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ORIGINAL ARTICLE

Void content and initial surface absorption of palm kernel shell laterized concrete

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Abstract: This study investigates the viability of incorporating palm kernel shell (PKS) and laterite as sustainable replacements for conventional granite and sand aggregates in concrete. Through detailed analysis of void content and initial surface absorption, the durability and environmental suitability of PKS-laterized concrete were evaluated under varying water-cement ratios and replacement levels. Results indicate that both PKS and laterite increase void content and surface absorption, with these effects intensified at higher water-cement ratios. However, a mix containing 10% PKS and 10% laterite demonstrated durability metrics comparable to those of traditional concrete, showing strong resistance to chloride ingress and suitability for severe coastal environments. At a 0.4 water-cement ratio, PKS-laterized mixes achieved durability standards for coastal and urban applications, whereas a 0.45 ratio proved effective for moderate coastal exposures. These findings support the potential of PKS-laterized concrete as a sustainable building material, reducing reliance on natural aggregates while maintaining performance. Further research is recommended to confirm the long-term durability of these mixes across diverse environmental exposures and to refine mix designs for optimal strength and permeability. This study contributes to the field of eco-friendly construction materials, aligning with global sustainability goals and resource conservation.

Keywords: sustainable concrete, palm kernel shell, laterite, durability, permeability, environmental exposure

1 Introduction

Concrete is a foundational material in modern construction due to its versatility, strength, and durability. It is the most widely used building material globally, forming the backbone of structures such as buildings, bridges, dams, and roads [1]. While concrete's durability ensures the longevity and safety of these structures, its production significantly contributes to environmental challenges, particularly through the extraction of natural aggregates and the high carbon footprint associated with cement [2–6]. Mining for conventional aggregates like sand, gravel, and crushed stone causes habitat destruction and pollution, prompting a shift toward sustainable alternatives [7–10]. To address these impacts, innovations in concrete mix designs increasingly focus on the integration of recycled and alternative materials aimed at reducing the environmental footprint of construction [11–13]. Among these alternatives, agricultural and industrial by-products, such as palm kernel shells (PKS), have emerged as viable substitutes for coarse aggregates [14,15]. PKS, a byproduct of the palm oil extraction process, is readily available in regions like Indonesia, Malaysia, Nigeria, and Thailand, offering a

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sustainable solution for managing agricultural waste [16–18]. By incorporating PKS into concrete, resource depletion is minimized, waste disposal is managed, and the environmental footprint of construction is reduced, contributing to global sustainability goals [19–22].

Additionally, PKS offers unique properties as a coarse aggregate; its lightweight nature reduces the overall weight of concrete, which may also lead to cost savings in structural applications [22–25]. However, due to its inherent porosity, increasing palm kernel shell (PKS) content in concrete raises water absorption, which can disrupt the concrete matrix and potentially compromise durability [26,27]. While previous studies have explored the impact of PKS on absorption and permeability, limited research has investigated how PKS influences void content and surface permeability when used alongside other sustainable materials such as laterite.

Similarly, laterite, a soil rich in iron and aluminum oxides, has been studied as a replacement for natural sand in concrete mixes, offering advantages such as reduced environmental impact, cost-effectiveness, and enhanced sustainability [28–32]. The void content and sorptivity of laterized concrete were explored to assess its resistance to permeation [33]. Findings demonstrated that, while void content and sorptivity values decreased with curing age and richer mix proportions, increasing laterite content led to higher void content and sorptivity. Limiting laterite content to 20% was shown to provide permeation resistance comparable to conventional concrete, highlighting the importance of balancing laterite content to maintain durability. However, most studies focused solely on laterite's effect on permeability without considering the simultaneous use of PKS and laterite in modifying concrete durability properties.

