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Sustainable Sandcrete Block Production Using Orange Peel Ash as Partial Cement Replacement

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Abstract

This study explores the potential of Orange Peel Ash (OPA) as a sustainable pozzolanic material for the partial replacement of Ordinary Portland Cement (OPC) in Sandcrete block production. Driven by the need to reduce the environmental impact of cement manufacturing and promote agricultural waste reuse, the research assessed the influence of OPA on the physical and mechanical properties of Sandcrete blocks. Experimental investigations were conducted on Sandcrete specimens with OPC partially replaced by OPA at 0%, 5%, 10%, 15%, 20%, and 25% by weight. The characterization involved particle size distribution, oxide composition via X-ray fluorescence (XRF), and specific gravity determination in accordance with BS standards. Performance was evaluated based on density, water absorption, and compressive strength. Results showed that the fine aggregate was well-graded, and the OPA exhibited a specific gravity of 2.45 within the acceptable range for agro-waste ashes. The incorporation of OPA had a marginal effect on block density and water absorption, both remaining within the acceptable limits of NIS 87:2007. However, compressive strength decreased with increasing OPA content. The control specimen achieved 2.62 N/mm², while 10% OPA replacement retained a sufficient strength of 1.70 N/mm² for non-load-bearing applications. Beyond 15% replacement, strength dropped below viable thresholds. The findings support the viability of ≤10% OPA replacement as a cost-effective and eco-friendly alternative in Sandcrete block production for non-structural use. This study encourages further research on optimizing OPA reactivity through chemical or thermal activation to expand its application in sustainable construction.

Keywords: *Orange Peel Ash (OPA), Sandcrete Blocks, Cement, Pozzolanic Materials, and Sustainable Construction.*

1.0 Introduction

Sandcrete blocks are a fundamental building unit across sub-Saharan Africa, widely favoured for their low cost, ease of production, and accessibility of raw materials. Typically made from a mixture of sand, water, and Portland cement, they are used extensively in non-load-bearing walls for both residential and commercial construction (Emmanuel et al., 2025). However, the cement component, while critical to strength development, comes with significant environmental and economic drawbacks. The manufacturing of ordinary Portland cement (OPC) is highly energy-intensive and contributes to about 7% of global CO_2 emissions, making it one of the most carbon-polluting industrial activities worldwide (Ige et al., 2024). With increasing emphasis on sustainable infrastructure, there is a growing need to explore alternative, eco-efficient binders that can partly replace cement in engineering applications without compromising structural integrity.

Alongside the environmental cost of cement, another issue persists: agricultural waste. In many developing regions, organic waste is generated in large quantities with little to no structured disposal methods. Nigeria, for instance, being a major citrus-producing country, produces tonnes of orange peels annually. These peels are typically discarded in open dumps or burned, contributing to environmental degradation (Ogo et al., 2024). Yet, when processed thermally under controlled conditions, orange peel waste yields an ash that contains significant levels of silica, calcium, and potassium elements commonly associated with pozzolanic activity (Rajak et al., 2025). These properties present an engineering opportunity: converting this waste into a supplementary cementitious material (SCM) for Sandcrete block production.

In engineering research, several agro-waste ashes have been successfully applied as partial cement replacements. Examples include rice husk ash (RHA), palm kernel shell ash (PKSA), and sugarcane bagasse ash. These materials have demonstrated improved performance characteristics such as enhanced strength, reduced permeability, and increased chemical stability (Prayuda et al., 2023). Although chemically similar to these ashes, orange peel ash remains under-researched in the context of masonry units. The effectiveness of OPA as a partial binder depends on multiple factors, including its fineness, calcination temperature, and compatibility with other mix components. From an engineering perspective, these variables influence the hydration process, strength gain, and long-term durability of the resulting blocks.

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Ultimately, integrating orange peel ash into Sandcrete block production offers a pathway toward more environmentally responsible engineering practices. It not only reduces the carbon footprint associated with cement use but also promotes the use of locally sourced, renewable materials. In regions like Nigeria, where urbanisation is rising and the demand for affordable housing is high, innovations such as this have the potential to reshape the future of construction materials and infrastructure development (Adedeji, 2023).

