for multiple comparisons (adjusted $\alpha = 0.05/16 = 0.0031$) and should therefore be treated with caution rather than as firm evidence of a difference at that specific condition. The statement that CPA 'consistently outperformed' WPA is accordingly revised: CPA mixes numerically exceeded the corresponding WPA mixes at most, but not all, replacement levels and ages, and this difference is statistically robust only when the data are pooled across the full experimental range, not at any individual replacement level in isolation. A larger number of replicate cubes per condition (e.g. $n = 6$) would be needed to reliably detect pairwise differences of the magnitude observed here (typically 0.3–2.0N/mm²). As a distribution-free robustness check on the significant replacement-level effect reported above, given the borderline normality of the WPA-series residuals noted earlier, a Kruskal-Wallis test was

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also run on the 28-day strengths within each series; both confirmed a significant effect of replacement level (CPA: H = 12.61, p = 0.013; WPA: H = 13.50, p = 0.009), corroborating the parametric ANOVA result without relying on the normality assumption.

Table 5 Tukey HSD Grouping of 28-Day Compressive Strength, CPA Series (Mean ± SD, n = 3; Means Sharing a Letter Are Not Significantly Different, p > 0.05)

Mix	Mean (N/mm²)	SD	CoV (%)	Tukey grouping
M0 (Control)	26.20	0.46	1.8	a
C5	24.70	1.07	4.4	ab
C10	22.60	0.79	3.5	b
C15	22.70	0.94	4.1	b
C20	18.90	0.91	4.8	c

Table 6 Tukey HSD Grouping of 28-Day Compressive Strength, WPA Series (Mean ± SD, n = 3; Means Sharing a Letter Are Not Significantly Different, p > 0.05)

Mix	Mean (N/mm²)	SD	CoV (%)	Tukey grouping
M0 (Control)	26.20	0.46	1.8	a
P5	24.40	0.70	2.9	ab
P10	22.90	0.72	3.1	b
P15	20.70	0.90	4.3	c
P20	17.50	0.78	4.5	d

Tukey's test was applied separately within each series (i.e., control plus the four replacement levels of a single ash), so the grouping letters in Table 5 and Table 6 indicate significance only within their own series; a mix in Table 5 and a mix in Table 6 sharing the same letter should not be read as evidence that the two are statistically indistinguishable from one another; that cross-series comparison is addressed separately by the Welch's t-tests reported above. Within each series, only the 5% replacement mix (C5 or P5) is not significantly different from the control (sharing letter 'a'), while every mix at 10% replacement and above differs significantly from the control. This confirms, with formal statistical support, that 5% is the highest replacement level at which strength is statistically indistinguishable from unblended OPC concrete in either series. The coefficient of variation (CoV) of the triplicate results ranged from 1.8% to 4.8% across the nine mixes at 28 days (overall range across all mixes and ages: 1.8–6.9%, mean 4.0%), which is well within the limits generally considered indicative of good laboratory quality control for concrete cube testing (typically < 10%), lending confidence to the reliability of the reported means.

Applying the characteristic-strength approach of BS EN 206:2021 ($f_{ck} = f_m - 1.64s$, using the sample standard deviation as an estimate of the population value), the control mix achieves a characteristic 28-day strength of 26.20 − 1.64×0.46 = 25.4N/mm², which narrowly exceeds the M25 characteristic strength requirement of 25N/mm² a materially tighter margin than the 1.2N/mm² suggested by the mean value alone. None of the replacement mixes meet this characteristic-strength criterion (C5: 23.2N/mm²; P5: 22.1N/mm²), reinforcing that even the recommended 5% replacement mixes should be treated as approaching, rather than meeting, full M25 structural requirements without further mix optimization or a small increase in binder content.

➢ *Strength Activity Index and Predictive Modelling*

To assess pozzolanic performance against an independent standard criterion, the Strength Activity Index (SAI) of each blended mix was computed as the ratio of its mean compressive strength to that of the control at the same age, expressed as a percentage, following ASTM International (2023). ASTM C618 requires an SAI of at least 75% relative to the control at either 7 or 28 days for a material to be considered pozzolanically active. Figure 6 presents the SAI of all eight blended mixes at 7 and 28 days.