Several studies have evaluated PKS and laterite independently in concrete applications. For instance, one analysis explored the porosity and permeability of concrete using raw dura PKS, finding that higher PKS content leads to increased permeability [34]. Another study on laterized concrete found that while laterite can enhance sustainability, excessive replacement levels may negatively impact permeability and void content [30]. However, none of these studies examined the combined effect of PKS and laterite on void content and initial surface absorption (ISAT) in concrete, which is a critical durability parameter in aggressive environments.

These studies suggest that while PKS and laterite can improve the sustainability of concrete, they may also lead to increased porosity and reduced mechanical strength. Permeability and water absorption are critical parameters in assessing the long-term durability of concrete, particularly in environments exposed to aggressive chemicals or moisture [35]. High permeability and absorption rates increase the risk of chemical ingress and corrosion of embedded steel, leading to structural deterioration [36–38]. Tests such as the Initial Surface Absorption Test (ISAT) and the void content test are commonly used to quantify these properties, with lower absorption and void content indicating a denser, more durable concrete [39–42].

While the use of PKS in concrete has been investigated, especially as a lightweight aggregate, limited research addresses how the porosity of PKS interacts with laterite to influence the permeability and water absorption properties of concrete. Existing studies provide insights into the mechanical and absorption properties of PKS-laterite concrete [43-44] but do not address void content or Initial Surface Absorption Test (ISAT) measurements, which are essential for understanding surface permeability. This lack of comprehensive data on the impact of PKS and laterite on permeation properties forms the critical research gap that this study aims to address. Specifically, the objectives of this study are to: (a) Investigate the effect of varying PKS and laterite contents on void content and water absorption of concrete; (b) Quantify the influence of PKS and laterite on permeability using ISAT and void content tests; (c) Provide insights into the practical implications of using PKS and laterite in sustainable concrete applications.

By exploring the interaction between PKS and laterite, this study contributes to the development of concrete mixes that not only reduce the environmental footprint of construction but exhibit durability-related characteristics essential for long-term performance. These findings provide insights into the practical application of PKS-laterized concrete in coastal, tropical, and other aggressive environments where permeability control is crucial. Moreover, the study highlights the suitability of lightweight concrete with improved thermal insulation properties for tropical climates, reinforcing its potential for sustainable building applications. Understanding the relationship between the mechanical and permeation properties of PKS-laterized concrete will advance knowledge in sustainable construction technologies, offering a pathway for optimizing the use of agricultural by-products in concrete while aligning with global sustainability goals and promoting eco-friendly construction practices.

While this study provides valuable data on the permeability characteristics of PKS-laterized concrete, it is limited to specific water-cement ratios and short-term durability assessments. Further research is needed to evaluate its long-term performance under diverse environmental conditions.

2 Materials and Methods

2.1 Materials

The concrete mixes in this study were prepared using Ordinary Portland Cement (OPC) 42.5R as the primary binder, conforming to BS EN 197-1 [45]. Potable water, compliant with BS EN 1008 [46], was used for mixing, curing, and testing to maintain consistency across all specimens. The fine aggregate was natural river sand, meeting the requirements of BS EN 12620 [47]. Prior to mixing, it was confirmed that 36.5% of the fine aggregate particles passed through a 600 µm sieve. This percentage passing through the 600 µm sieve is an important factor in determining an appropriate fines content for the concrete mix [48]. Locally sourced crushed granite, with a maximum particle size of 20 mm, served as the coarse aggregate.

