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Review

The Potential of Cassava Peel Ash (CPA) as a Cement Replacement Material for Sustainable Concrete Production: A Review

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Abstract

The growing demand for sustainable, resource-efficient construction materials has heightened interest in agricultural waste-derived supplementary cementitious materials, among which cassava peel ash (CPA) has emerged as a promising alternative. This review critically evaluates cassava peel ash (CPA) as a potential pozzolanic material for cement and concrete applications, with emphasis on its physicochemical characteristics, fresh and hardened performance, and durability behaviour. The literature indicates that CPA, a material derived from the calcination of cassava peels, possesses appreciable pozzolanic potential. It is a lightweight material; however, CPA-based concretes maintain normal weight densities. CPA generally prolongs setting times, reflecting a moderated hydration process. At low to moderate replacement levels, typically not exceeding 15% by mass of cement, CPA-based concretes demonstrate acceptable mechanical performance with notable potential for late-age strength development. Durability performance is significantly enhanced, with improved resistance to acid, sulphate, and chloride ingress, as well as reduced drying shrinkage, primarily due to the pozzolanic activity that promotes matrix densification and pore structure refinement. However, excessive cement substitution adversely affects binder reactivity and matrix integrity, with observed variations in its quality, pozzolanic activity and strength development largely attributed to differences in cassava variety, soil chemistry, combustion conditions and processing methods. Despite all these glaring potentials, major knowledge gaps regarding the long-term durability, alkali-silica reaction susceptibility, thermal performance, life-cycle assessment, industrial-scale production implementation and establishing quality-control protocols persist. Furthermore, predictive modelling and optimization approaches remain underutilized despite their potential to address the inherent variability associated with agro-waste-derived materials. When properly processed and proportioned, CPA is a viable, eco-efficient supplementary cementitious material for durable concrete and low-to-moderate strength applications in sustainable construction.

Keywords

Cassava peel ash; sustainability; concrete; supplementary cementitious materials; construction

1. Introduction

Concrete is the most widely used construction material. It is composed of cement, aggregates, water and admixtures [1]. Among these constituents, cement, the binder, is the costliest and most environmentally unfriendly element [2], with its production accounting for about 8% of all CO_2 emissions globally [3].

Concrete is usually formed by a process called hydration, a chemical reaction where water reacts with cement to form a hardened matrix binding the aggregates. It's global acceptability and popularity stem from the ready availability of the materials needed to form this compound, its suitability for most structures, its mouldability and resistance to detrimental environmental factors such as weathering and chemical attacks.

Concrete applications are found in the construction, renovation and maintenance of buildings and infrastructure that contribute significantly to the development, economic progress and increased GDP of world economies. This therefore highlights the indispensability in the dynamics of cement and the concrete industry from both the economic and social perspective [4].

However, despite numerous benefits including the provision of safe living conditions for people around the world, the production process of this very useful composite violates the principles of sustainable development, impacting significantly on the natural environment [5]. The large amount of energy utilized, the high consumption of natural resources and the substantial volume of greenhouse gas emissions are among the basic challenges posed by processes leading to the production of concrete.

From the depletion of our natural resources formed over geological timescales to the distortion of our landscapes by pits left behind by large-scale mining [6], cement production is energy-intensive, accounting for almost 15% of the total energy consumed by manufacturing [7-11]. This process requires extremely high temperature of 1400-1500°C in the kilns for clinkerization, resulting in high energy-related emissions [12, 13].

Furthermore, cement is considered an economically unstable material as it relies heavily on energy costs and as such may experience price fluctuations in response to any fluctuation in the cost of energy. A tonne of cement, depending on the type of cement and the production process, accounts for about 40-50% of the total production cost, requiring 60-130 kg of fuel and about 105 kWh of electricity [12, 14, 15]. A study by Oni *et al*., [16] reported that the production of one tonne of cement requires 3.12 GJ of energy at ₦4875.41 ($25.66), with cement prices in Nigeria estimated to be four times the price in Egypt and South Africa and ten times the price in the United States.

Recent developments in Nigeria in 2024 for instance, shows the imposition of over 200% electricity tariff increase for electricity consumers on Band A from about ₦66/kWh to ₦225/kWh, the base price of natural gas was increased from $2.18/MMBTU to $2.42/MMBTU, with the wholesale price for commercial gas increased to $2.92/MMBTU from $2.50/MMBTU by the various regulatory agencies. Furthermore, diesel prices rose sharply, with Automotive Gas Oil (AGO) prices increasing from about ₦815/litre to approximately ₦1,462/litre. These increases were further compounded by substantial naira depreciation against the US dollar, given that energy inputs such as diesel and gas are dollar-denominated and largely import-dependent in Nigeria [17, 18].

These unsavoury events triggered an escalation in the cost of energy in the Nigerian cement industry, which substantially elevated the production expenditures and operational costs of cement manufacturers, cumulating to approximately ₦1.12 trillion in 2024 from ₦598.14 billion recorded in 2023 [19, 20]. This significantly altered the market economics and the cost structure of the commodity, ultimately pushing the retail prices above the affordability threshold for a considerable proportion of Nigerian consumers [21], with the combined effect of electricity and fuel costs ensuring upward pressure on the market price, which has reportedly reached approximately ₦12,000 per bag [22]. This highlights a cost environment in which energy volatility and economic policies play a critical role in shaping cement pricing, affordability and industrial performance.

To address these challenges, the incorporation of Supplementary Cementitious Materials (SCMs) in the development of sustainable concrete has garnered much attention and become an area of great interest to researchers and professionals in the construction industry [23]. SCMs possess pozzolanic properties providing a significant source of reactive silica and alumina as an alternative binder for cement, at relatively low cost and with a smaller ecological footprint in their extraction [24]. They are employed either as partial substitutes for Portland cement clinker in the manufacture of composite cements or as partial replacements for cement in concrete production [25]. The incorporation of supplementary cementitious materials (SCMs) in concrete offers significant environmental, social, and economic advantages, thereby contributing meaningfully to sustainability objectives, specifically by enhancing waste elimination, reducing carbon dioxide (CO_2) emisssions, and improving concrete workability, durability and strength.

Although several researchers have employed the use of a wide range of SCMs such as GGBFS [26, 27], fly ash [28, 29], silica fume [30, 31], banana leaf ash [32], groundnut shell ash [33], saw dust ash [34-36], coconut shell ash [37], metakaolin [38, 39], ground scoria [40], sugar cane bagasse ash [23, 41], Rice Husk Ash [42, 43], coffee husk ash [44], termite mound [45, 46], locust beans pod ash [47], animal bone ash [48], animal dung ash [49, 50], orange peel ash [51, 52], Bamboo leaf ash [53, 54], Egg shell ash [55], plantain peel ash [56], periwinkle shell ash [57], millet husk ash [58], palm kernel shell ash [59, 60], wheat straw ash [61], cassava peel ash [62, 63] there still exist the need for exploring new materials as supply is only not inexhaustible but some materials may regionally be unavailable.

In certain regions of the world, the demand for supplementary cementitious materials is increasingly outstripping supply, especially in developing countries where concrete consumption is projected to grow rapidly, and conventional SCMs such as fly ash and ground granulated blast-furnace slag are not produced locally [25]. The use of already established and standardized SCMs such as fly ash and blast furnace slag in recent years has had its supply dwindle; this trend is driven by the decline in coal usage, mainly due to the decommissioning of coal-fired power plants, shifts in steel production practices, broader economic stagnation and regulatory uncertainties [64].

For instance, Fly ash, a widely used SCM in concrete, is produced as a by-product of coal combustion in thermal power plants. Although Nigeria possesses coal reserves, the coal sector has been underexploited for power generation and industrial use as coal mining and coal-fired electricity generation have diminished, resulting in limited fly ash by-product streams for construction. Similarly, granulated blast furnace slag (GGBS), another major SCM produced when molten blast furnace slag is quenched and ground, is closely linked to integrated iron and steel production. In Nigeria, the iron and steel industry has remained largely stagnant. As a result, the steady generation of blast furnace slag necessary for widespread SCM use is effectively absent. Consequently, concrete producers generally cannot rely on supplies of these already established conventional materials and must source alternative SCMs or import conventional materials. These structural gaps in coal-based power generation and blast furnace steelmaking constrain the availability of conventional SCMs, necessitating the exploration of locally available alternative materials such as cassava peel ash and other agro-industrial residues to partially replace cement in concrete.

Developing countries face significant challenges in managing domestic and agricultural wastes due to rapid population growth and accelerating urbanization. The reuse of these wastes presents a compelling solution that promotes cost savings and conserves natural resources from further depletion, thereby fostering environmental sustainability, which aligns with the Sustainable Development Goal of transforming waste into wealth [65].

Cassava is a major carbohydrate source, with Africa serving as the leading production hub. During processing, the tubers are peeled, and the resulting peel constitutes the initial stage of solid waste generation. As a top global producer of cassava, Nigeria faces a significant challenge from the accumulation of this agricultural waste, which generates unpleasant odours, releases heat and gases, and attracts flies and other disease-carrying vectors [66]. Processing of cassava generates an amount of cassava waste, of which 20% is cassava peels (CP) [67]. These wastes are disposed of in landfills owing to the lack of cost-effective technologies for waste management in developing countries like Nigeria [68]. This results in several hazards, which include greenhouse gas emissions, with each ton of these wastes emitting between 195 and 361 kg of CO_2 [69, 70]. The problem posed by these wastes is expected to worsen as industrial production of cassava-based products, including cassava flour and garri, is anticipated to grow [62]. Consequently, the partial substitution of cement with CPA provides a dual advantage by reducing dependence on conventional cement, thereby reducing CO_2 emissions, while simultaneously offering a sustainable pathway for managing agricultural waste, particularly in regions with extensive cassava cultivation [71]. Furthermore, incorporating CPA reduces the calcium hydroxide content in the hardened matrix, as excess calcium hydroxide, a byproduct of cement hydration if left unreacted, can make concrete susceptible to deleterious chemical reactions that compromise its long-term durability [72]. By consuming calcium hydroxide through pozzolanic activity, CPA mitigates these adverse effects, thereby improving the stability and extending the service life of concrete structures.

At present, there does not appear to be a comprehensive review focused on the use of CPA as a supplementary cementitious material in concrete, its microstructure, geopolymer systems, and durability. Most CPA publications are experimental studies, while reviews usually discuss CPA as part of broader reviews on agricultural waste ashes and supplementary cementitious materials (SCMs) [73], or soil stabilization materials [74].

Given the relatively limited literature on cassava peel ash (CPA) in cementitious materials, dispersed across diverse publications, a formal systematic review protocol was not adopted. Consequently, a broad and flexible literature search strategy, considered more appropriate, was employed to capture the breadth of existing research, maximize the retrieval of relevant studies and provide a comprehensive overview of current knowledge. The literature reviewed in this study was identified through a broad search of major scientific databases, with additional relevant studies identified through backward citation tracking of key publications, thus providing a substantial body of literature consulted for the review. This review systematically examines the physical, chemical, mechanical, and microstructural characteristics of CPA, explores its performance in both conventional cementitious and alkali-activated binder systems, and advances practical pathways for industry-academia partnerships, standards formulation, and large-scale market adoption. It provides an overview and critical evaluation of existing research, which includes a summary of the findings, the current state and potential future directions.

2. Cassava: Its Origin

Cassava (Manihot esculenta Crantz) is a vital crop particularly in developing countries, especially in Africa [75]. Originating from the Amazon region, cassava is a tropical root crop that serves as a staple food for approximately 800 million people globally [76]. Cassava is a starchy rooted perennial plant in the spurge family (Euphorbiaceae) that is commonly grown as an annual crop across tropical and subtropical regions for its edible tubers [77]. Cassava was introduced to Africa in the sixteenth and seventeenth centuries by Portuguese explorers and has since evolved into a critical food security crop for millions of people. It is currently ranked third among the most important staple foods in Africa, after maize and rice [75]. Globally, cassava utilization is predominantly food-oriented, with consumption occurring mainly in the form of fresh roots as well as processed products such as flour and fermented derivatives.

2.1 Global Cassava Production

Global cassava production increased from 286 million tonnes in 2017 to approximately 315 million tonnes in 2021, representing a growth of about 9% (Table 1). Africa remains the dominant cassava-producing region, accounting for roughly 204 million tonnes in 2021, up from 177 million tonnes in 2017. In terms of global production rankings, Asia follows Africa in second place, while the Americas, the Caribbean and Oceania rank third, fourth and fifth respectively.

Table 1 Cassava production quantity (tonnes) 2017-2021.

Region	2017	2018	2019	2020	2021
World	286,717,815	301,076,715	296,320,563	303,750.832	314,806,747
Africa	177,011,550	195,653,093	188,945,045	193,878,150	203,572,940
Asia	82,308,573	78,553,052	80,740,682	80,740,682	84,252,473
Americas	27,150,283	26,619,441	26,379,923	26,773,117	26,714,972
Caribbean	1,747,475	1,673,893	1,751,772	1,499,794	1,501,367
Oceania	247,410	251,131	254,912	251,410	266,362

Source: Otekunrin [75].