This study focuses on evaluating the performance of orange peel ash (OPA) as a partial binder in hollow Sandcrete block production. It investigates how OPA incorporation influences key engineering properties such as compressive strength, water absorption, and durability. The broader objective is to determine whether OPA can serve as a viable SCM that supports sustainable construction goals while addressing the dual challenge of rising cement prices and poor agricultural waste management.

2.0 Materials and Methods

2.1 Materials

The following materials were used in the production of the Sandcrete blocks, utilizing Orange peel ash as a partial binder.

2.1.1 Cement

The binder utilized in this research was Ordinary Portland Cement (OPC), procured from an authorized wholesale distributor located in Kaduna, Nigeria. This cement conforms to relevant Nigerian Industrial Standards (NIS) and was selected for its consistent quality and widespread use in structural and non-structural concrete works.

2.1.2 Orange Peel

The orange peel used as a supplementary material was collected from local fruit vendors operating along roadside stalls. The collected biomass was sun-dried and prepared for further processing, serving as a potential pozzolanic additive due to its high silica content.

2.1.3 Fine Aggregate

The fine aggregate used in this study was well-graded sharp sand, sourced from a vendor situated near the block production site. It was derived from the banks of Kubbani river. Before use, the sand was air-dried and visually inspected to ensure it was free from organic matter, clay lumps, or other deleterious substances, in line with (BS EN 12620:2002+A1:2008) specifications for aggregates in concrete.

2.1.4 Water

Portable water, clear and free from suspended particles and harmful contaminants, was utilized throughout the mixing and curing process. The water met the standard requirements of ASTM C1602 for mixing and curing concrete, ensuring that no adverse chemical reactions would compromise the integrity of the matrix.

2.2 Methods

2.2.1 Sieve Analysis

To assess the particle size distribution of the fine aggregate and orange-peel ash (OPA), a mechanical sieve analysis was conducted in accordance with **BS EN 933-1**. This test method provides essential data on grading characteristics, which influence workability, packing efficiency, and the overall performance of Sandcrete mixtures.

2.2.2 Chemical/Oxide Composition Test

The oxide composition of the calcined orange peel ash (OPA) was characterized through X-ray fluorescence (XRF) spectroscopy, in accordance with (BS EN 196-2:2013). This analytical technique enabled the quantification of major and minor elemental oxides, such as SiO_2, Al_2O_3, and Fe_2O_3, which are critical indicators of the pozzolanic potential and suitability of OPA as a partial cement replacement in Sandcrete production.

2.2.3 Specific Gravity

The specific gravity of the fine-grained particles was determined using the pycnometer method, conducted in accordance with (BS 812-2, 1995). This test provided a measure of the relative density of the material compared to water.

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2.2.4 Sandcrete Blocks Production

Six Sandcrete mix batches were designed, each sufficient to fill a standard block mould of dimensions 450 mm × 225 mm × 225 mm**.** All mixes were proportioned at a binder-to-aggregate ratio of 1:8 by weight. The control specimen (Mix 0%) consisted of 100% Ordinary Portland Cement (OPC) as the sole binder with fine aggregate. The five remaining batches incorporated orange peel ash (OPA) as a partial cement replacement in incremental proportions of 5%, 10%, 15%, 20%, and 25% by weight of OPC.

2.2.5 Casting and Curing

Steel moulds were used for casting and were pre-treated with a suitable mould release agent to prevent adhesion between the mould surface and the fresh Sandcrete. The mixing was performed manually, and the fresh mix was placed into the mould using a hand trowel, followed by manual compaction using a 2.5 mm diameter steel rod. This was complemented by mechanical vibration using a vibrating Sandcrete block machine to enhance density and minimize entrapped air.

Twenty-four hours after casting, specimens were cured in accordance with BS EN 12390-2 guidelines for curing concrete and mortar specimens, and were continuously cured for 7 days as recommended by NIS 587:2007 to ensure adequate hydration and strength development.

2.2.6 Density and Water Absorption

Density and water absorption tests were carried out on the hardened Sandcrete blocks in accordance with the relevant provisions of the Nigerian Industrial Standard (NIS 587:2007).