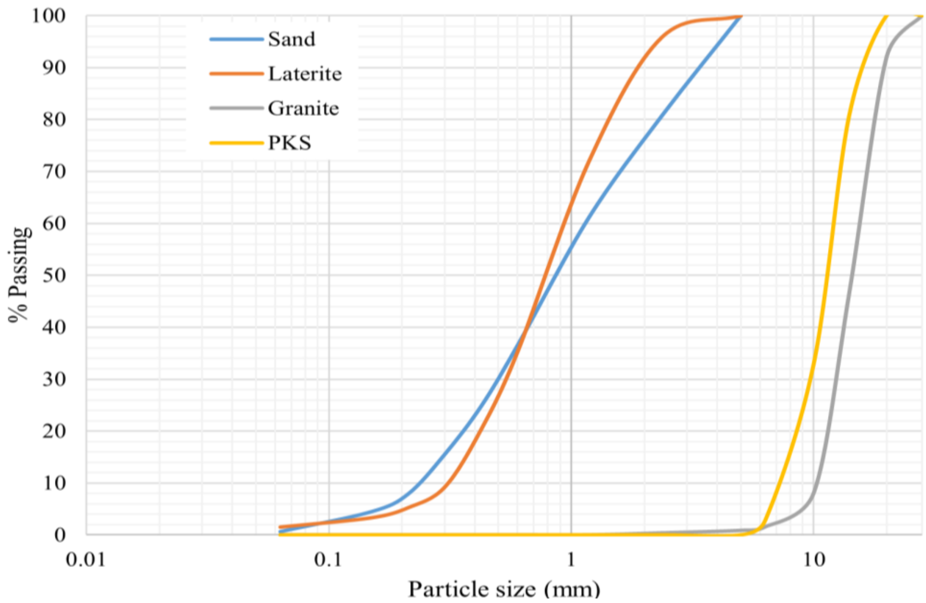


Fig. 1. Gradation curves of the aggregates

Table 1. Chemical composition of the cement, laterite, and PKS

Compound	(%) in the cement	(%) in the laterite	(%) in the PKS
Calcium Oxide (CaO)	63.3	0.14	5.1
Silicon Dioxide (SiO_2)	22.1	18.38	55.2
Magnesium Oxide (MgO)	2.6	0.23	4.4
Sodium Oxide (Na_2O)	0.3	0.06	1.32
Iron Oxide (Fe_2O_3)	3.8	51.4	8
Potassium Oxide (K_2O)	0.8	0.12	-
Sulfur Trioxide (SO_3)	2.3	-	0.2
Aluminum Oxide (Al_2O_3)	3.3	26	20.2
Titanium Dioxide (TiO_2)	-	0.5	-
Phosphorus Pentoxide (P_2O_5)	-	0.06	-
Manganese Oxide (MnO_2)	-	0.12	-
LOI	1.1	2.47	4.1

Laterite soil, collected locally, was air-dried and sieved through a 5 mm sieve to ensure a uniform particle size distribution before its use as a partial replacement for river sand. Palm kernel shells (PKS), a byproduct sourced from local palm oil mills, were cleaned, air-dried, and sieved to remove impurities and standardize particle size. The PKS were then used to replace a portion of the coarse aggregate. The chemical compositions of the cement, laterite, and PKS are presented in **Table 1**, while **Table 2** summarizes the grading and physical properties of the sand, laterite, granite, and PKS. Grading curves for these aggregates are shown in **Fig. 1**.

Table 2. Characteristics of aggregates

Properties	Laterite	Sand	Granite	PKS
Fineness modulus	2.85	3.01	6.99	6.67
Coefficient of uniformity	3.20	4.88	1.55	0.94
Coefficient of curvature	0.94	0.92	0.94	1.55
Specific gravity	2.51	2.66	2.72	1.58
Moisture content (%)	2.47	1.11	1.61	3.86
Liquid limit (%)	25.0	-	-	-
Plastic limit (%)	14.0	-	-	-
Plasticity index (%)	11.0	-	-	-

2.2 Replacement Levels and Mix Design

The study investigated various combinations of replacement levels for laterite and palm kernel shells (PKS) in concrete. Laterite was used to replace natural sand, and for each laterite level (10%, 20%, and 30% by mass), crushed granite was replaced with PKS at the corresponding percentages. These specific replacement levels were chosen based on prior studies [15,49–52]. which indicate that replacements up to 30% can maintain a balance between strength and permeability while ensuring acceptable workability. This systematic approach enables evaluation of how increasing amounts of these sustainable materials affect concrete properties, facilitating the observation of trends in workability, void content, and permeability as the replacement percentages increase. When both materials are used at their maximum level (30% each), the total replacement reaches 60%. This full-factorial design not only assesses the performance of concrete with significant replacement of both fine and coarse aggregates but also establishes a baseline to determine whether the synergy between PKS and laterite may allow for higher replacement levels of these sustainable materials in a concrete mix (i.e., beyond 30% in total) without compromising strength and durability. All aggregates were brought to a saturated surface-dry (SSD) condition before mixing to ensure consistent water content across all mixes.