2.2 Cassava Production in Nigeria

Cassava is a root and tuber crop cultivated across all ecological zones of Nigeria, with the highest concentration in the southern regions and the middle belt. Being rich in carbohydrates, starch, protein, fats, fiber, and minerals, it serves as a dependable source of dietary energy, sweeteners, and industrial raw materials [78]. Nigeria remains the world's leading cassava producer, contributing about 63 million tonnes in 2021, which corresponds to roughly 20% of global output. Other major producers include the Democratic Republic of Congo, Thailand, Ghana, and Brazil (Table 2). As the foremost producer, Nigeria alone accounts for about 31% of Africa's total cassava production and about one-fifth of global supply and, as such, has the highest volume of Cassava Peel [79].

Table 2 Top 10 cassava producing countries (2021).

Rank	Country	Production (tonnes)	% Production
1	Nigeria	63,031,377	20.02
2	DR Congo	45,673,454	14.51
3	Thailand	30,108,352	9.56
4	Ghana	22,681,510	7.20
5	Brazil	18,098,115	5.75
6	Indonesia	17,749,000	5.64
7	Vietnam	10,565,589	3.36
8	Angola	9,866,553	3.13
9	Cambodia	7,722,226	2.45
10	Cote d'Ivoire	6,961,620	2.21
	Rest of the World	82,348,952	26.16
	World total	314,806,748	100

Source: Otekunrin [75].

2.3 Cassava Peel Ash (CPA)

Cassava peel, a by-product of cassava processing for both domestic and industrial purposes, has been reported to account for 20-35% of the tuber's weight, particularly when hand peeling is employed [79]. These wastes contribute to environmental pollution, as methods like burning or natural decomposition often fail to fully eliminate them. Recycling them into new building materials presents a practical solution to mitigate this environmental issue [62, 63, 80]. Cassava peel ash is produced by burning the waste generated from cassava processing [78]. The peels are first dried, burnt to ashes, ground to a fine powder and sieved to obtain a fineness comparable to that of cement, which is then incorporated into concrete by replacing cement to produce CPA/OPC blended concrete [62, 79].

The temperature range for the calcination of CPA has been reported to be approximately 500-850°C [81, 82]. Several researchers used a temperature of 600°C [71, 83, 84]; the temperature of 650°C was employed by [66, 85], while [86, 87] employed a calcination temperature of 800°C. Temperatures around 700°C have, however, been frequently identified as optimal because they promote sufficient combustion of organic matter while limiting excessive crystallization of silica, which could reduce pozzolanic reactivity. An earlier study by Salau and Olonade [88], as reported by Salau *et al*., [89], showed that CPA possesses pozzolanic reactivity when calcined at 700°C for 90 minutes and contains more than 70 per cent of combined silica, alumina and ferric oxide. Olatokunbo *et al*., [62] reported satisfactory strength and durability at optimal levels using CPA calcined at 700°C, while Adebisi *et al*., [90] identified 700°C as the optimum calcination temperature to achieve enhanced ash quality and silica development. A more recent study by Fatahiyudin & Kamarudin [91] confirms that CPA-derived silica produced at 700-800°C yields high-purity amorphous silica with better thermal stability. Other recent studies by [92-96] also used 700°C and reported satisfactory strength and durability for CPA-blended cementitious binders.

Studies indicate that sieving CPA through 75-150 µm sieves produced sufficiently fine particles that improved particle packing and secondary hydration reactions. Several concrete studies specifically adopted a 150 µm sieve and reported acceptable fresh and hardened concrete properties [81]. Studies by [71, 80, 83, 84, 86, 87, 97, 98] employed the use of CPA having a fineness of 75 µm, while [63, 66, 79, 81, 82, 89, 99] employed a fineness of 150 µm, with all studies reporting satisfactory performance.

Figure 1 (a) and (b) display the cassava peelings and their transformation to ash.

(a) (b)

Figure 1 (a) Cassava peel; (b) Cassava peel ash. Source: Akinpelu *et al*., [71].

3. Physical Properties of CPA

Cassava peel ash (CPA) exhibits a range of physical properties that significantly influence its suitability and performance as a supplementary cementitious material in concrete. These properties are largely governed by the ash production process, including combustion temperature and duration, oxygen availability, and the degree of unburnt carbon, as well as post-processing treatments such as grinding and sieving.

Previous studies have reported bulk density values for CPA to range between 820 and 852 kg/m^3, indicating a substantially lower density compared to ordinary Portland cement (OPC) [72, 92]. Compacted bulk density values as high as 1649 kg/m^3 have been reported following densification and improved packing [78]. The moisture content of CPA is typically low, with values around 1.7%, reflecting good storage stability and minimal adverse effects on mix water demand [98].

The specific gravity of CPA varies depending on source material and processing conditions, with reported values ranging from 1.74 to 2.53 [72, 79, 92, 97]. Nanosized cassava peel ash (NCPA) has a specific gravity of approximately 2.10, making it about 1.4 times lighter than cement [96].

Particle size distribution and fineness are critical parameters controlling the pozzolanic reactivity of CPA. To ensure suitability for use in cementitious systems, CPA is typically ground and sieved to fine particle sizes. The literature reports particle sizes of 75-150 µm as commonly recommended for effective pozzolanic activity.

Fineness modulus is the index number that represents the mean size of the aggregate particles obtained after performing sieve analysis with standard sieves [99]. Fineness modulus values of 1.88 and 2.13 have been reported for finely processed CPA [72, 92], while higher values such as 6.53 have been observed when coarser fractions were retained [100].

The specific surface area of CPA, which directly influences its reactivity, has been reported using different test methods. Values of approximately 4930 cm^2/g determined by the nitrogen adsorption method have been reported for finely processed CPA [98], whereas other studies report surface area values around 310 m^2/kg, depending on treatment and grinding conditions [99]. A higher specific surface area enhances the interaction between CPA particles and cement hydration products, thereby promoting pozzolanic reactions and improving matrix densification.

4. Setting Times of CPA Concrete

Initial setting times depict the time when water is added to cement and the point at which the cement paste begins to lose its plasticity, while the final setting time is the elapsed time between water addition and the stage at which the cement paste has completely lost its plasticity and attained sufficient rigidity. [101] defines the initial set as the time when the Vicat needle penetrates the paste to a depth of 25 mm, and the final set as the time when the Vicat needle no longer leaves a complete circular impression on the cement surface.

The setting-time behaviour of OPC/CPA concrete is characterised by a systematic increase in both the initial and final setting times with increasing CPA content, reflecting the slower pozzolanic reactivity and reduced hydration kinetics of CPA relative to OPC. This controlled retardation enhances workability retention and reduces heat of hydration, leading to lower heat evolution, supporting the suitability of CPA-blended cement systems for sustainable and mass concrete applications where thermal cracking is a concern.

Ogunbode & Akanmu [78] reported that increasing CPA content from 0% to 40% prolonged the initial setting time from 95 to 140 minutes and the final setting time from 155 to 230 minutes. Similarly, Hamzat *et al*., [100] observed increases in the initial setting time from 90 to 125 minutes and the final setting time from 153 to 210 minutes as CPA replacement increased from 0% to 30%. Comparable trends were reported by Raheem *et al*., [63], who recorded increases in initial and final setting times from 95 to 140 minutes and from 155 to 230 minutes, respectively, for CPA contents up to 20%.

Ogbonna *et al*., [99] further demonstrated that CPA addition increased the initial setting time from 52 to 123 minutes and the final setting time from 591 to 788 minutes, confirming the retardation effect of CPA on cement hydration. This behaviour is primarily attributed to the reduction in effective cement content and reactive surface area with increasing CPA replacement, which slows the hydration process and delays setting.

Additionally, Amusan *et al*., [102] reported that cassava peel ash-blended concrete (CPABC) exhibited satisfactory setting characteristics, with initial and final setting times within acceptable ranges for structural applications. Olatokunbo *et al*., [62] also observed that at lower replacement levels (5-10%), both initial and final setting times increased progressively, indicating that CPA-blended concrete is not prone to false setting.

Although numerous studies have reported increased setting times for CPA-Cement blended systems, however, in alkali-activated CPA-Cement systems, a reduced setting time has been reported [103]. Time evaluation is a fundamental means of understanding the hydration behaviour and field applicability of cement blends. The extended setting times observed in CPA blends, therefore, indicate a slow rate of pozzolanic interaction occurring within the blended system. It also suggests some limitations in its applicability to precast concrete requiring early demolding, repair materials needing rapid hardening, while presenting some benefits in mass concrete works requiring slower heat evolution.

CPA, like other SCMs such as fly ash, may reduce early heat production in concrete, indicating its effectiveness in concrete temperature control [64]. Although studies on the thermal characteristics of CPA-OPC systems are limited, with calorimetric data on CPA blends still emerging [91], experimental studies consistently show reduced cement content which implies a reduction in the clinker minerals (C_3S and C_3A), that contribute mainly to early heat release. CPA's denser microstructure also suggests a reduction in the localized heat accumulation, improving thermal conductivity uniformity and heat diffusion pathways. These observations collectively support lower hydration heat, improved thermal control potential, and temporal redistribution of heat evolution, all of which are crucial in mass concrete applications. A study by Grema *et al*. [104] on the thermal properties of cassava peelings using TGA/DTG identified its thermal characteristics for utilization as a good biochar precursor. The study concluded that CPA not only reduces thermal energy but also shortens the time required and facilitates the pyrolysis process.

5. Workability of CPA Blended Concrete

The influence of cassava peel ash (CPA) on the workability of concrete is strongly governed by replacement level, water-binder (w/b) ratio, and ash fineness. Several studies report an initial enhancement in workability at low CPA contents [83, 92]. A study by R. Abdulwahab *et al*., [92] observed a marked increase in slump from 33 mm in control mixes to 87 mm at 5% CPA replacement.

Similar trends of enhanced workability were reported by [63, 93, 100, 102]. However, this enhancement in workability; becomes impaired at a certain CPA replacement level. Conversely, a substantial body of literature indicates a workability reduction in CPA cement blends [62, 65, 89, 99, 105].

The enhanced workability of CPA blends may be due to the slow formation of hydration products with early stiffening abilities due to the low hydration rate and heat in CPA concrete. CPA, like other pozzolans, is effective at lowering the heat of hydration [97]. The low heat evolution implies a slow setting process, reduced water consumption, and an extended plastic phase. Its replacement of cement reduces the amount of clinker materials that influence hydration in concrete, thereby slowing the hydration process, which leaves more moisture in the pores of the concrete matrix, leading to an improved workability [106]. Consequently, in practice, CPA cementitious systems may remain workable for an extended period compared to pure OPC systems due to the slow formation of hydration products [107]. Slump reduction is, however, observed at a certain replacement level as CPA content increases, particularly beyond 10-15% replacement.

The w/b ratio also exerts a significant influence on the workability of CPA-cementitious systems. At higher w/b ratios, the extra water compensates the CPA water demand, making the filler effect more noticeable, thereby improving the workability. Studies by [62, 108] showed an optimum workability at a slightly high w/b ratio of 0.55; Awolusi *et al*., [86] reported satisfactory workability at a w/b of 0.61. Salau *et al*., [89] demonstrated that increasing the w/b ratio from 0.55 to 0.70 significantly improved slump values at all CPA contents, restoring workable mixes with true slumps even at higher replacement levels. Similarly, Owolabi *et al*., [105] identified an optimum workability at a w/b ratio of 0.75, confirming that additional mixing water is necessary to counteract the increased water demand.

The improved workability can also be attributed to the filler effect of fine CPA particles. The fineness of the ash due to its micro-filer effect reduces particle friction thereby enhancing flow and promoting better paste lubrication. Cementitious systems containing coarse CPA particles however exhibit reduced slump and workability owing to the increased water demand caused by the higher specific demand and the porous nature of the coarse CPA.

CPA seems to exhibit a dual influence on concrete workability. At low replacement levels (5-10%), it may enhance slump due to particle packing and lubrication effects, whereas higher dosages significantly increase water demand and reduce workability unless compensated by increased w/b ratios.

6. Water Absorption of CPA Blended Concrete

The water absorption and porosity characteristics of CPA-blended concrete are strongly influenced by the replacement level and curing age. At lower CPA contents, particularly around 5% cement replacement, water absorption is minimized due to pore refinement resulting from pozzolanic reactions that enhance the interfacial transition zone and reduce permeable voids [62]. However, at higher replacement levels, excess CPA particles that are not fully consumed in the pozzolanic reaction may act as inert fillers, leading to the formation of additional permeable pores and increased water absorption.