2.2.7 Compressive Strength

The compressive strength test was performed on the cured hollow Sandcrete block specimens of size dimensions 450 mm × 225 mm × 225 mm using a hydraulic compression testing machine, in accordance with the procedures outlined in Nigerian Industrial Standard NIS 87:2007.

3.0 Results and Discussion

3.1 The particle size distribution (Fine aggregate)

The particle size distribution curve of the fine aggregate sample, as shown in Figure 1, revealed a well-graded profile based on the calculated coefficients. The coefficient of uniformity (Cu) was determined to be 6.72, and the coefficient of curvature (Cc) was found to be 1.1. According to (British Standards Institution, 2010), a fine aggregate is considered well-graded if Cu > 4 and 1 ≤ Cc ≤ 3. These values indicate that the fine aggregate possesses a broad range of particle sizes with an even distribution, which enhances packing density and reduces void ratio in the Sandcrete matrix.

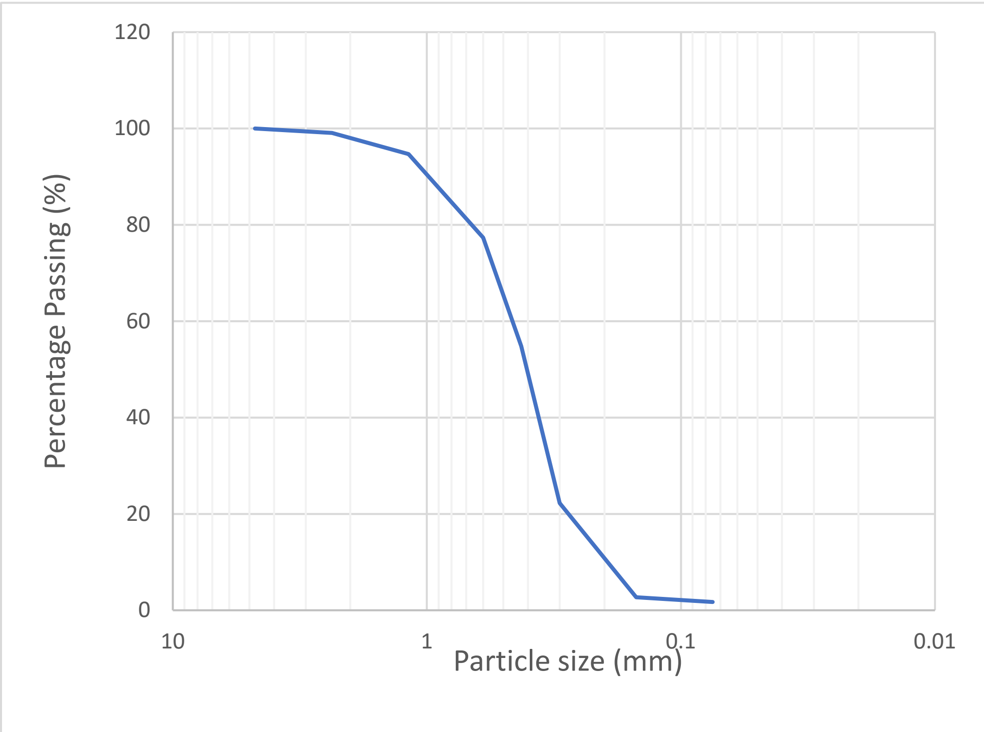

Figure 1: Particle size distribution

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Well-graded aggregates typically improve the mechanical performance of composite materials by ensuring better interlocking and minimizing cement paste demand, thereby improving both workability and compressive strength (Yasin et al., 2024). Similar observations were made by (Umukoro, 2023), who reported that well-graded fine aggregates significantly improve the density and durability of Sandcrete blocks, especially when used with pozzolanic materials such as agricultural ashes. Moreover, the identified gradation aligns with standard recommendations for fine aggregates used in Sandcrete production, enhancing the structural integrity and service life of masonry units (BS 882:1990).