The mix design followed the Building Research Establishment (BRE) Design Guide [48] and targeted a characteristic strength of 50 N/mm ^{2} with a slump range of 60–180 mm to ensure durability, structural applicability, and adequate workability with alternative materials. This strength level enables the study to assess whether laterite and PKS can effectively substitute traditional aggregates in high-strength concrete while maintaining essential durability properties. The fine, clay-like particles of laterite can increase internal friction within the mix, potentially reducing workability. To counteract this, the earlier stated slump range was chosen from the BRE Design Guide to maintain consistent flow across mixes containing laterite and PKS. The specified strength and workability led to a water-cement ratio of 0.4, from which a free water content of 225 kg/m ^{3} was obtained. This free water content was determined based on crushed aggregate with a maximum size of 20 mm and the targeted slump range. The cement content was then calculated using the chosen free water content and water-cement ratio.

In a saturated surface-dry state, the total aggregate content was calculated by subtracting the cement and free-water content from the estimated wet density of the concrete. The fine-to-coarse aggregate ratio was determined by considering the maximum aggregate size, target workability, fine aggregate grading (percentage passing a 600 µm sieve), and the water-cement ratio. The final mix proportions used in the research for each mix variation, calculated for a target strength of 50 N/mm ^{2}, a slump of 60–180 mm, and a water-cement ratio of 0.4, are presented in **Table 3**. The effect of water-cement ratio on the concrete properties was evaluated by increasing the ratio to 0.45 and 0.6. The water content of 225 kg/m ^{3} was maintained across all replacement levels and water-cement ratios. For water-cement ratios of 0.45 and 0.6, the cement content was adjusted to 25.31 kg and 18.98 kg per mix variation, respectively, while the water content remained constant at 11.39 kg. All other material contents remained unchanged.

Table 3. Mass of constituent materials for the test concrete at 0.4 water-cement ratio

Mix Variation	Cement (kg)	Water (kg)	Sand (kg)	Laterite (kg)	Granite (kg)	PKS (kg)
Control Mix	28.48	11.39	31.02	0.00	50.61	0.00
10% Laterite, 10% PKS	28.48	11.39	27.92	3.10	45.55	5.06
10% Laterite, 20% PKS	28.48	11.39	27.92	3.10	40.49	10.12
10% Laterite, 30% PKS	28.48	11.39	27.92	3.10	35.43	15.18
20% Laterite, 10% PKS	28.48	11.39	24.82	6.20	45.55	5.06
20% Laterite, 20% PKS	28.48	11.39	24.82	6.20	40.49	10.12
20% Laterite, 30% PKS	28.48	11.39	24.82	6.20	35.43	15.18
30% Laterite, 10% PKS	28.48	11.39	21.71	9.31	45.55	5.06
30% Laterite, 20% PKS	28.48	11.39	21.71	9.31	40.49	10.12
30% Laterite, 30% PKS	28.48	11.39	21.71	9.31	35.43	15.18

2.3 Specimen Preparation and Testing Methods

The concrete specimens, prepared according to BS EN 12390-2 [53], were cast for compressive strength, void content, and initial surface absorption tests. Concrete specimens were cast in standard steel cube molds (150 mm × 150 mm × 150 mm) to ensure uniform geometry across all samples. The specimens were compacted in three layers, each layer tamped to remove air voids, then covered with a damp cloth and plastic sheeting to prevent moisture loss. After 24 hours, the specimens were de-molded and immediately placed in a water tank maintained at 23 ℃ to ensure complete hydration and strength development.