Experimental results further indicate that water absorption generally decreases with curing age as continued hydration and secondary pozzolanic reactions progressively densify the cementitious matrix. Results from a study showed that conventional concrete (0% CPA) had the highest water absorption, followed by 5% CPA blended concrete [65]. Although water absorption values tend to increase with higher CPA replacement levels at early ages, long-term curing significantly mitigates this effect, with specimens at 180 days exhibiting lower absorption than those at 28 days across all mix proportions [62].

Many studies have reported increased water absorption with increasing CPA content [66, 96, 98, 108]. Other studies reported reduced absorption when CPA was incorporated at low replacement levels and with fine particle sizes [80, 83]. At high CPA replacement, commonly observed in replacement levels between 15-20%, the cement dilution effect becomes significant. This can be further aggravated if the ash comprises coarse porous particles, which lead to high total porosity, increased capillary voids and consequently an increase in water absorption. This effect can be minimized by incorporating fine CPA at low replacement levels [65, 81, 106, 108]. At low replacement levels, typically below 10%, the pozzolanic reactivity of fine CPA produces secondary C-S-H that fills pores, improving particle packing and decreasing permeability.

For CPA-cement blended concrete, increasing tthe w/b ratio tends to increase water absorption because of higher capillary porosity. Low water-cement ratios produce dense concrete with fewer capillary pores, while high water ratios increase porosity, leading to greater water absorption and reduced durability [109]. However, with extremely low w/b ratios, the workability becomes poor and the compaction becomes inadequate, thereby increasing the water absorption. Therefore, the lowest water absorption is usually achieved not at the lowest possible w/b ratio, but at an optimum moderate w/b ratio combined with finely ground CPA and low-to-moderate replacement levels.

7. Density

Existing studies consistently indicate that cassava peel ash (CPA) has substantially lower bulk density and specific gravity than ordinary Portland cement (OPC), which has implications for the unit weight of CPA-modified concrete [62]. At the material level, this lower density suggests a potential reduction in the self-weight of concrete members when OPC is partially replaced with CPA. However, at the composite level, most experimental investigations report that CPA-blended concretes generally fall within the density range of normal-weight concrete. Amusan *et al*., [102] reported densities ranging from 2281 to 2548 kg/m^3 for cassava peel ash-blended concrete (CPABC), noting that density increases with curing age but decreases with increasing CPA content beyond an optimum replacement level. A slight increase in density was observed at low replacement levels (up to about 3%), attributed to improved particle packing. In contrast, higher substitutions resulted in marginally lower densities compared with the control mix. The density of concrete incorporating CPA is influenced by the replacement level and curing duration [78].

Studies by Salau *et al*., [89] and Olatokunbo *et al*., [62] further demonstrated that concretes containing 0-25% CPA, at 5% replacement intervals, exhibited densities between approximately 2410 and 2493 kg/m^3 and 2414 and 2473 kg/m^3, respectively. These values classify CPA-blended concretes as normal-weight concrete, with no appreciable variation in density across the replacement levels investigated. Owolabi *et al*., [105] reported comparable findings, with densities ranging from 2.391 to 2.485 g/cm^3, concluding that CPA had no significant effect on concrete density relative to the control mix. The limited influence of CPA on concrete density, despite its lower specific gravity, has been attributed to the dominant role of aggregates in governing concrete unit weight, as well as factors such as air content and aggregate size distribution [62, 89]. While CPA reduces binder density, its incorporation, particularly at low to moderate replacement levels, does not significantly alter the concrete density classification.

The variability in density of CPA concrete can be attributed to the source variability conditioned by soil, processing, and drying conditions. This is largely because CPA affects both the solid-phase packing and the formation of hydration products, and these responses depend strongly on the mix proportions. Mix design parameters such as higher water binder ratios tend to cause a more pronounced density reduction as excess water leaves behind voids after evaporation. Also, higher CPA replacement levels reduce density through the dilution effect at the early ages, as lower OPC produces less solid hydration products (C-S-H), while at low replacement levels, the fine particles act as a filler, thereby improving the packing density, reducing the void ratio, and as such can maintain density even at moderate replacement levels. Typically, CPA concrete exhibits lower density at early ages but shows partial recovery with age and significantly improved densification at later ages.

8. Chemical Properties of CPA

X-ray Fluorescence (XRF) spectrometry is employed to identify and quantify the elemental oxide composition of a pozzolan, providing essential information for evaluating its suitability as a supplementary cementitious material [71]. The chemical oxide compositions reported by different authors are summarized in Table 3.

Table 3 Oxide composition of cassava peel ash (CPA)%.

Reference	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	MnO	LOI	SG	SiO_2 + AL_2O_3 + Fe_2O_3
[105]	55.20	13.06	2.83	8.37	6.80	0.41	9.70	2.96	-	-	1.21	71.09
[79]	56.81	7.74	7.21	6.94	3.93	0.43	4.64	4.05	-	6.78	1.95	71.76
[62]	59.72	11.1	1.52	8.42	5.22	0.05	6.82	2.08	-	5.07	-	72.34
[68]	54.39	11.85	5.81	10.41	0.15	1.05	13.09	0.44	-	2.81	-	71.66
[97]	51.79	9.57	4.23	10.20	2.9	1.37	10.74	1.52	-	6.10	2.53	65.59
[86]	39.26	16.98	14.76	5.03	2.42	0.30	4.36	4.54	-		-	71.00
[93]	59.45	7.96	3.56	3.44	0.97	0.00	10.86	0.25	-	9.33	-	70.97
[96]	61.70	12.50	2.52	9.42	6.32	0.05	6.82	2.10	-	5.07	2.10	76.72
[98]	83.0	2.9	2.7	1.3	0.8	-	2.8	-	-	5.6	2.32	88.60
[92]	42.26	19.79	14.57	0.43	0.4	0.38	1.31	0.33	2.50	0.03	-	76.62
[81]	55.93	19.88	6.02	9.85	3.2	0.98	Trace	-	1.55	12.5	-	81.83
[71]	72.5	3.48	1.76	4.63	0.12	0.02	6.02	0.21	0.7	0.63	-	77.74
[94]	66.12	9.82	4.71	10.5	1.43	2.5	1.9	1.24	-	1.8	2.3	80.65

Note: SG = specific gravity; LOI = Loss on ignition.

The most dominant oxide in CPA is amorphous silica (SiO_2), with most reported values exceeding 50%. High silica content is a key indicator of pozzolanicity, as reactive SiO_2 reacts with calcium hydroxide [$Ca(OH)_2$] released during cement hydration to form calcium silicate hydrate (C-S-H), thereby enhancing strength and durability.

The alumina (Al_2O_3) content in CPA generally ranges from approximately 2.9% to 19.79%. Alumina present in an amorphous, reactive form rather than as crystalline impurities contributes to the formation of C-A-S-H gel, an additional hydration product that enhances the long-term strength development of concrete. The durability benefits of alumina are its ability to chemically bind chlorides, thus reducing the free chloride concentration and mitigating corrosion in reinforced concrete [110, 111]. Furthermore, alumina can help mitigate ASR by reducing pore-solution alkalinity and modifying reactive silica surfaces [112, 113].

Iron oxide (Fe_2O_3) is in the range of 1.41%-14.76%. The relatively high Fe_2O_3 content reported in some CPA studies may be linked to the cultivation of cassava on ferruginous tropical soils rich in iron oxides, coupled with differences in mineral uptake and ash processing conditions [114]. Iron oxide is not a major contributor to strength development but primarily influences the color of SCMs and may exert a secondary influence on heat evolution [115].

The CaO content of CPA ranges from 0.43% to 10.50%, suggesting it may function as a low-calcium pozzolan or, in some cases, exhibit moderate self-cementing behavior [116]. This variability is largely attributed to differences in combustion conditions and mineral uptake during plant growth, as higher calcination temperatures and soil-derived impurities can increase calcium content in the ash [117].

MgO content is generally below 5%, within acceptable limits for cementitious materials. Low MgO levels are desirable because excessive MgO can delay expansion due to brucite formation [118]. MgO hydrates more slowly than free lime, and its conversion to $Mg(OH)_2$ is associated with volumetric expansion, which can induce delayed expansion and potential instability in concrete [119]. Thus, the reported values indicate minimal risk of unsoundness when CPA is used as a partial cement replacement.

The alkali oxides Na_2O and K_2O in CPA exhibit significant variability, with K_2O content reaching 13.09% in some studies. According to [120], most agro-waste, such as biomass and crop-residue ashes, contain relatively high potassium content. Alkalis can enhance pozzolanic activity by increasing the pore solution pH; however, excessive alkali levels may increase the risk of alkali-silica reaction (ASR) in the presence of reactive aggregates and may also delay setting time [66].

Alkali-silica reaction (ASR) is the reaction between concrete pore solution and the reactive siliceous minerals found in certain aggregates [121]. ASR occurs in three basic stages: dissolution of the metastable silica (accelerated by alkalinity and temperature), gel formation and swelling of the gel - where the already formed porous high surface area silica gel with several hydrophilic groups undergoes osmosis, water adsorption and swelling [122]. It causes severe structural damage which shortens the lifespan of concrete structures by exerting significant expansion and internal pressure, posing great concern in terms of concrete durability and long-term performance [123-125]. SCMs with high alkali content e.g., Na_2Oeq >3.0 wt.% (calculated as $Na_2O + 0.658K_2O$), are of great concern, as these alkalis may dissolve in concrete's pore solution and elevate its pH [120]. High K_2O in concrete increases the sodium oxide equivalent (Na_2Oeq), thereby elevating the concrete solution's alkalinity, resulting in the dissolution of reactive silica in aggregates. Several agencies limit the alkali in concrete within the range of 2.5-4.5 kg/m^3 Na_2Oeq, considering the reactivity of the aggregates and their conditions of exposure, while the use of low reactivity aggregates or lithium-based admixtures has been recommended as ASR mitigation measures where supplementary cementitious materials with high K_2O are used [122, 125-127]. Recent studies have also shown that surface-waterproofing aggregates treated with silane and polyvinyl alcohol (PVA) can mitigate the adverse effects of ASR while significantly enhancing the compactness of the interfacial transition zone (ITZ) in concrete [128, 129].

The trace amounts of MnO, MgO, and Na_2O indicate minor mineral inclusions without adverse effects on performance [71]. SO_3 content generally remains below 4.54%, within acceptable limits. Moderate SO_3 levels can regulate setting time through controlled ettringite formation, whereas excessive amounts may lead to expansion and durability concerns. The reported values suggest that CPA is suitable for use in blended cement systems when properly proportioned. MnO occurs in small quantities (about 2.5%) and is typically inert in cement chemistry, with no significant influence on hydration or strength development.

Loss on ignition (LOI) values range mostly between 0.03% and 12.5%, reflecting variations in combustion efficiency and residual unburnt carbon. Lower LOI values indicate improved ash quality and better compatibility with cement, whereas higher LOI may increase water demand and reduce workability. ASTM C618 recommends a maximum LOI of 10% for pozzolanic materials.

Pozzolanic qualification is achieved when the combined content of SiO_2, Al_2O_3, and Fe_2O_3 equals or exceeds 70%. Reported values of 77.74% [71], 76.62% [92], and 70.97% [93] exceed the minimum requirement specified in [130]. The combined amount of Silica (SiO_2), Aluminum (Al_2O_3), and Ferrite (Fe_2O_3) for most of the CPA utilized in the studies was in the range of 65.59-88.60%. This suggests that these ashes were optimally calcined and well processed [88]. Understanding the chemical composition of CPA is essential for assessing its suitability for sustainable construction and other industrial applications, as compliance with quality and environmental standards ensures optimal performance while minimizing potential drawbacks [117].

Table 3 shows that Cassava Peel Ash (CPA) exhibits substantial variability in its chemical composition typical of agricultural ashes because of their variation in chemistry which depends largely on factors such as calcination temperature and duration, soil chemistry and cultivation environment, cassava variety and agricultural practices, ash collection and contamination by soil particles, grinding fineness, and analytical methods [74, 114, 131-134]. This underscores the need to standardize CPA as a supplementary cementitious material, adopting controlled processing conditions and standardized characterization protocols to reduce the observed chemical variability.

9. Pozzolanic Behaviour of CPA Blended Concrete

The incorporation of CPA into concrete mixtures initiates a pozzolanic reaction in which the reactive silica present in CPA combines with calcium hydroxide (portlandite) to form additional calcium silicate hydrate (C-S-H) gel, the primary hydration product responsible for strength development in concrete. The formation of additional C-S-H contributes significantly to the densification of the cement matrix, thereby enhancing the mechanical properties and durability of the concrete. CPA exhibits adequate chemical and mechanical properties to act as a supplementary cementitious material, with optimal replacement levels of 5-15% to enhance strength development through pozzolanic reactions.