3.2 Oxide Composition Test (OPC and OPA)

The chemical composition of OPC and OPA was determined using X-ray Fluorescence (XRF) analysis in line with BS EN 196-2. Table 1 presents a comparison of key oxides relevant to their potential cementitious and pozzolanic behaviour.

Table 1: Oxide Composition OPC and OPA

S/N	Oxide Compound	OPC Composition (%)	OPA Composition (%)
1	CaO	65	37.02
2	SiO_2	21	2.38
3	Al_2O_3	6	3.66
4	Fe_2O_3	3.9	0.88
5	MgO	1.4	3.4
6	SO_3	0.02	1.82
7	TiO_2	0.28	0.18
8	MnO	0.01	0.08
9	BaO	0.02	0.55
10	V_2O_5	0.02	0.01

The chemical oxide compositions of Ordinary Portland Cement (OPC) and Orange Peel Ash (OPA) are presented in Table 1. The OPC sample showed a dominant presence of calcium oxide (CaO) at 65%, followed by silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) at 21% and 6% respectively. These oxides are typical of cementitious materials and are responsible for the hydraulic properties of OPC (Yadav et al., 2020).

In contrast, the OPA sample contained 37.02% CaO, with noticeable levels of Al_2O_3 (3.66%) and MgO (3.40%), indicating moderate reactivity. However, the relatively low content of SiO_2 (2.38%) suggests a limited pozzolanic potential when compared to other agro-waste ashes such as rice husk or palm kernel shell ash (Nadir & Ahmed, 2021). Despite the lower silica content, the presence of alumina and magnesia contributes to latent hydraulic behavior, which may still support partial cement replacement. The comparative analysis of OPC and Orange Peel Ash (OPA) reveals that OPA contains significantly lower amounts of key pozzolanic oxides (SiO_2, Al_2O_3, Fe_2O_3), with a combined value of only 6.92%. This falls far below the minimum thresholds established in standards such as ASTM C618 for pozzolanic materials. As a result, OPA cannot be classified as a pozzolan and is unlikely to contribute meaningfully to cementitious reactions in concrete or sandcrete production. Additionally, the total oxide composition of OPA is considerably below 100%, reflecting its high organic content and substantial unburnt carbon typical of citrus-based ashes.

3.3 Specific Gravity Test

The specific gravity of Orange Peel Ash (OPA) was determined using the pycnometer method in accordance with BS 812-2:1995. The test results are summarized in Table 2.

Table 2: Specific Gravity Determination for Orange Peel Ash

Parameter	Notation	Value (g)
Mass of empty pycnometer bottle	W_1	24.4
Mass of bottle + dry sample	W_2	48.64
Mass of bottle + dry sample + water	W_3	137.67
Mass of a bottle filled with water only	W_4	124.32
Specific Gravity	G_s	2.45

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Similarly, the specific gravity of the fine aggregate was also evaluated using the pycnometer method, as shown in Table 3.

Table 3: Specific Gravity Determination for Fine Aggregate

Parameter	Notation	Value (g)
Mass of empty pycnometer bottle	W_1	24.4
Mass of bottle + dry sample	W_2	58.29
Mass of bottle + dry sample + water	W_3	145.4
Mass of a bottle filled with water only	W_4	124.48
Specific Gravity	G_s	2.64

The results presented in Tables 2 and 3 show that the specific gravity of Orange Peel Ash (OPA) was 2.45, while that of the fine aggregate was 2.64. The specific gravity of OPA falls within the expected range for pozzolanic agro-waste ashes, which typically vary between 2.2 and 2.6, depending on their oxide composition and calcination conditions. According to Son (2024), agro-waste ashes like sugarcane bagasse ash and rice husk ash exhibit specific gravities between 2.3 and 2.5, indicating their suitability for partial cement replacement without significantly affecting the unit weight of concrete or Sandcrete blocks. The specific gravity of the fine aggregate (2.64) aligns with values reported for natural river sand, which typically ranges between 2.60 and 2.70 (Gurumoorthy et al., 2025). This confirms that the sand used in this study possesses adequate density and is appropriate for use in Sandcrete production.