For the void content test, each 150 mm cube was cut into four portions, each with a volume of 843.75 cm^3, ensuring ease of measurement while complying with ASTM C642-06 [54], which specifies a minimum specimen volume of 350 cm^3. This approach allowed for multiple measurements per cube while ensuring that each portion was free from observable cracks, fissures, or shattered edges. The ISAT and void content specimens were oven-dried to constant mass at 105 ℃. The compressive strength test was conducted on the 150 mm cubic specimens following BS EN 12390-3 [55] at 28 days of curing.

A total of 150 concrete cubes were cast for this study. 30 cubes were tested for compressive strength at 28 days, with three specimens per mix variation. Another 30 cubes were used for the void content test, each cut into four portions, resulting in 120 test portions. The remaining 90 cubes were allocated for the ISAT test, with three cubes per mix variation tested at 28, 56, and 90 days to evaluate surface permeability over time.

The void content test followed ASTM C642-06. The procedure involved measuring the mass of the specimen in different states to determine the total interconnected void space within the hardened concrete. The oven-dry mass (A) was first determined by drying the specimen at 105 ℃ until a constant mass was achieved, ensuring that all moisture was removed and representing the solid mass without absorbed water. Afterward, the saturated mass after immersion (B) was obtained by submerging the specimen in water at 21 ℃ for at least 48 hours, allowing accessible pores to absorb water until no further weight gain was observed. Once the specimen reached full saturation under immersion, it was then subjected to boiling for 5 hours and subsequently cooled for 14 hours, after which the saturated mass after boiling (C) was recorded. Boiling forces water into deeper, previously inaccessible voids, allowing full saturation of the interconnected pore network. Finally, the immersed apparent mass (D) was determined by fully suspending the specimen in water, where it experiences a buoyant force.

The mass measurements were taken in grams (g) to calculate the void content. In this calculation, $(C-A)$ represents the total amount of water absorbed by the specimen, including both water absorbed into accessible pores (from immersion) and water forced into deeper, interconnected permeable voids (from boiling). Since water has a density of 1 g/mm^3, the difference $(C-A)$ not only quantifies the absorbed water but also directly corresponds to the volume of voids within the concrete, expressed in mm. The difference $(C-D)$ represents the mass of water displaced by the specimen when fully submerged, which is equal to the mass of an equivalent volume of water. Since this mass-to-volume conversion follows the same density relationship, $(C-D)$ also represents the total volume of the specimen in mm^3. Thus, the void content percentage was obtained by comparing $(C-A)$ (volume of voids in mm^3) with $(C-D)$ (total specimen volume in mm^3). The void content was determined using Eq. (1):

$$VoidContent(\%) = \frac{C-A}{C-D} \times 100 \tag{1}$$

Initial surface absorption test (ISAT) was carried out following BS 1881-208 [56]. The test measured the rate of water absorption by the concrete surface. The tap was turned off after 10 minutes, and the average distance moved by water along the capillary tube in a minute over three readings was recorded and multiplied by the calibration factor (C_f) to obtain ISAT 10 values using Equation 2:

$$ISAT_{10} = N_{10} \times C_f \tag{2}$$

Where $ISAT_{10}$ is initial surface absorption measured 10 minutes after water first contacted the concrete surface; N_{10} = The number of scale divisions moved in one minute, recorded ten minutes after water first made contact with the concrete surface; C_f = Calibration factor of the capillary tube.