The Pozzolanic activity index (PAI) measures the ability of pozzolanic materials to react with calcium hydroxide ($Ca(OH)_2$), for the purpose of forming the additional C-S-H needed to enhance concrete's strength and durability [94]. A study by Ogbonna *et al.*, [99] indicated that CPA demonstrated a PAI of 75.8%, while Ayodele *et al*., [93] found strength gains of 77.8% and 84.2% obtained for 5% and 10% replacement of cement with CPA. Both studies report values above the minimum 75% strength gain stipulated by ASTM C618-12a [130] for the suitability of the pozzolan for replacing cement. Ganesh *et al*. [94] analysed the pozzolanic activity index (PAI) for CPA cement replacement at 5%-20%. At 5% CPA, PAI increased from 100% at 28 days to 102% at 90 days; at 10% CPA, an increase from 101% at 28 days to 105% at 90 days; at 15% CPA, PAI also increased, starting at 104% at 28 days to 110% at 90 days, demonstrating a gradual enhancement in strength. At 20% CPA, the strength enhancement was not significant, with strength moving from 100% at 28 days to 101% at 90 days, indicating that pozzolanic activity of CPA increases with optimal proportions of pozzolanic materials and the adequate supply of calcium hydroxide ($Ca(OH)_2$), and declines with the excessive amount of pozzolanic material or when curing conditions are suboptimal.

The strength activity index (SAI) further evaluates pozzolanic performance by comparing the strength of blended cement to that of control concrete. According to ASTM C618-12a [130], the SAI must be 75% at 7 and/or 28 days for a material to qualify as a pozzolan. The variation in the Strength Activity Index (SAI) and the optimum replacement level of CPA in concrete blends is strongly influenced by curing age, mix proportions/water-binder ratio, and CPA processing conditions, including calcination temperature, grinding fineness, and sieving size. Salau *et al*., [89] using a mix ratio of 1:2:4 and a relatively high water-binder ratio found that for CPA-cement blends, 5% CPA met this threshold at 7 days, while at 15%, CPA achieved 79% at 28 days, while at 120 days the value at 15% CPA replacement increased to 87%, suggesting progressive pozzolanic activity and optimal cement replacement up to 15%. Beyond this level (20-25%), SAI values remained below 75% across all ages. A study by Ikponmwosa & Olonade [106] also reported that concrete containing up to 15% CPA had strength activity index above 75%. These findings suggest that extended curing substantially enhances CPA reactivity, allowing for structurally viable concrete at higher replacement levels. [92] evaluated CPA replacements between 1% and 5% in M20 concrete with a richer 1:1.5:3 mix and curing periods up to 90 days. Although later-age strength gain was observed, the optimal replacement was only 1%, at which compressive strength (32.9 MPa) remained comparable to that of the control (33.1 MPa). Beyond this level, strength reduction became significant. The lower optimum threshold was likely due to the denser mix matrix and lower tolerance for dilution effects in higher-strength concrete systems.

The processing of cassava peels to obtain finer CPA particles presents an ash that possesses larger specific surface areas that can accelerate pozzolanic reactions and improve filler effects within the cement matrix. A study by Nwa-David *et al*., [96] using nanosized CPA generally reported better mechanical performance indicating that reducing particle size enhances ash reactivity and particle packing efficiency.

Chemical characterization further confirms CPA's pozzolanic potential. The combined content of SiO_2, Al_2O_3, and Fe_2O_3 in CPA is 72.34%, exceeding the ASTM C618-12a [130] minimum requirement of 70% for pozzolanic materials. Additionally, the loss on ignition (LOI) of 5.07% and SO_3 content of 2.08% fall within acceptable limits. Positive results from pozzolanicity tests corroborate these findings, indicating that CPA satisfies the criteria for a high-reactivity pozzolan. However, materials slightly below the chemical thresholds may still exhibit pozzolanic behavior [62].

10. Mechanical Properties

10.1 Compressive Strength of CPA Blended Concrete

Across the literature, CPA-blended concretes consistently exhibit strength gain with curing age, reflecting ongoing hydration and secondary pozzolanic reactions. However, a systematic reduction in early-age compressive strength relative to plain OPC concrete is widely reported asCPA replacement levels increase.

At early curing ages (7-28 days), higher CPA contents generally result in pronounced reductions in strength due to cement dilution and the relatively slow kinetics of CPA pozzolanic reactions [63, 89, 135]. Most studies identify 5% CPA replacement as the threshold for minimizing early-age strength loss, with higher dosages (10-20%) causing significant reductions in 28-day strength [63, 89, 92]. Consequently, several authors report optimum CPA contents between 1-5% when early-age strength performance is prioritized [65, 80, 92]. Notwithstanding early-age reductions, CPA-blended concrete demonstrates progressive late-age strength development, attributed to delayed pozzolanic reactions between reactive silica/alumina in CPA and calcium hydroxide released during cement hydration. At curing ages beyond 50-90 days, concretes incorporating 5-15% CPA often attain compressive strengths comparable to, or in some cases exceeding, the control mix [72, 89]. This age-related increase in strength substantiates the pozzolanic nature of CPA. It aligns with ASTM C618-12a [130] requirements, which permit blended cements to achieve 65-90% of control strength at 28 days with further improvement at later ages [62, 93].

Higher replacement levels (20-40%) generally lead to persistent strength deficits despite prolonged curing, indicating an upper limit beyond which cement dilution outweighs pozzolanic benefits [63, 99]. Nevertheless, some authors report that CPA contents up to 10-15% can still satisfy minimum structural strength requirements, particularly for normal-strength concrete applications [62, 93].

A notable exception is observed with nanostructured cassava peel ash (NCPA), where significant strength enhancement is reported with increasing replacement level and curing age. NCPA-modified concretes achieved optimum compressive strength at approximately 19.5% replacement, surpassing conventional CPA performance due to improved particle packing, higher reactivity, pore refinement, and enhanced formation of C-S-H and C-A-H gels [96]. This highlights the influence of CPA processing and fineness on the evolution of strength.

Salau *et al*., [89] found that the control concrete (0% CPA) attained a 28-day compressive strength of 18.7 N/mm^2. Partial replacement of cement with cassava peel ash (CPA) resulted in a reduction in early-age strength, with values of 15.6, 15.3, and 14.7 N/mm^2 recorded for 5%, 10%, and 15% CPA, corresponding to strength reductions of 16.5%, 18.2%, and 21.4%, respectively, with further increases in CPA content leading to more pronounced reductions. At 120 days, the control concrete achieved a compressive strength of 22.3 N/mm^2, representing a 16.1% increase relative to its 28-day strength. In comparison, concretes incorporating 5%, 10%, and 15% CPA attained compressive strengths of 22.2, 21.2, and 19.4 N/mm^2, corresponding to strength gains of 29.7%, 27.8%, and 24.2%, respectively. This indicates that CPA has the potential to contribute to late-strength development when not more than 15% by weight of cement is used.

Ettu *et al*., [72] studied the strength of OPC-CWA binary-blended cement concrete with 5-10% replacement of OPC with CWA and reported that the CWA concrete was comparable to the control at 50 days of curing. The strength of the binary blended cement concrete was higher than that of the control at 90 days of curing for 5-15% replacement. Consequently, OPC-CWA binary-blended cement concrete was considered structurally suitable for high-strength applications, particularly when curing ages exceed 50 days, and optimal performance is achieved within the 5-15% replacement range.

Raheem *et al*., [63] investigated the feasibility of cassava peel ash (CPA) as a partial cement replacement in concrete. CPA was incorporated at replacement levels ranging from 0 to 20% by weight of cement at 5% increments. Concrete was proportioned using a nominal mix ratio of 1:2:4, and cube specimens were cured for periods between 7 and 28 days. found that for the control mix (0% CPA), the 28-day compressive strength was 28.0 N/mm^2. In contrast, mixes incorporating 5%, 10%, 15%, and 20% cassava peel ash (CPA) recorded strengths of 14.82, 13.85, 14.75, and 9.85 N/mm^2, respectively, indicating an overall reduction relative to the control. Except for the 20% CPA replacement level, the strength disparity between the control concrete and CPA-blended mixes progressively diminished with curing age, particularly at 28 days for the 5%, 10%, and 15% replacement levels. Based on the assessment of strength development, CPA replacement levels between 5% and 15% were identified as optimal.

Abdulwahab *et al*., [92] reported that the compressive strength of concrete incorporating 5% cassava peel ash (CPA) exhibited a consistent reduction relative to the control mix (0% CPA) across all curing ages. Specifically, strength values decreased from 16.5 to 13.5 N/mm^2 at 7 days, 21.2 to 16.8 N/mm^2 at 14 days, 25.3 to 17.7 N/mm^2 at 28 days, 30.4 to 20.4 N/mm^2 at 56 days, and 33.1 to 24.5 N/mm^2 at 90 days, corresponding to percentage reductions of 18.2%, 21.9%, 30.0%, 32.9%, and 26.0%, respectively. Notably, although strength loss persisted at later ages, the relative reduction at 90 days was lower than those recorded at 28 and 56 days, indicating a delayed strength contribution from CPA.

CPA blended concretes typically exhibit lower compressive strength than non-blended concrete, ranging from about 15-30% at 28 days, given replacement levels of 5-15%, although larger reductions may occur depending on ash quality and mix design. However, between 28 and 120 days, CPA mixtures commonly exhibit 1.5-2.0 times greater relative strength gain than corresponding OPC concretes. They either approach, match, or occasionally exceed the strength of control concretes after 90-120 days of curing. These findings strongly suggest that CPA functions as a slow-reacting pozzolan, with its principal contribution occuring during the later stages of hydration through the gradual consumption of calcium hydroxide and formation of secondary calcium silicate hydrate (C-S-H). Consequently, evaluations based solely on 28-day strength substantially underestimate the long-term mechanical performance of CPA-blended concrete, particularly when replacement levels are maintained within the optimum range of 5-15%.

The early strength reductions observed at higher CPA contents are primarily attributable to the slow kinetics of the pozzolanic reaction rather than a complete loss of cementitious potential. The underlying mechanism for the lower early-age strength in Cassava Peel Ash (CPA)-blended concrete is mainly due to the dilution effect, which reduces the OPC clinker content and the minerals responsible for rapid early hydration and strength gain. The slow pozzolanic reaction causes a slow formation of secondary C-S-H gel, which delays pore refinement and early microstructural densification, while the reduced hydration kinetics limit the formation of hydration products responsible for early stiffness and strength [89].

Reports from previous studies show improved mechanical and durability properties at moderate CPA replacement levels in concrete [74]. As such, moderate replacement levels are preferred in practice to provide a compromise (optimal) between sufficient early-age strength and improved later-age performance. A range of (5-15%) replacement has been suggested by previous studies for structural concrete, as higher percentages significantly delay strength development at the early ages [80, 81, 84, 94, 99, 136]. Other approaches for early strength development with CPA could involve the application of prediction and optimization models, which enable systematic optimization of mix parameters that will allow for early strength achievement [81, 96]. Moreover, the use of CPA alkali-activated binders offers another strategy for early strength development, shortened setting time, and improved overall concrete performance at the early ages [103, 136].

10.2 Flexural Strength of CPA Blended Concrete

Owing to its brittle nature, plain concrete fails abruptly in flexure; consequently, the contribution of concrete flexural strength is often secondary in reinforced concrete members where steel reinforcement primarily resists tensile stresses [89].

Studies on Cassava Peel Ash (CPA)-blended concrete indicate that the flexural strength generally decreases with increasing CPA replacement, particularly at early curing ages, but improves with curing age across all replacement levels.

Salau *et al*., [89] reported that flexural strength development in CPA concrete followed trends similar to those of compressive strength development. Notably, concretes containing 5%, 10%, and 15% CPA exhibited flexural strengths comparable to the control specimen at extended curing ages of 90 and 120 days. At 120 days, the average percentage difference relative to the control was 4.1%, 6.8%, and 11.4% for 5%, 10%, and 15% CPA replacement levels, respectively, indicating long-term strength convergence due to sustained pozzolanic reactions. Hamzat *et al*. [100] reported a 15% increase in flexural strength with CPA replacement, reaching about 13.7 MPa at 90 days. A similar trend was reported by Ismail *et al*., [95]. Ogbonna *et al*., [99] revealed the best flexural strength at 5% CPA replacement with a strength of approximately 15.2 MPa at 90 days. Awolusi *et al*., [86] predicted a flexural strength increase from 11.85 MPa at 28 days to 14.95 MPa at 90 days under optimum conditions of 3% CPA, Ogunbode *et al*., [98] reported a flexural strength about 19% higher than control when combined with 0.5% kenaf fibre, while Ganesh *et al*., [94] observed a 4% improvement in flexural strength at 28 days which attained a 10.4% increase at 90 days using an optimum CPA replacement of 15% beyond which the flexural strength decreased. The increase in flexural strength is due to a more pronounced pozzolanic reaction, which produces additional C-S-H and strengthens the concrete matrix. However, mixes containing up to 15% CPA still achieved satisfactory strength activity performance at later ages due to continued pozzolanic reactions. This suggests that the secondary C-S-H generated by the pozzolanic reaction is particularly effective in improving crack resistance and tensile stress transfer.