3.4 Density of Sandcrete Blocks

The density of Sandcrete blocks is a key parameter influencing structural strength, durability, and material handling during construction. Figure 2 illustrates the variation in density (kg/m³) of Sandcrete blocks at different replacement levels of Ordinary Portland Cement (OPC) with Orange Peel Ash (OPA). All blocks were cast with a constant volume of 0.0177 m³, and the average mass was recorded to determine density at replacement levels ranging from 0% to 25%.

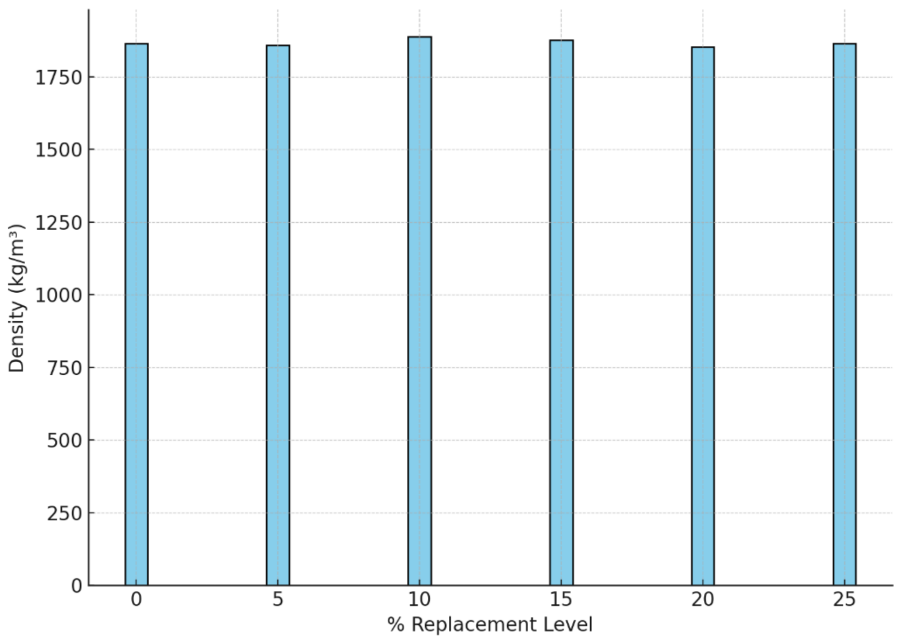

Figure 2: Variation in density of OPA

The results show that the density of Sandcrete blocks ranged from 1853.1 kg/m³ to 1887.1 kg/m³, with the highest density recorded at 10% OPA replacement. This slight variation in density is expected due to the lower specific gravity of OPA compared to OPC, as confirmed in earlier results and similar studies (Sojobi et al., 2021). However, the density values across all mix variations remained within the typical range for Sandcrete blocks (1600–2000 kg/m³) as recommended by NIS 87:2007, indicating that partial substitution of OPC with OPA does not compromise the block's structural mass significantly. The observed increase in density at 10% and 15% replacement may be attributed to better packing density and improved particle interaction, which has also been reported in the work of Olubajo et al. (2019). Beyond 15%, a slight reduction

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in density is noticeable, possibly due to reduced cementitious content and a corresponding increase in porosity, an effect also noted in studies using other agro-waste ashes (KİLANİ et al., 2022).

3.4 Water Absorption of Sandcrete Blocks

Water absorption is a critical parameter in evaluating the durability and porosity of Sandcrete blocks. Excessive water absorption indicates high pore connectivity, which can compromise the long-term performance of blocks when exposed to weathering and aggressive environments. Figure 3 illustrates the variation in water absorption (%) of Sandcrete blocks produced with varying levels of Orange Peel Ash (OPA) as a partial replacement for Ordinary Portland Cement (OPC), based on laboratory measurements of dry and wet mass.