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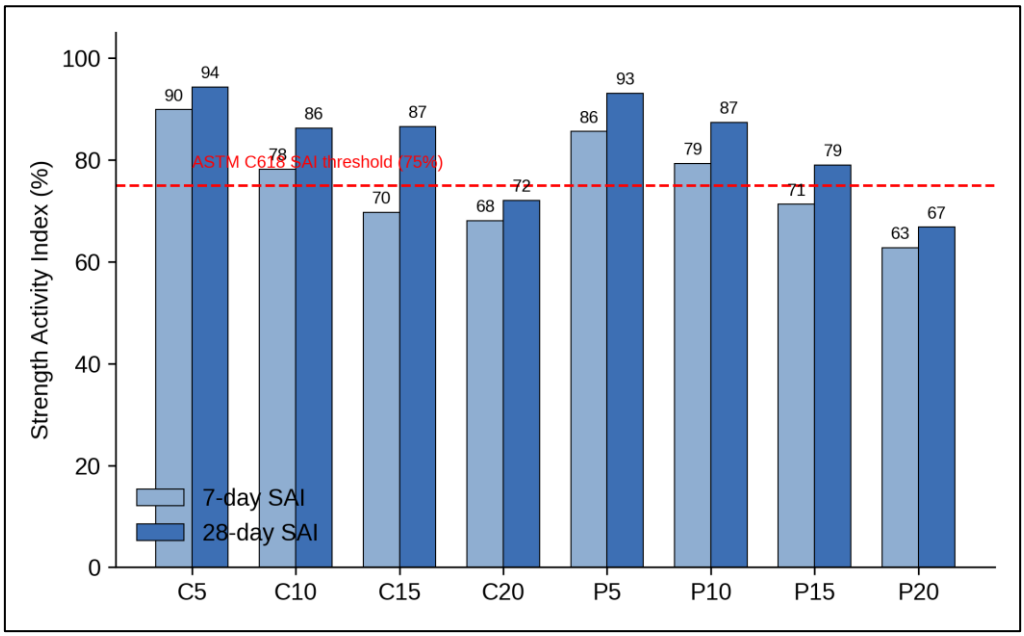


Fig 6 Strength Activity Index of CPA and WPA Mixes at 7 and 28 Days, Relative to the ASTM C618 Threshold

At 28 days, every mix up to and including 15% replacement exceeded the 75% threshold in both series (CPA: 94.3%, 86.3% and 86.6% at 5%, 10% and 15% respectively; WPA: 93.1%, 87.4% and 79.0%), confirming pozzolanic activity is retained well beyond the 5% level recommended as optimal for strength alone. Only the 20% mixes fell short of the threshold at 28 days (CPA: 72.1%; WPA: 66.8%). At 7 days, only C5 and P5 exceeded 75%, reflecting the delayed pozzolanic reaction discussed in Section 3.4; all higher replacement levels required curing beyond 7 days to develop sufficient activity. This SAI analysis therefore corroborates, from an independent standards-based criterion, the compressive strength evidence that 5% replacement is optimal, while indicating that 10–15% replacement remains pozzolanically viable for less strength-critical applications.

To provide a predictive tool for intermediate replacement levels, quadratic regression models were fitted to the 28-day compressive strength data (Figure 7) using the least-squares method, with replacement level (R, in %) as the independent variable:

$$f_{c,CPA} = 25.997 - 0.195R - 0.0069R^2 \quad (R^2 = 0.926) \qquad (2)$$

$$f_{c,WPA} = 26.060 - 0.222R - 0.0100R^2 \quad (R^2 = 0.996) \qquad (3)$$

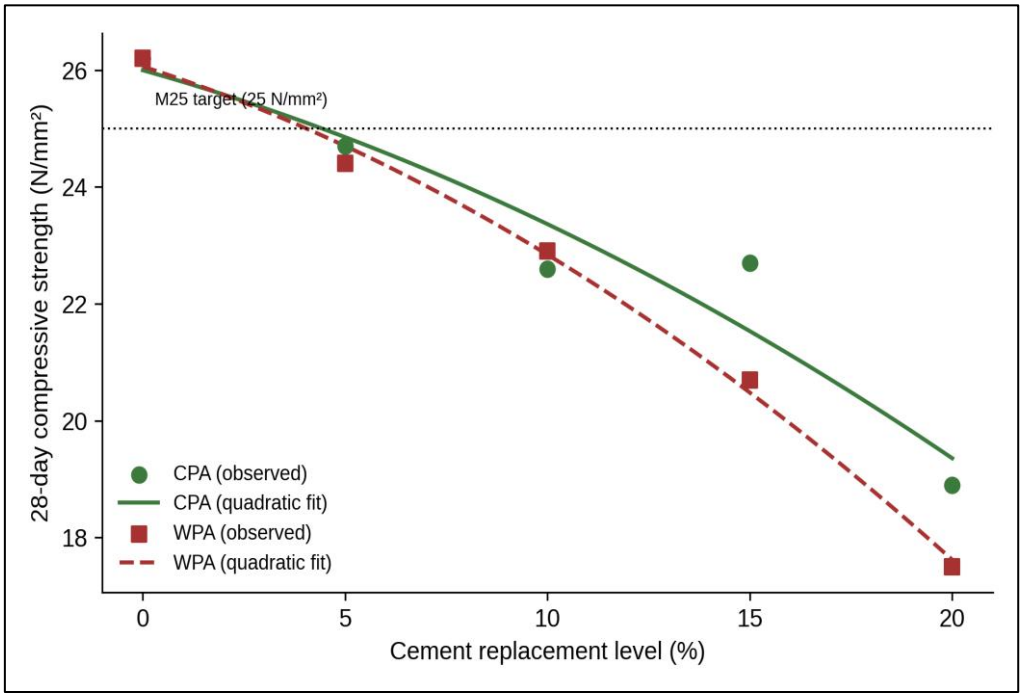


Fig 7 Quadratic Regression Models for 28-Day Compressive Strength versus Cement Replacement Level

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The WPA model gives an excellent fit (R^2 = 0.996), while the CPA model fits well but less tightly (R^2 = 0.926), reflecting the slight non-monotonic dip observed between C10 and C15 (22.6 and 22.7N/mm², respectively) in the underlying data. A linear fit was also tested for comparison (CPA: R^2 = 0.913; WPA: R^2 = 0.977) but the quadratic form was retained as it captures the accelerating strength loss at higher replacement levels evident in Figure 4. These equations allow the 28-day strength of an intermediate mix (e.g. 7% or 12% replacement) to be estimated without additional casting, and provide a locally calibrated alternative to the central-composite response-surface models reported by Iro et al. (2024) for CPA concrete.

➢ *Embodied Carbon Reduction Potential*

Because this study is partly motivated by environmental concerns, we calculated an indicative estimate of the cement-related embodied carbon avoided at each replacement level. The Ordinary Portland Cement content of the control mix was first derived from the reported mix proportions (cement:sand:granite = 1:2:4 by mass, free water/cement ratio = 0.50) and the measured specific gravities of OPC, river sand and granite (Section 3.2), using the absolute volume method and assuming 1% entrapped air. This gave a cement content of approximately 325.9kg per cubic metre of concrete for the control mix, a plausible value for a nominal 1:2:4 mix of this water/cement ratio. As replacement is defined on a binder-mass basis (Table 1), the total binder content was assumed to remain approximately constant across all mixes, so that the OPC content at replacement level R is $325.9\,x\,(1-\frac{R}{100})\mathrm{kg/m^3}$.

An embodied-carbon factor of 0.90 tonnes of CO_2 per tonne of OPC was adopted, consistent with widely reported global estimates for Portland cement manufacture, which are of the order of one tonne of CO_2 per tonne of cement produced, encompassing both calcination and fuel-related process emissions (United Nations Environment Programme, 2010). The embodied carbon of the ash by-products themselves was treated as negligible relative to virgin clinker production, consistent with common practice in comparative assessments of waste-derived SCMs; a full life-cycle assessment including the energy used in cassava-peel and waste-paper collection, drying and incineration was outside the scope of this study. Table 7 summarizes the results.