10.3 Split Tensile Strength of CPA Blended Concrete

Although concrete is not typically designed to resist tensile stresses, its tensile strength remains a critical parameter for crack control and serviceability limit state. Previous studies have shown that the split tensile strength of cassava peel ash (CPA) blended concrete increases with curing age but is strongly influenced by the level of cement replacement. According to Abdulwahab *et al*., [92], tensile strength improved consistently as curing progressed from 7 to 90 days across all CPA replacement levels. For the control mix (0% CPA), the split tensile strength increased from 1.8 N/mm^2 at 7 days to 3.5 N/mm^2 at 28 days, and then to 4.1 N/mm^2 at 90 days, reflecting the normal hydration-driven strength gain of Portland cement. However, increasing CPA content generally reduced split tensile strength relative to the control. At 28 days, concretes containing 1-5% CPA exhibited tensile strengths of 3.9, 3.8, 3.6, 3.6, and 3.2 N/mm^2, respectively, with the optimum performance recorded at 1% CPA replacement. Beyond this level, a progressive decline in tensile strength was observed, indicating that higher CPA dosages adversely affect tensile resistance, particularly at extended curing ages. These trends are consistent with the findings of [62], who reported that while split tensile strength generally increases with curing age, it decreases as CPA replacement levels increase from 5% to 25%. Based on tensile performance and serviceability considerations, CPA replacement levels of 15-20% were identified as potentially acceptable for enhancing the serviceability behaviour of binary blended cement concrete.

11. Durability Performance of Cassava Peel Ash (CPA)-Blended Concrete

Durability is a critical factor in infrastructure development, as structures are expected to have long service lives [137].

Ogbonna *et al.*, [82] investigated the durability of CPA concrete by monitoring weight loss and residual mechanical strength following immersion of concrete mixtures with various CPA replacement levels in concentrated sulphuric acid (H_2SO_4) and sodium hydroxide (NaOH) solutions, and by examining them at different curing ages. The results indicated that deterioration due to both acidic and alkaline exposure was strongly dependent on curing duration and CPA content. Specimens subjected to prolonged curing exhibited significantly lower rates of weight loss and strength reduction compared to those exposed at early curing ages, reflecting the beneficial role of continued hydration and pozzolanic reaction in refining the pore structure. Despite this curing-age dependency, an overall reduction in durability performance was observed with increasing CPA replacement levels. Optimal performance was recorded at 5% CPA replacement for specimens cured for 90 days. At this replacement level, weight losses of only 0.56% and 0.50% were measured under H_2SO_4 and NaOH exposure, respectively, while corresponding compressive strength losses were limited to 6.04% and 6.13%.

Similarly, Olatokunbo *et al.*, [62] assessed the acid resistance of CPA concrete in a 5% sulphuric acid solution prepared with distilled water for 180 days. The durability performance was quantified by measuring changes in specimen weight and compressive strength before and after exposure, and the results were compared with those of the control mix. The percentage weight loss relative to the control mix at CPA replacement levels of 5, 10, 15, 20, and 25% was 0.6%, 0.9%, 0.5%, 1.3%, and 1.9%, respectively. Among the investigated mixes, the concrete containing 15% CPA exhibited the lowest weight loss, indicating the highest resistance to acid attack.

Ayodele *et al.*, [93] investigated the durability of concrete specimens immersed for 30 days in aggressive environments, including 1% sulfuric acid (H_2SO_4), 5% sodium sulfate (Na_2SO_4), and 5% sodium chloride (NaCl) solutions. The reduction in compressive strength after exposure to these media was used as an indicator of resistance to acid, sulphate, and chloride attack, providing insight into the long-term performance of CPA-blended concrete under harsh service conditions.

A study by Akinpelu *et al*., [71] observed that with the incorporation of 7% CPA into mortar, high Ca (40.10 wt%) and O (20.40 wt%) contents accompanied by substantial Al (15.45 wt%) and Si (8.10 wt%), were observed, indicating a well-developed hydration matrix. Exposure to sulfate media however, induced pronounced elemental redistribution, evidenced by a 10 wt% increase in Ca, a 12.10 wt% reduction in O, and an increase in Si to 12.50 wt%. These changes reflect sulfate-driven decalcification and degradation of calcium silicate phases, coupled with relative enrichment of silica-rich residues.

Olatokunbo *et al*., [62] evaluated the durability of CPA-blended concrete in terms of chloride resistance using the rapid chloride penetration test at curing ages of 7, 28, and 90 days. The measured charge passed for CPA concrete specimens decreased from 4400 coulombs at 7 days to 3650 coulombs at 28 days and further to 2464 coulombs at 90 days. In comparison, the corresponding values for the control (normal) concrete were 6650, 5608, and 2750 coulombs, respectively. At all curing ages, CPA concrete exhibited significantly lower charge passed than the control mix, indicating reduced chloride ion permeability. By 90 days, the chloride permeability of CPA concrete was markedly lower than that of the control concrete, demonstrating its superior resistance to chloride ingress.

Olonade and Abdullah [108] studied the effect of calcium and sodium sulphates on the strength of blended cassava peel ash (CPA) cement mortar. CPA replaced 20% by weight of several cement brands, with samples made from these cement brands exposed to a 50 g/l concentration of calcium and sodium sulphate solutions for 90 days. The results indicated that sulphate attack had varying effects on flexural and compressive strengths depending on the cement brand, while the incorporation of CPA improved resistance to sulphate attack by mitigating strength reduction. Alhamami [138] examined sulphate durability from agro-based precursors Cassava Peel Ash (CPA), Rice Husk Ash (RHA) and metakaolin (MK) as an alternative to Portland cement. Specimens were immersed in 5% sodium sulphate for up to 90 days, and performance was assessed by compressive strength retention, mass loss, and surface deterioration. The mix with 50% CPA, 33% MK and 17% RHA achieved the highest sulphate resistance, retaining 89.54% strength with only 17.3% weight loss, suggesting that CPA contributed much more significantly to enhancing the sulphate durability.

Durability enhancement in CPA cementitious systems is basically controlled by it's microstructure. CPA participates in pozzolanic reactions that produce additional calcium silicate hydrate (C-S-H), which fills capillary voids, refines the pore structure, and densifies the interfacial transition zone, thereby reducing permeability and enhancing resistance to sulfate ingress, chloride penetration, and other durability-related deterioration mechanisms. Ogunbode *et al*., [98] reported that finely ground CPA promoted a denser matrix and stronger fibre-matrix bonding in kenaf fibre concrete, reduced voids and improved interfacial transition zones (ITZ). The reduced permeability achieved through pore refinement has important implications for durability. Numerous studies have shown that refined pore systems reduce permeability indicators, such as water absorption and sorptivity, thereby improving resistance to sulfate and acid attack. Abdulwahab and Uche [80] observed a decreased water absorption with CPA, due to improved pore structure and compactness. CPA improved resistance to H_2SO_4 and $MgSO_4$ attack, reducing weight loss compared to control. The reduced ingress of aggressive ions was attributed to a denser and less permeable matrix. Ayodel *et al*., [93] in a study of lateritic concrete demonstrated that a CPA cementitious system containing 5% CPA and 20% laterite sand presented remarkable strength and durability performance due to refinement in the pore structure, leading to decreased permeability. Similarly, Akinpelu *et al*., [71] demonstrated that microstructurally dense CPA mortars experienced lower strength losses during sulfate exposure than control specimens. Permeability measurements are therefore essentially macroscopic manifestations of the underlying microstructure.

Cassava Peel Ash (CPA) enhances the sulphate and chloride resistance of concrete mainly through the mechanism of pozzolanic reaction and pore refinement similar to other SCMs such as fly ash and silica fume [73]. CPA consumes free calcium hydroxide, thus inhibiting the formation of gypsum, ettringite, brucite, M-S-H gel, and thaumasite, which are expansive products that can induce internal stresses that could initiate cracks, spalling, and eventual loss of strength [139]. The dense pore structure achieved reduces permeability, which slows sulphate ion penetration [71]. Similarly, the refined pore structure decreases chlorine diffusion, with the alumina contributing to limited chlorine binding, thereby reducing reinforcement deterioration. Further insights into the chemical durability mechanisms were provided by [80, 92], who observed that sulphate attack in CPA self-compacting concrete (SCC) reduced progressively with increasing CPA content relative to the control mix. This behaviour was attributed to the lower calcium oxide (CaO) content of CPA compared to ordinary Portland cement, resulting in reduced calcium hydroxide availability and consequently improved sulphate resistance.

Table 4 below summarizes some studies and their findings.

Table 4 Summary of some of the studies and their key findings.

Author(s) & Year	Concrete Grade	Mix Design	W/B Ratio	CPA Range	Optimum CPA	Curing Ages	Key Findings
[92]	M20	1:1.5:3	0.45	0-5% (1% interval)	1%	7, 14, 28, 56, 90 days	• CPA increased workability from 33 mm at 0% to 87 mm at 5% CPA. • Compressive strength decreased with higher CPA; optimum at 1% (32.9 N/mm^2 vs. 33.1 N/mm^2 control). • Split tensile strength also decreased with higher CPA; optimum at 1% (3.9 N/mm^2 vs. 4.1 N/mm^2 control).
[140]	Self-compacting concrete (SCC) Grade 35	OPC: 475 kg/m^3 FA: 804.1 kg/m^3 CA: 885.9 kg/m^3 (1:1.7:1.9)	0.40 (190/475) kg/m^3	0-25% CPA (5% interval)	5% CPA	3, 7, 28 Days	• Slump flow decreased with CPA (691 mm-642 mm); mixes up to 15% met EFNARC limits, but 20-25% fell slightly below. • Passing ability reduced at higher CPA (20-25%), failing EFNARC minimum. • Segregation resistance improved with CPA, all within EFNARC limits. • Compressive strength declined with CPA content, but at 5% CPA, 28-day strength slightly exceeded grade 35 i.e. 35.6 MPa • Response Surface Methodology (RSM) model accurately predicted compressive strength with high R^2 (0.965).

[80]	Grade 35	OPC: 475 kg/m^3 FA: 804.1 kg/m^3 CA: 885.9 kg/m^3 (1:1.7:1.9)	0.40 (190/475) kg/m^3	0-25% CPA (5% interval)	5% CPA	3, 7, 28 Days	• At 5% CPA, 28 days compressive strength slightly exceeded design grade by 2.86%. • 5% CPA reduced water absorption by 21.15% as compared to the control. • 5% CPA improved resistance in 5% H_2SO_4 (approximately 5% less loss in weight compared to the control) and in 5% $MgSO_4$ (approximately 8% less loss in weight compared to the control). • 5% CPA had approximately a 5% higher weight loss compared to the control at an elevated temperature of 1000°C.
[71]	Fibre reinforced Mortar	Cement (7 kg); Sand (20.2 kg) (1:3)	0.50	0-21% (7% interval)	14% CPA, 1% Sisal fibre	7, 28, 56 Days	• Sulfate resistance improved with CPA. The best compressive strength retention was 5.93% loss at 120 days. • Mortars with CPA showed lower expansion and weight loss under Na_2SO_4 attack. • Flexural strength loss was moderate with 14.68% at 120 days. • Microstructural analysis confirmed pore refinement with CPA, contributing to durability.

[131]	Sand-crete block (mortar)	1:8	0.45-0.60 (0.45 optimum)	0-30% (5% interval)	5% CPA	28 days	• Compressive strength decreased with CPA replacement, but 5-10% CPA still produced blocks meeting minimum strength requirements for non-load bearing walls. • Density reduced slightly with CPA, making blocks lighter. • Water absorption increased with CPA, but remained within acceptable limits at low replacement levels. • Optimization model identified 5-10% CPA as the best balance between strength, durability, and sustainability.
[86]	Bamboo reinforced structural beam	OPC: 675 kg/m^3 FA: 990 kg/m^3 CA: 660 kg/m^3 (1:1.5:1)	0.61	0, 10, 20% (CPA) 12, 14, 16 mm (Bamboo)	3% CPA; 16 mm bamboo	28, 56, 90 Days	• Flexural strength increased with curing age; strain decreased with age. • Beam depth strongly influenced flexural strength; higher length/depth ratios gave higher strength and lower strain. • CPA content had negligible effect beyond 10-20%, but low replacement (≈3%) was optimal.