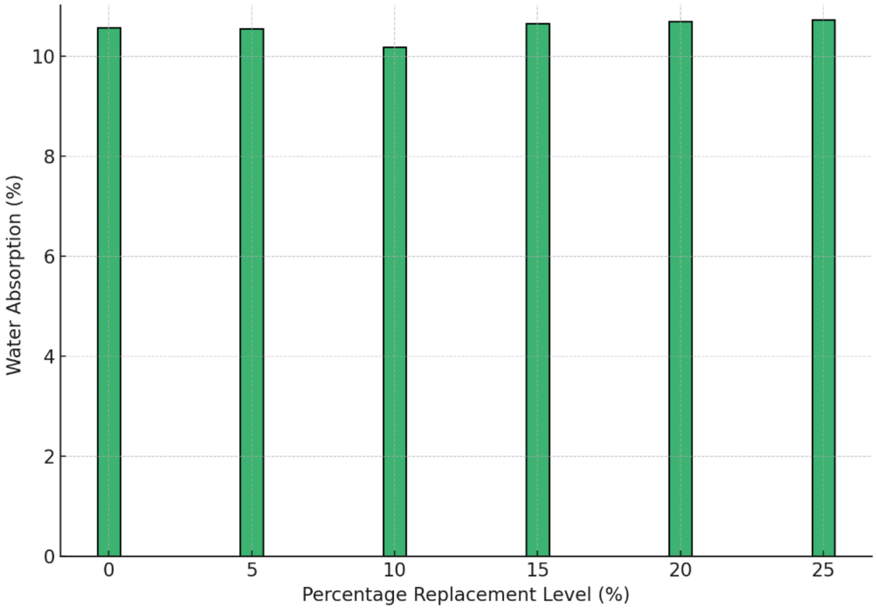

Figure 3: Variation in water absorption

As shown in Figure 3, water absorption across all replacement levels remained within a narrow range of 10.17% to 10.72%, suggesting that the introduction of OPA had minimal impact on the pore structure of the Sandcrete blocks. The lowest water absorption (10.17%) was recorded at 10% replacement, indicating enhanced compactness and reduced porosity at this level. This trend aligns with the findings of (Khanna & Kasilingam, 2025), who reported improved microstructural densification in blended cement composites incorporating agro-waste ashes at moderate replacement levels. However, a slight increase in water absorption was observed beyond 15% OPA content, peaking at 10.72% for the 25% replacement level. Despite these minor variations, all water absorption values remained within the acceptable limits prescribed by NIS 87:2007, which recommends a maximum of 12% for Sandcrete blocks. This implies that OPA can be effectively used in block production without compromising durability, especially when replacement is limited to ≤15%, where performance is optimized.

3.5 Compressive Strength

Compressive strength is a critical measure of the load-bearing capacity and overall structural performance of Sandcrete blocks. Figure 4 illustrates the relationship between the percentage replacement of Ordinary Portland Cement (OPC) with Orange Peel Ash (OPA) and the average compressive strength (N/mm²) of Sandcrete blocks. The results help assess the structural viability of OPA-blended blocks for construction applications.

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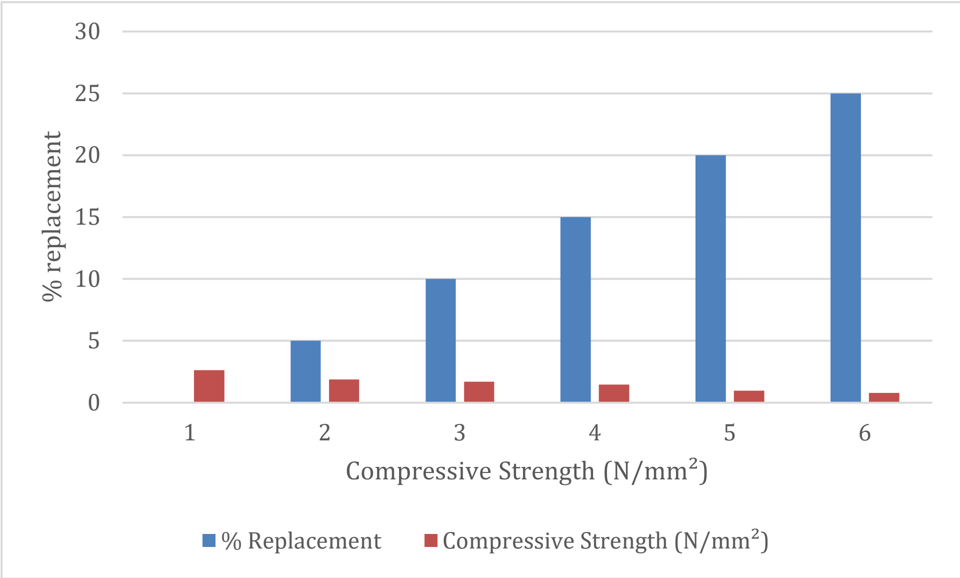