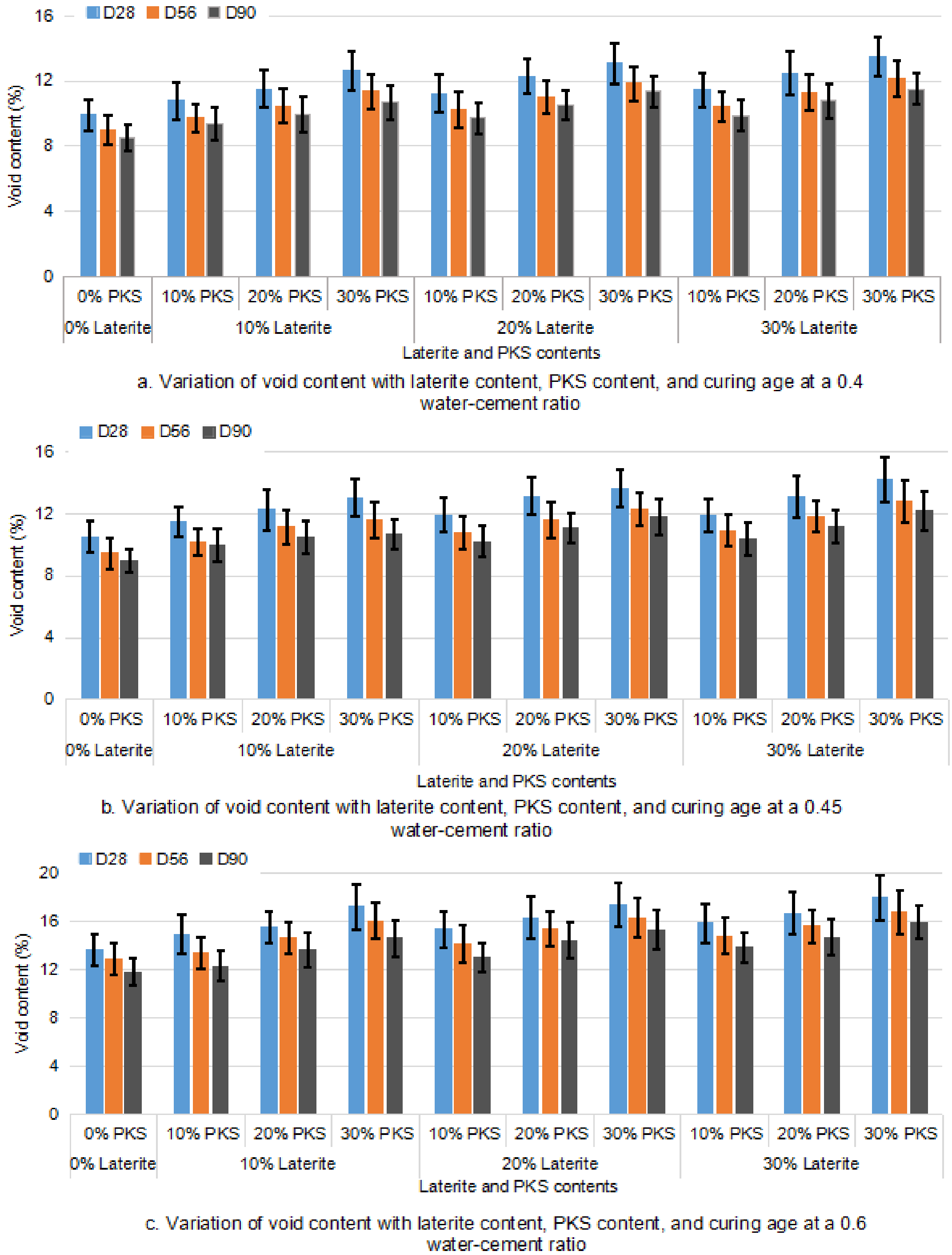
All specimens for void content and initial surface absorption were tested at 28, 56, and 90 days of curing to monitor the evolution of these properties over time. Additionally, no further normalization factors were applied, as all specimens were prepared and tested under identical conditions to ensure comparability.