[65]	Concrete	1:2:4	0.55	0-10% (2.5% interval)	5%	7, 14, 21, 28 days	• Slump reduced with increase in CPA from 45 mm at 0% CPA to 25 mm at 10% CPA. • Compressive strength of 2.5% CPA was almost the same as the control, with 5% CPA achieving more than the control at 28 days. • Water absorption increased with age but decreased with an increase in CPA. 0% CPA had the highest of 6.70%, while 5% CPA had 5.72%; the lowest was 5.32% at 2.5% CPA at day 28.
[100]	Concrete	1:2:4	0.50	0-30% (5% interval)	5% (compressive), 15% (flexural)	21, 28, 56, 90 days	• Slump increased with addition of CPA (12-18 mm). • Setting time increased with CPA content. The initial setting time increased from 90 to 125 min, while the final setting times increased from 153 to 210 min. • Compressive strength decreased with CPA, but 5% replacement gave values close to control (≈20-25 N/mm^2 at 28-90 days). • Flexural strength improved up to 15% CPA achieving 13.7 N/mm^2 at 90 days.

[106]	Concrete	1:2:4	0.50-0.8 Optimum = 0.7	0-25% (5% interval)	5-10%	7, 28, 56, 90, 210 Days	• Workability reduced with increased CPA. • Shrinkage increased with time, decreased with CPA, showing improved dimensional stability. • Compressive strength reduced at higher CPA levels, but 5-10% CPA gave values close to control. • Optimum CPA replacement was 5-10%, balancing strength, shrinkage resistance, and durability.
[81]	Concrete Grade 25	OPC: 290 kg/m^3; FA: 776.35 kg/m^3; CA: 1198.65 kg/m^3 (1:2.7:4)	0.50	-	2.4% (Compressive), 7.45% (Flexural)	28 days	• Compressive strength was achieved with the highest value of 28.51 MPa at 2.4% CPA. • Flexural strength was achieved with the highest value of 10.36 MPa at 7.45% CPA. • Central Composite Design (CCD) optimization led to a further enhancement of the compressive and flexural strengths by 4.43% and 5.37%, respectively. • The numerical optimization gave a desirability score of 1.0. The adequacy tests performed demonstrated a robust correlation between laboratory results and model-simulated values, as confirmed by the student's t-test.

[96]	Concrete	1:1.5:3	Varied w/b	0-20% (1.5% interval) nanosized CPA	19.5%	7, 14, 28, 56, 90 and 150 days	• Compressive strength at 19.5% nanosized CPA gave the highest strength of 36.90 MPa at 150 days. • Predictive modeling error was less than 10%. The predictive network was reliable at a 95% confidence level with calculated T-value (-0.11) less than T-table (2.04).
[99]	Concrete (grade 35)	OPC: 290 kg/m^3; FA: 776.35 kg/m^3; CA: 1198.65 kg/m^3 (1:2.7:4)	0.45	0-40%	5-10% CPA	3, 7, 28, 60, 90 days	• Slump decreased with an increase in CPA content. • Setting time increased. The initial setting time increased from 52 to 123 min; final from 591 to 788 min for CPA replacement from 0 to 40%. • Compressive strength was low at early ages, but strength gain improved at longer curing; 5% CPA attained values about 94% of the control at 90 days. • Flexural strength demonstrated a similar trend to compressive strength, with 5% CPA performing best, achieving about 89% of the flexural strength of the control at 90 days. • Pozzolanic Activity Index (PAI) = 75.8%, confirming CPA's suitability as SCM.

[78]	Concrete	OPC: 309 kg/m^3; FA: 680 kg/m^3; CA: 1430 kg/m^3 (1:2.2:4.7)	0.65	0-40% CPA (cement) 0-40% laterite (sand)	30% CPA with 30% laterite	7, 21, 28, 56, 90 days	• Slump decreased with increasing CPA and laterite from 110 mm down to 38 mm. • Setting time increased with CPA, initially increased from 95 to 140 min; finally increased from 155 to 230 min. • Density decreased with an increase in CPA and laterite (from 2537 kg/m^3 at 0% CPA/lat. to 2204 kg/m^3 at 30% CPA/lat.). • Compressive strength decreased at early ages with CPA and laterite, but improved at longer curing ages of 56-90 days. CPA/OPC laterized concrete achieved 49-75% of control strength at 28-90 days.
[98]	Kenaf fibre reinforced CPA blended Concrete	OPC: 539 kg/m^3; FA: 814 kg/m^3; CA: 850 kg/m^3 (1:1.5:1.6)	(205/539) kg/m^3 = 0.40	0% and 10% CPA	10% CPA with 0.5% kenaf fibre	7, 28, 91 days	• Slump decreased with CPA and fibre; control gave 190 mm, 10% CPA achieved 155 mm, CPA + 0.5% fibre gave a slump of 60 mm, abd CPA + 1% fibre gave a slump of 20 mm. • Compressive strength: CPA reduced compressive strength at early ages; 10% CPA mix showed 14% lower strength at 28 days compared to control, and 4% reduction at 91 days. • Tensile strength improved with the inclusion of kenaf fibres (CPA + KBF)

							at later ages, up to a 19% gain at 91 days. • Flexural strength was highest at 0.5% fibre with CPA, 6.2 N/mm^2 at 91 days (19% higher than control). • Microstructure was enhanced with additional C-S-H gel formation and stronger fibre-matrix bonding.
[89]	Concrete	1:2:4	0.55, 0.60, 0.65, 0.70 optimum = 0.70	0-25%	15% CPA	7, 28, 56, 90, 120 Days	• Slump decreased with CPA content. Workability improved as w/b increased. • Density remained within normal concrete range. • Compressive strength decreased with CPA content at early ages but improved at later ages due to pozzolanic activity. At 28 days, 5-15% CPA achieved SAIs of 79-83%; at 120 days, SAIs rose to 87-99%. • Flexural strength increased with curing age but decreased with an increase in CPA content.

[63]	Concrete	1:2:4	0.6-0.70	0-20%	5-15% CPA	7, 14, 21, 28 days	• Slump decreased as CPA content increased. • Water absorption with CPA replacement, reflecting higher porosity. Absorption values within range up to 15% CPA. • Compressive strength decreased with CPA content at early ages but improved with curing age. • Density reduced slightly with CPA, but values remained within normal concrete range.
[105]	Concrete	1:2:4	0.55, 0.60, 0.65, 0.75. (Optimum 0.75)	0-20%	5% CPA	7, 14, 21, 28 days	• Slump decreased as CPA content increased. • CPA had no significant effect on concrete densities. • Compressive strength increased with curing age but decreased with higher CPA content.
[62]	Concrete (Grade 30)	1:1:1.5	0.60	0-25%	10% CPA	7, 14, 28, 90, 120, 180 days	• Slump decreased with CPA content increase. • Water absorption increased with CPA replacement. Absorption values were still within acceptable limits up to 15% CPA. • Density values remained within normal concrete range.

							• Compressive strength decreased with CPA content at early ages but improved with curing age due to pozzolanic activity. Optimum strength balance at 10-15%. • The durability and acid resistance improved considerably at a 10% CPA replacement.
[94]	Concrete	Paver blocks for heavy traffic (1:1:3)	(186/548) Kg/m^3 = 0.32	0-20% (5% interval)	15% CPA	28 and 90 Days	• Flexural strength peaks at 15% CPA (7.8 MPa at 28 days to 9.44 MPa at 90 days), an increase of approximately 21%. • Workability decreased with increasing CPA from 95 mm at 0% CPA to 60 mm at 20% CPA. • Compressive strength peaked at 15% CPA (56.7 at 28 days to 68.5 MPa at 90 days), a 20.8% increase, then declined at higher replacements. • Water absorption increased slightly with CPA, but remained within limits for paver blocks at 3.1%. • Microstructural analysis confirmed pozzolanic reaction and dense matrix formation at optimum CPA. • PAI at 5% CPA increased from 100% at 28 days to 102% at 90 days; at 10% CPA, from 101% at 28 days to 105% at 90 days; at 15% CPA, from 104% at 28 days to 110% at 90 days.

[141]	Cement paste	-	0.40	0-10% (5% interval)	5% CPA	7, 14, 21 and 28 days	• At 5% CPA: compressive strength reduced by 3.41%, flexural strength by 3.33%, slump reduced by 17.65% below control, water absorption increased by 6.86%. • At 10% CPA: compressive strength reduced by 11.36%, flexural strength by 11.67%, slump reduced by 41.18%, water absorption increased by 20.58%.

12. Drying Shrinkage

Drying shrinkage is a critical time-dependent deformation in concrete that significantly contributes to cracking, thereby increasing the susceptibility of concrete structures to aggressive environmental agents. The formation of shrinkage-induced microcracks facilitates the ingress of deleterious substances such as chlorides and carbon dioxide, consequently accelerating the corrosion of embedded steel reinforcement [106]. The influence of cassava peel ash (CPA) on the drying shrinkage behaviour of concrete has been examined with particular emphasis on particle size, replacement level, and curing age. Olatokunbo *et al*., [62] reported that the average particle size of CPA exerts a significant effect on shrinkage deformation. Their results showed that concrete incorporating 20% CPA exhibited higher shrinkage than the control mix, while a 15% CPA replacement produced shrinkage values comparable to those of conventional concrete. Interestingly, a further increase in CPA content to 25% resulted in shrinkage values lower than those of the control mix. This behaviour was attributed to the high fineness of CPA particles, which enhances pozzolanic reactivity and promotes pore refinement within the cement paste matrix. The refined pore structure reduces capillary tension during moisture loss, thereby mitigating shrinkage deformation. Consequently, the incorporation of micro-fine CPA particles was shown to be effective in reducing drying shrinkage. Complementary findings were reported by [106], who investigated the effect of cassava peel ash (CPA) on the shrinkage property of concrete. Cement was replaced with CPA at replacement levels of 0, 5, 10, 15, 20 and 25% by weight of cement, used as the binder to produce concrete specimens, while water-binder ratios (w/b) were varied between 0.5 and 0.8. The long-term shrinkage strains of CPA-modified concrete were measured under controlled environmental conditions, with an average temperature of 24°C and relative humidity of 64.28%. Their study revealed that concrete containing up to 15% CPA exhibited approximately 24% lower shrinkage strain than normal concrete at curing ages of 90 days and beyond. Furthermore, the rate of shrinkage deformation was consistently lower in CPA-blended concretes (15% replacement) compared to the control mix, indicating improved dimensional stability over time.

Shrinkage strain reduction in Cassava Peel Ash (CPA)-blended concrete can be attributed to the pore refinement, reduced paste volume and internal moisture regulation. This mechanism is consistent with the general behaviour of pozzolans, in which pozzolanic reactivity reduces permeability and capillary porosity over time [68]. The pore refinement is attributed to the formation of additional C-S-H gels, which fill capillary pores and decrease the volume of evaporable water, reducing the shrinkage strain since drying shrinkage is mostly due to loss of capillary water and capillary tension in connected pores.

CPA replacement creates a dilution effect by reducing the total amount of cement, leading to lower early hydration product volume and lower overall paste available to undergo volumetric contraction as less shrinkage-active hydrated gel is formed per unit volume. Also, like other agro-wastes, CPA particles are porous, with high surface area and high water-absorption capacity, which reduces the water available for hydration [94]. Through this micro internal curing effect, water is slowly released during hydration, maintaining the internal relative humidity for longer periods, thereby reducing the internal drying shrinkage.

13. Microstructure of CPA Blended Concrete

Concrete microstructure refers to the internal arrangement, morphology, and distribution of its constituent phases at the microscopic level. The study of concrete microstructure is essential as macroscopic properties of concrete are controlled primarily by its microstructural characteristics.

Ogunbode *et al*., [98], in a study of the microstructure of CPA blended concrete using scanning electron microscopy (SEM), analysed both the Portland cement (CEM I) and cassava peel ash (CPA) concrete specimens, which revealed the formation of calcium-silicate-hydrate (C-S-H) gel, confirming the progression of hydration reactions. A more uniformly distributed, denser C-S-H gel was observed in the CEM I concrete after 91 days, compared to the control.

Similarly, Akinpelu *et al*., [71] investigated the microstructural characteristics of cassava peel ash (CPA) to assess its suitability as a supplementary cementitious material in mortar. The SEM micrograph (Figure 2) indicates highly irregular morphologies with folded and flake-like structures that increase specific surface area, which enhances pozzolanic interaction with calcium hydroxide, while the presence of deep crevices and surface fissures promotes mechanical interlocking with the cement matrix and improves microstructural bonding. Overall, the SEM analysis demonstrated a dense, well-formed and relatively uniform microstructure characterized by hydration products such as calcium hydroxide (CH) and calcium silicate (CS).