Table 7 Estimated Cement-Related Embodied Carbon per Cubic Metre of Concrete by Replacement Level

Replacement (%)	OPC content (kg/m³)	CO_2 emissions (kg/m³)	CO_2 avoided vs control (kg/m³)	Reduction (%)
0	325.9	293.3	—	—
5	309.6	278.7	14.7	5
10	293.3	264.0	29.3	10
15	277.0	249.3	44.0	15
20	260.8	234.7	58.7	20

Because both ashes replace OPC on an equal-mass basis, the percentage reduction in cement-related CO_2 emissions equals the replacement percentage exactly, independent of the emission factor assumed. On this basis, the 5% replacement level recommended in this study as optimal for strength (Section 3.4) and confirmed as pozzolanically active (Section 3.5) corresponds to an estimated 14.7kg CO_2 avoided per cubic metre of concrete, equivalent to approximately 14.7 tonnes of CO_2 avoided per 1,000m³ of concrete produced, for a strength penalty of only 6% relative to the control at 28 days. At 15% replacement, which Section 3.5 shows remains pozzolanically active in both series, the estimated saving rises to 44.0kg CO_2/m³ (15%), at the cost of retaining only 80–87% of control strength. This trade-off between strength retention and carbon reduction provides a quantitative basis for selecting a replacement level appropriate to the structural demands of a given application.

IV. CONCLUSIONS

This study assessed the compressive strength characteristics of concrete produced with domestically derived cassava peel ash and waste paper ash as partial replacements for ordinary Portland cement at five replacement levels. Cassava peel ash satisfies the ASTM C618 chemical requirement for a Class N natural pozzolan, while waste paper ash does not, though its substantial calcium oxide content suggests mild latent hydraulic activity. Both ashes have lower specific gravity than the cement they replace, which, together with their higher fineness, accounts for the progressive reduction in workability observed with increasing replacement. Compressive strength decreased progressively with increasing replacement in both series; a two-way ANOVA confirmed that both replacement level and curing age had statistically significant effects on strength in each series ($p < 0.001$). Cassava peel ash mixes numerically exceeded the corresponding waste paper ash mixes at most replacement levels, and a three-way ANOVA confirmed this difference is statistically significant when pooled across all replacement levels and ages ($p = 0.002$); however, pairwise comparisons at individual replacement levels did not reach significance, so this advantage should not be overstated at any single condition. None of the replacement mixes fully attained the M25 design strength at 28 days; the control mix alone met this target. Tukey's post-hoc test showed that only 5% replacement in either series (94.3% and 93.1% of control, respectively) is statistically indistinguishable from the control at 28 days, providing formal statistical support, not merely numerical proximity, for recommending 5% as the optimal replacement level for concrete approaching M25-grade requirements. Independent confirmation via the ASTM C618 Strength Activity Index showed that pozzolanic activity is in fact retained up to 15% replacement in both series at 28 days, and quadratic regression models are proposed to predict strength at any intermediate replacement level. An indicative

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embodied-carbon estimate further suggests that cement-related CO_2 emissions can be reduced by approximately 5% for every 5% of cement replaced by either ash, offering a viable, locally derivable pathway to reducing both the strength penalty and the carbon footprint of structural concrete production in Delta State and the wider Niger Delta region. Replacement levels above 10% will generally require a water-reducing admixture to restore workability. Future research should investigate the flexural, tensile and durability properties of these concretes with a larger number of replicate specimens per condition, and examine binary or ternary blends of the two ashes.

➢ *Authorship Contribution Statement*

Ogheneyerhovwo Sunday conducted the investigation and data curation and prepared the original draft, with methodological input. K. O. Oseni and E. Jemirigbe supervised the work and contributed to its conceptualisation, methodology, and review and editing of the manuscript. S. I. Aule supervised the work and contributed resources, and reviewed and edited the manuscript. M. A. Odua contributed resources, assisted with conceptualisation and methodology, and proofread the manuscript. Afe Osu Peter and Oniovosa Henry Francis contributed to its methodology, and review and editing of the manuscript. . All authors read and approved the final manuscript.

➢ *Conflict of Interests*

The authors declare no conflict of interest. This research received no external funding.

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