Figure 4: Relationship between percentage replacement of (OPC) with (OPA)

The compressive strength values presented in Table 4 show a consistent decline with increasing levels of Orange Peel Ash (OPA) used as a partial replacement for Ordinary Portland Cement (OPC). The control sample (0% replacement) recorded the highest strength at 2.62 N/mm², aligning with the minimum strength requirement for load-bearing sandcrete blocks as specified by NIS 87:2007, which sets the threshold at 2.5 N/mm². At 5% OPA replacement, the strength decreased to 1.87 N/mm², indicating a 28.6% reduction compared to the control. The decline continued progressively with higher replacement levels: 1.70 N/mm² at 10%, 1.46 N/mm² at 15%, 0.97 N/mm² at 20%, and 0.80 N/mm² at 25%. This trend reflects the diminished availability of calcium silicate hydrate (C-S-H), the primary strength-giving compound in cementitious materials, due to the partial replacement of OPC with a less reactive material like OPA. These findings are consistent with those of Blesson & Rao (2023), who noted that agro-waste ashes typically have lower cementing efficiency and therefore reduce early compressive strength when used in higher proportions. However, at replacement levels of up to 10%, the blocks retained sufficient strength for non-load-bearing wall units, making OPA a viable eco-friendly partial substitute in low-strength construction applications. Moreover, the pattern aligns with pozzolanic activity behavior, where strength is initially retained due to filler effects and potential secondary hydration, but declines when the cementitious matrix becomes insufficient to form a dense microstructure.

The consistent reduction in compressive strength observed with increasing orange peel ash (OPA) content is likely due to its non-pozzolanic or weakly pozzolanic nature. Unlike true pozzolanic materials, which react with calcium hydroxide to form additional strength-giving C–S–H gel, OPA contains very low levels of reactive silica and alumina, limiting its contribution to secondary hydration. Consequently, replacing OPC with OPA primarily reduces the available cementitious material, leading to a continuous decline in compressive strength rather than the initial strength gain typically seen with conventional pozzolans.

4.0 Conclusion

This study has investigated the feasibility of incorporating Orange Peel Ash (OPA) as a partial replacement for Ordinary Portland Cement (OPC) in the production of Sandcrete blocks. Through a series of laboratory evaluations, including particle size analysis, oxide composition testing, specific gravity measurement, and performance-based assessments of density, water absorption, and compressive strength, the findings provide compelling evidence on the potential and limitations of OPA as a sustainable pozzolanic material.

The particle size distribution analysis confirmed that the fine aggregate used was well-graded, in line with BS 1377-2, which supports efficient packing and contributes to mechanical integrity. XRF analysis revealed that OPA contains moderate levels of reactive oxides such as CaO, Al_2O_3, and MgO, which are essential for cementitious behaviour, although its low silica content suggests limited pozzolanic reactivity compared to traditional pozzolans.

The specific gravity of OPA (2.45) falls within the acceptable range for agro-waste ashes, and its substitution had minimal impact on the density of the resulting Sandcrete blocks, which remained between 1853 and 1887 kg/m³ well within the acceptable range of NIS 87:2007. Water absorption results were stable and below the 12% maximum threshold of NIS 87:2007, indicating that the use of OPA does not significantly compromise the durability of the blocks when replacement is kept at or below 15%.

However, the compressive strength test results demonstrated a clear trade-off. While the control sample achieved 2.62 N/mm², meeting the minimum requirement for load-bearing walls, the strength decreased steadily with increasing OPA content, dropping to 0.80 N/mm² at 25% replacement. Nonetheless, at ≤10% replacement, the blocks maintained compressive strengths above 1.70 N/mm², making them suitable for non-load-bearing or partition wall applications based on NIS 87:2000.

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