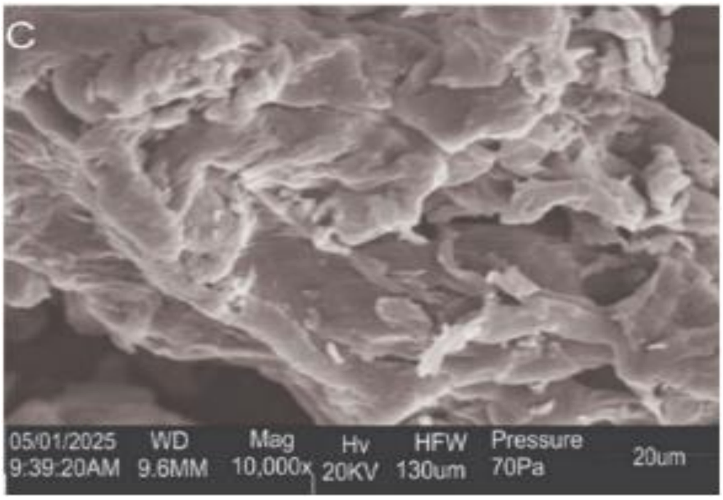

Figure 2 SEM of CPA blended concrete. Source: Akinpelu *et al*., [71].

Ganesh *et al*., [94], in a study of a cementitious matrix incorporating both cassava peel ash (CPA) and glass fiber (GF), reported a dense and refined microstructure with an observed formation of needle-like calcium silicate hydrate (C-S-H) gels and the reduced visibility of large portlandite crystals, indicating active pozzolanic reactions between the silica-rich CPA and calcium hydroxide released during hydration.

Consequently, CPA-modified concrete mixtures demonstrate improved performance, particularly in strength development, primarily due to microstructural modification and reduced residual $Ca(OH)_2$ content.

14. Alkali Activation of CPA

Alkali-activated binders, also known as geopolymers, are being extensively researched as a possible conventional cement substitute in concrete composition [142]. The activation of SCMs using alkaline precursors for geopolymer concrete (GPC) offers a sustainable alternative to complement the rising demand for binder alternatives for infrastructural development. They have emerged as sustainable alternatives to conventional Portland cement due to their significantly lower carbon footprint. Alkali-activated binders present advantages of local adaptation with the availability of suitable materials, promote early strength gain, have a lower heat of hydration, lower cost and a hardened, water-tight, and less soluble binder as compared to Portland cement hydrates [73, 143].

GPC produced with alkali-activated CPA has been reported to possess superior mechanical properties when compared to CPA-added cement concrete, offering enhanced properties such as early strength development and reduced setting times, which are properties considered necessary in construction, where structural elements must attain sufficient load-carrying capacity within a short period after concreting, to accelerate construction schedules, thereby improving productivity and minimizing delays. However, little has been done in terms of exploring CPA's applicability to alkali activation [73, 103].

A study by Baenla *et al*., [144] investigated the feasibility of partially replacing low-reactive volcanic ash with cassava peel ash (CPA), at replacement levels ranging from 0-30% by mass in geopolymer synthesis. The findings revealed that the gradual incorporation of CPA significantly improved the fresh and hardened properties of the geopolymer system. Specifically, replacing volcanic ash with CPA resulted in a substantial reduction in the initial setting time (by approximately 64%), indicating enhanced early-age reactivity. At the same time, the compressive strength of specimens cured at ambient temperature increased markedly, reaching up to a 733% improvement at 28 days compared with the control mix containing only volcanic ash. Microstructural and chemical analyses showed that CPA contributed additional reactive phases, promoting more effective alkaline activation. An optimal replacement level of about 20% CPA produced denser and more compact geopolymer matrices, with a more homogeneous distribution of Na^+ ions. This improved ion distribution was associated with a notable reduction in efflorescence. Durability assessment through immersion in a 5% sulphuric acid solution for 28 days demonstrated that all geopolymer specimens, including those containing CPA, remained structurally intact, indicating good resistance to acid attack.

Similarly, Taku *et al*., [145] examined the performance of cassava peel ash (CPA) as a supplementary cementitious material in ordinary Portland cement (OPC) mortars, with particular emphasis on the effects of lime and alkali activation using potassium hydroxide (KOH). The study adopted a fixed replacement level of 10% CPA by mass of OPC and evaluated four binder systems: OPC (control), OPC-CPA, OPC-CPA-Lime, and OPC-CPA-Lime-KOH. The results showed that the OPC-CPA-Lime mortar exhibited superior overall performance compared to the other blended systems. In particular, the inclusion of 4% lime (by mass of CPA) significantly enhanced compressive strength, allowing the CPA-lime blended mortar to perform comparably with the OPC control in terms of both strength and durability. The addition of lime was also found to improve the pozzolanic reactivity of CPA, thereby contributing to better strength development. Furthermore, the incorporation of KOH as an alkali activator improved the durability by reducing water absorption and apparent porosity.

The combined system containing 10% CPA, 4% lime, and 2% KOH produced the most balanced performance in terms of mechanical strength and resistance to fluid ingress. This confirms that alkali activation is primarily governed by the nature of the precursor materials and the activating solution [146].

A more recent study by Santhanam *et al*., [103] explored the potential of CPA as a precursor for geopolymer through alkaline activation with sodium hydroxide (NaOH). Results indicated that alkali-activated CPA enhanced early-age concrete strength, outperforming CPA concrete. The study also reported that increasing the molarity of NaOH from 2 M to 14 M enhanced compressive, split tensile, flexural, and bond strengths by 50-85% at 7 days of curing.

15. CPA and Other Additives

The adoption of binary blended cements has emerged as a promising pathway to reduce the environmental footprint of Portland cement, primarily by incorporating a single supplementary cementitious material (SCM) to partially replace clinker. While such systems have demonstrated measurable reductions in carbon emissions and improvements in selected performance metrics, their effectiveness is often constrained by inherent material-specific limitations.

Abdulwahab *et al*. [83] investigated the durability and strength performance of self-compacting concrete (SCC) incorporating cassava peel ash (CPA) and rice husk ash (RHA) as partial cement replacements at levels ranging from 5%-25%. Durability indicators evaluated included water absorption, resistance to sulphuric acid (H_2SO_4) and magnesium sulphate ($MgSO_4$) attacks, and performance under elevated temperature exposure. Results showed that SCC achieved its target design strength of 35 N/mm^2 when CPA content was limited to about 5% and combined CPA-RHA replacement did not exceed 10%. The inclusion of CPA and RHA significantly reduced water absorption due to pore refinement and improved microstructural densification. Enhanced resistance to chemical degradation was observed, with CPA improving sulphate and acid resistance and further gains achieved when RHA was incorporated. However, exposure to high temperatures led to a reduction in mechanical performance compared to the control mix, with degradation increasing as CPA and RHA content increased. Overall, the study identified 5% CPA as the optimum replacement level for Grade 35 SCC, particularly when durability against chemical attack and reduced permeability are prioritized over thermal resistance.

Adetoye *et al*., [97] in an experimental study evaluated the compressive strength of concrete in which ordinary Portland cement (OPC) was partially replaced with cassava peel ash (CPA) and wood ash (WA) at replacement levels of 0-25%. Concrete was produced using a 1:2:4 mix ratio and a constant water-cement ratio of 0.5. Compressive strength testing at 28 days revealed a progressive reduction in strength with increasing replacement levels. The control mix achieved 27.11 N/mm^2, while mixes containing 5-15% CPA or WA recorded strengths above the minimum 20 N/mm^2 requirement for plain concrete as specified by British Standards. Replacements of 20% and 25% resulted in strengths below acceptable limits, rendering them unsuitable for structural applications. The study established that moderate incorporation of pozzolanic materials (5-15%) can yield adequate strength while significantly reducing cement consumption. Additionally, the utilization of CPA and WA was shown to mitigate environmental pollution associated with agro-waste disposal and reduce the carbon footprint of concrete production. The authors concluded that CPA and WA are suitable supplementary cementitious materials at low replacement levels but should be limited to a maximum of 15% to maintain structural adequacy.

Bello *et al*., [147] examined the effectiveness of cassava peel ash-lime (CPA-Lime) admixture in improving the geotechnical properties of lateritic soils for road construction. CPA contents of 2-8% and lime contents of 1-3% were evaluated. Stabilization with CPA-Lime significantly reduced plasticity indices, indicating improved workability and reduced swelling potential. Optimum performance was achieved at 4-6% CPA combined with 2-3% lime, depending on soil type. Maximum dry density increased to between 1.68 and 1.92 Mg/m^3, while soaked CBR values improved substantially, reaching up to 19.1%. These values satisfied minimum requirements for subgrade and fill materials in highway construction. The study concluded that CPA-Lime admixture is an effective, economical and sustainable stabilizer for lateritic soils.

Obute *et al*., [66] assessed the performance of concrete incorporating cassava peel ash (CPA) and rice husk ash (RHA) as a ternary binder system to reduce Portland cement usage. CPA content was fixed at 5%, while RHA varied from 0-25% of the total binder, with a water-binder ratio of 0.65. Results indicated that optimum compressive strength occurred at a combined replacement level of 20% (5% CPA + 15% RHA). Increasing CPA-RHA content generally reduced early-age strength, but prolonged curing improved strength development, with values comparable to the control after 28 days. Water absorption decreased with increasing replacement levels, indicating enhanced durability and workability declined as CPA-RHA content increased. The study concluded that CPA-RHA concrete is suitable for applications where long-term performance is prioritized over early strength development.

Studies have also explored the combined incorporation of cassava peel ash (CPA) and fiber reinforcement in concrete to exploit synergistic interactions between pozzolanic cement replacement and discrete crack-bridging mechanisms. CPA alters the cementitious matrix through filler effects and secondary hydration, while fibers enhance tensile resistance, energy absorption, and post-cracking behavior.

Ogunbode *et al*., [98] investigated the combined effects of cassava peel ash (CPA) and kenaf bio-fibre (KBF) on the fresh, mechanical, and microstructural properties of concrete. KBF of 5 cm length was incorporated at volume fractions ranging from 0-1.0%. Concrete mixtures were prepared with 10% CPA replacing Portland cement (CEM I). Although the VeBe time improved, reflecting better cohesion, CPA and KBF reduced slump values, indicating decreased workability, which may be attributed to the hydrophilic nature of natural fibres [148]. Compressive strength showed no significant improvement; however, tensile and flexural strengths increased due to fibre reinforcement. Microstructural analysis revealed that KBF acted as crack-bridging elements, enhancing load transfer and controlling crack propagation. The synergistic use of CPA and KBF contributed to improved ductility and post-cracking behavior without compromising structural integrity.

Similarly, Akinpelu *et al*., [71] evaluated the sulfate resistance and microstructural performance of fiber-reinforced mortar incorporating cassava peel ash (CPA) as a partial cement replacement. Mortar mixes were produced with 0%, 7%, 14%, and 21% CPA and sisal fiber contents of 0%, 1%, and 2%, yielding twelve mixes (C1-C12). Durability was assessed by immersing specimens in a 5% Na_2SO_4 solution for up to 120 days. Results showed that performance strongly depended on CPA dosage. The mix containing 14% CPA and 1% sisal fiber exhibited the lowest compressive strength loss (5.93%) and moderate flexural strength loss (14.68%) at 120 days, indicating optimal resistance to sulfate attack while maintaining structural integrity. Higher CPA contents significantly increased degradation, with mixes containing 21% CPA recording compressive strength losses of up to 40.55%. SEM and XRD analyses supported these findings. Optimal CPA incorporation refined the matrix and preserved stable calcium silicate and silica phases, thereby enhancing chemical resistance. In contrast, excessive CPA led to calcium hydroxide depletion, increased porosity, and microcracking after sulfate exposure. Sisal fiber had minimal influence on phase stability but improved mechanical performance by controlling cracks. Overall, 14% CPA with 1% sisal fiber emerged as the most durable and sustainable mix design.

Cassava peel ash (CPA) contributes marginally to early-age strength while promoting substantial strength development at later curing ages due to delayed pozzolanic activity. Consequently, integrating CPA with an additional, more reactive SCM offers a viable strategy to induce synergistic interactions, thereby overcoming early-age performance deficits while preserving or enhancing long-term strength development.

16. Optimization of CPA

Optimization is the systematic process of selecting the best possible combination of variables to achieve a desired objective while satisfying given constraints. In concrete technology, it means adjusting mix parameters such as cement content, water-to-binder ratio, supplementary cementitious materials (SCMs), aggregates and admixtures to maximize performance, minimize cost, environmental impact, or material usage.

The heterogeneous nature of concrete makes achieving the desired engineering properties inherently complex, thereby necessitating the application of optimization techniques. Furthermore, the conventional trial-and-error methods and single-factor analyses do not adequately capture the complex interactions among mix components, often resulting in inconsistent and non-optimal outcomes. Moreso, the proportion of CPA used as a cement replacement is a critical factor, as both excessive and insufficient replacement levels can adversely affect mechanical strength, durability, and workability. Consequently, a systematic optimization approach is required to determine the optimum CPA content that maximizes its benefits in structural concrete.

In recent years, researchers have increasingly adopted advanced approaches to evaluate concrete performance by accounting for interactions among mix constituents. These approaches include statistical, computational, and analytical methods, which enable systematic assessment of multiple variables and their combined effects. Statistical experimental design, in particular, allows for the evaluation of individual factors and their interactions while identifying optimal combinations that enhance concrete performance.

Nwa-David *et al*., [96] investigated the use of nanosized cassava peel ash (NCPA) as a partial replacement for cement in concrete and developed an artificial neural network (ANN) model to predict its compressive strength. Experimental data were generated for concrete mixes containing up to 20% NCPA replacement and tested at curing ages of 7, 14, 28, 56, 90, and 150 days. A 6-10-1 ANN architecture was developed using 400 datasets, divided into training, validation, and testing subsets. The trained network achieved an R-value of 0.99909, indicating excellent agreement between predicted and experimental results. Model reliability was further confirmed using Student’s t-test, where the calculated t-value was below the critical value at a 95% confidence level.

The study concluded that ANN is a reliable, accurate, and time-efficient tool for predicting the compressive strength of nanosized CPA concrete.

Iro *et al*., [149] applied the central composite design (CCD) approach to optimize cassava peel ash (CPA) incorporation in concrete for improved mechanical performance. The study began with a physicochemical characterization of CPA to evaluate its pozzolanic potential. Concrete mixtures were then produced with varying proportions of CPA, cement, fine aggregates, and coarse aggregates, and laboratory tests were conducted to determine compressive and flexural strengths. The results indicated that an optimal mix ratio of 0.2:0.0875:0.3625:0.4625 produced a maximum compressive strength of 28.51 MPa. In comparison, a flexural strength of 10.36 MPa was achieved at a slightly higher coarse aggregate content. Quadratic predictive models were developed and statistically validated using Student's t-test, yielding p-values close to unity. The study concluded that CCD is effective for optimizing CPA-based concrete mixtures and demonstrated that CPA can significantly enhance strength while promoting sustainable waste utilization in concrete production.

Abdulwahab & Uche [140] examined the application of cassava peel ash (CPA) as a supplementary cementitious material in self-compacting concrete (SCC) and developed predictive models using Response Surface Methodology (RSM). Cement was partially replaced with CPA at levels ranging from 5% to 25%, and both fresh and hardened properties were evaluated. Results showed that replacing more than 15% of cement with CPA adversely affected slump flow and passing ability, while segregation resistance improved with increasing CPA content. Optimal performance was achieved with 5% CPA replacement and 28 days of curing, producing SCC of grade 35 compressive strength. The developed RSM models demonstrated a strong correlation between input variables and responses, confirming their predictive accuracy.

Amartey *et al*., [131] developed a predictive and optimization model for the compressive strength of sandcrete blocks produced with cassava peel ash (CPA) blended ordinary Portland cement (OPC). The study employed Scheffe's second-degree simplex lattice mixture theory to establish a regression model relating compressive strength to mix proportions. The resulting mathematical model accurately captured the interactions among mix constituents and was validated using Student's t-test at a 95% confidence level. The findings demonstrated that the model could reliably predict compressive strength for any desired mix proportion within the investigated range.

Awolusi *et al*., [86] investigated the combined use of cassava peel ash (CPA) and bamboo reinforcement in concrete beams, with emphasis on flexural behavior modeling using Response Surface Methodology (RSM). The developed RSM models showed high coefficients of determination, indicating strong agreement between predicted and experimental results. Optimal conditions were identified as 3% CPA replacement, 16 mm bamboo diameter, 500 mm beam length, and 150 mm beam depth. Under these conditions, flexural strengths of up to 14.95 N/mm^2 and increasing flexural strains were achieved with curing age. Validation experiments closely matched predicted values. The study concluded that RSM is effective for modeling bamboo-reinforced CPA concrete and that CPA-bamboo systems are viable for sustainable structural applications.

17. Industrial Scalability and Quality Control of Cassava Peel Ash (CPA) Production

The successful transition of cassava peel ash (CPA) from laboratory research to commercial supplementary cementitious material (SCM) depends on the Industrial scalability of CPA production and the quality of the produced ash. One of the major arguments for its industrial scalability is the abundance of cassava peel waste. Nigeria generates millions of tonnes of cassava peels, thereby providing a substantial stockpile of raw material needed for CPA production. Also, cassava peels are produced within an agricultural value chain expected to remain significant across many tropical countries. This makes CPA a potentially sustainable long-term SCM source. Furthermore, utilizing CPA presents certain economic and environmental benefits such as the low cost required to obtain the raw material, reduced disposal costs for cassava processors, potential reduction in cement consumption, lower embodied carbon than Portland cement, reduced burden on our environment, and the elimination of the harmful gases that will be generated from its indiscriminate disposal. Although CPA presents considerable potential as SCM, the lack of its adoption and extensive implementation in the industrial sector may be linked to challenges such as the variability the chemical composition which is influenced by source and calcination conditions, lack of quality control systems and standardized production protocols, inconsistent mix design and curing protocols, limited long-term durability and non-destructive evaluation data, and difficulty in defining universally optimal cement replacement levels [150]. Furthermore, industrial-level scalability would require continuous and semi-continuous thermal processing systems to maintain uniform temperature and calcination time. The industrial viability of establishing such systems, which will be more economical as decentralised production hubs given the geographical dispersion of cassava peel generation rather than a single centralized hub, depends on balancing these benefits against transportation costs, drying energy, calcination fuel requirements, grinding energy, and laboratory quality testing costs, which underscores the need for a comprehensive CPA environmental impact using a comprehensive life cycle assessment framework [151].

Cassava Peel Ash (CPA) exhibits inconsistencies owing to variability in its properties [77]. Hence the need for quality control measures. Calcination is arguably one of the most critical quality-control measures, as under-calcination would result in the retention of a high amount of unburnt organic matter and an increase in carbon content, while over-calcination would result in obtaining crystallized silica. Other measures include ash fineness, which influences pozzolanic activity, as well as performance tests such as the Strength Activity Index (SAI), water requirement, setting time, soundness, and durability indicators. Consequently, the commercialization of CPA will certainly require precise CPA specifications that address issues such as acceptable calcination temperatures, fineness limits, chemical composition etc. The establishment of such set standards will significantly improve the confidence among construction professionals and facilitate broader industry acceptance.

18. Challenges and Future Directions

Despite its potential as a sustainable and cost-effective construction material, the widespread adoption of cassava peel ash faces significant barriers. The widespread application of cassava peel ash-based concrete is constrained by the absence of region-specific standards and material characterization protocols, which leads to inconsistent performance outcomes. In addition, inadequate control during CPA production, particularly variations in combustion conditions and grinding processes, often results in incomplete calcination, non-uniform fineness, and residual carbon content, thereby increasing variability in concrete performance. To overcome these challenges, region-specific technical guidelines are required to accommodate variability in ash characteristics and ensure reliable performance. Achieving this will necessitate supportive policy instruments and coordinated collaboration among academia, industry, and government to validate CPA-based concrete, enhance sustainability, and promote regulatory and market acceptance.

Further efforts should therefore be targeted at studies that show the environmental and sustainability benefits of Cassava Peel Ash (CPA) using comprehensive life cycle assessment frameworks, as this can serve as a basis for its widespread adoption. Although few studies on the environmental impacts of cassava waste exist, a comprehensive environmental impact analysis using a standardized LCA framework of CPA over conventional cement replacement strategies is scarce. One such study found in the literature focused on the environmental impact assessment and material flow analysis of cassava waste management practices using the Global Emissions Model for Integrated Systems (GEMIS) package [70]. Another study by Sari *et al*., [151] investigated the economic and environmental effects of manufacturing glucose syrup from cassava peel waste using the Life Cycle Assessment technique and eco-efficiency calculations. These studies indicate that CPA has great potential in terms of major environmental and sustainability benefits. This underscores the need for a holistic assessment of carbon footprint, embodied energy, and environmental performance to enable reliable large-scale adoption of CPA as a sustainable construction material.

Also, future research efforts should focus on developing clear, widely adopted standards, guidelines, and regulations that provide a consistent basis for evaluating and implementing cassava peel ash (CPA) for safe, reliable use in the construction industry. A key focus is the optimization of the combustion process to achieve consistent chemical composition and enhanced pozzolanic activity. Establishing standardized production protocols will ensure compliance with engineering and regulatory requirements and support the scalability of CPA for large-scale construction applications [117].

Furthermore, future research efforts focus on the integration of emerging digital technologies, including machine learning (ML), artificial intelligence (AI), and the Internet of Things (IoT), to further optimize cassava peel ash (CPA)-cement blended concrete systems [137]. The application of ML and AI techniques can enable more accurate prediction and optimization of mix proportions, curing regimes, and performance parameters based on large experimental datasets. In addition, IoT-based sensing technologies can facilitate real-time monitoring of curing conditions, durability indicators, and in-service structural performance. The combined use of these technologies has the potential to enhance predictive accuracy, improve quality control, and support data-driven decision-making for the sustainable deployment of CPA-modified cementitious materials.

19. Conclusion

Concrete remains one of the most widely used materials today. Its production involves the use of cement, a highly environmentally unfriendly material whose production consumes disproportionately from our natural resources formed over lengthy geological timescales, consumes an enormous amount of energy, emits unhealthy levels of CO_2, and is highly dependent on energy volatility and economic policies for pricing, affordability, and industrial performance. This has led construction professionals and researchers to develop an interest in searching for environmentally friendly alternative materials to replace cement. One such material is the Cassava Peel Ash (CPA).

The Cassava Peel (CP), is an underutilized agro-waste found in certain regions of the world. Its ash, which has found application in the construction industry, is obtained by calcining the peels at about 700-750°C to produce Cassava Peel Ash (CPA), a high-amorphous silica material. CPA is a lightweight material with low specific gravity; however, concrete produced from CPA-cement blended systems has densities considered normal weight. This may be due to low CPA replacement levels in blended systems.

From a materials science perspective, CPA is a silica-rich, low-calcium pozzolan, confirming its strong pozzolanic potential but lack of self-cementing ability. Although studies have reported high values of CaO, which suggests that under certain conditions, CPA can also exhibit moderate cementing properties [116], CPA relies on external calcium sources from Portland cement to sustain hydration and strength development, contributing majorly to secondary C-S-H formation and microstructural refinement at later ages.

CPA, when well processed, has a combined composition of SiO_2, Al_2O_3 and Fe_2O_3 above 70% with the potential to enhance the durability of concrete in sulphate and chloride environments through pozzolanic reactions and pore structure refinement. The incorporation of CPA in concrete affects early-age strength, which improves with curing, due to delayed pozzolanic reaction, which may be a limitation for practical structural applications in situations where early strength is critical, making the incorporation of an optimum percentage replacement that can both achieve early-age strength, satisfy structural design requirements and ensure long-term durability very vital. As such, moderate replacement levels are recommended to provide a compromise between sufficient early-age strength and improved later-age performance. A range of (5-15%) replacement has been suggested by previous studies for structural concrete. Other approaches for achieving early strength development with CPA could involve applying prediction and optimization models and using CPA alkali-activated binders. Concrete produced by alkali activation of CPA exhibits better strength properties than CPA-cement blended systems, with enhanced early-age strength, making it a viable option when early-age strength is the priority.

From a young performer's perspective, CPA incorporation consistently delays setting times by moderating hydration kinetics and reducing the rate of heat evolution. This characteristic is particularly advantageous in mass concrete applications, where thermal cracking is a concern, positioning CPA-OPC blends as suitable binders for low-heat concreting. Hardened concrete incorporating CPA at low to moderate replacement levels (generally below 15%) maintains normal-weight density, confirming its compatibility with conventional structural classifications while supporting reductions in clinker content.

Durability performance emerges as a key strength of CPA-modified systems. Numerous studies demonstrate improved resistance to acid, sulphate, and chloride ingress, as well as reduced drying shrinkage, attributable to fineness-driven pozzolanic reactions that densify the cement matrix and refine pore structure. These attributes make CPA particularly suitable for applications where durability rather than high early strength governs design, including light structural elements and aggressive exposure environments. However, excessive cement replacement levels adversely affect binder reactivity, matrix cohesion, and long-term chemical resistance, highlighting the necessity of optimized mix design and adequate curing regimes to balance mechanical performance with durability enhancement.

Beyond technical performance, CPA aligns strongly with circular economy principles by valorizing agricultural waste, reducing environmental burdens associated with cement production, and advancing eco-efficient construction materials. Its demonstrated potential for late-age strength contribution and durability enhancement supports recommendations for its commercial production either as a standalone pozzolan or as blended CPA-cement products [79].

Although CPA has great potential, its quality varies with the variety, calcination temperature, and burning conditions, which may lead to inconsistent pozzolanic activity and strength development. Its incorporation raises uncertainties about its long-term performance, as there is insufficient data to assess its reliability [74].

Overall, CPA represents a credible pathway toward resource-efficient, low-carbon cementitious systems, provided that material characterization, processing consistency, and replacement thresholds are rigorously controlled to ensure performance reliability and environmental benefit.

Author Contributions

The sole author carried out all aspects of this work.

Competing Interests

The author declare that no competing interests exist.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the author. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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