Table 3. Void factor and percentage increase across different water-cement ratios with laterite and PKS replacement levels

% Laterite Replacement	% PKS Replacement	Void Factor - D28	Void Factor - D56	Void Factor - D90	Overall Mean	% Increase in Void Content
0.4 Water-cement ratio						
0	0	100	100	100	100	0
10	10	109	109	110	109.3	9.3
	20	116	117	117	116.7	16.7
	30	127	127	126	126.7	26.7
20	10	113	114	114	113.7	13.7
	20	124	123	124	123.7	23.7
	30	132	132	133	132.3	32.3
30	10	116	117	116	116.3	16.3
	20	126	126	127	126.3	26.3
	30	136	136	135	135.7	35.7
0.45 Water-cement ratio						
0	0	100	100	100	100	0
10	10	109	108	111	109.3	9.3
	20	117	118	117	117.3	17.3
	30	124	123	119	122	22.0
20	10	113	114	114	113.7	13.7
	20	125	123	124	124	24.0
	30	130	131	131	130.7	30.7
30	10	113	116	115	114.7	14.7
	20	124	125	124	124.3	24.3
	30	135	135	136	135.3	35.3
0.60 Water-cement ratio						
0	0	100	100	100	100	0
10	10	109	104	104	105.7	5.7
	20	114	114	116	114.7	14.7
	30	126	125	124	125	25.0
20	10	112	110	110	110.7	10.7
	20	119	120	122	120.3	20.3
	30	127	127	130	128	28.0
30	10	116	115	117	116	16.0
	20	122	121	125	122.7	22.7
	30	131	130	135	132	32.0

3 Results and Discussion

The void content values for different laterite and PKS replacement levels at w/c ratios of 0.4, 0.45, and 0.6 are presented in **Fig. 2a** to **2c** for curing periods of 28, 56, and 90 days. The results indicate that void content increases with higher w/c ratios, particularly at 0.6, which aligns with previous studies. For instance, a recent study [57] reported that increasing the w/c ratio from 0.4 to 0.6 in superabsorbent polymer (SAP)-modified cement pastes led to a corresponding rise in void content. Although the study focused on SAP rather than PKS-laterized concrete, the observed trend of increasing void content with higher w/c ratios is consistent with the findings of this study.



a. Variation of void content with laterite content, PKS content, and curing age at a 0.4 water-cement ratio

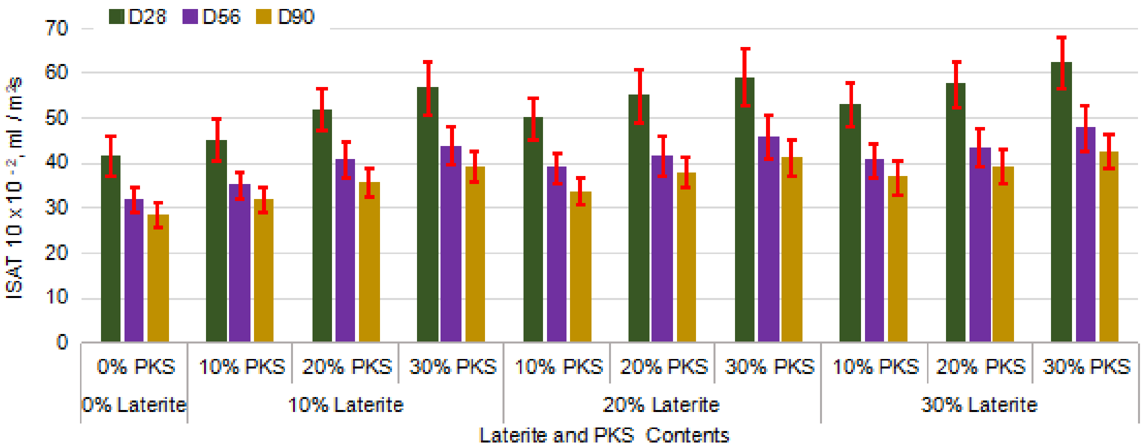
b. Variation of void content with laterite content, PKS content, and curing age at a 0.45 water-cement ratio

c. Variation of void content with laterite content, PKS content, and curing age at a 0.6 water-cement ratio

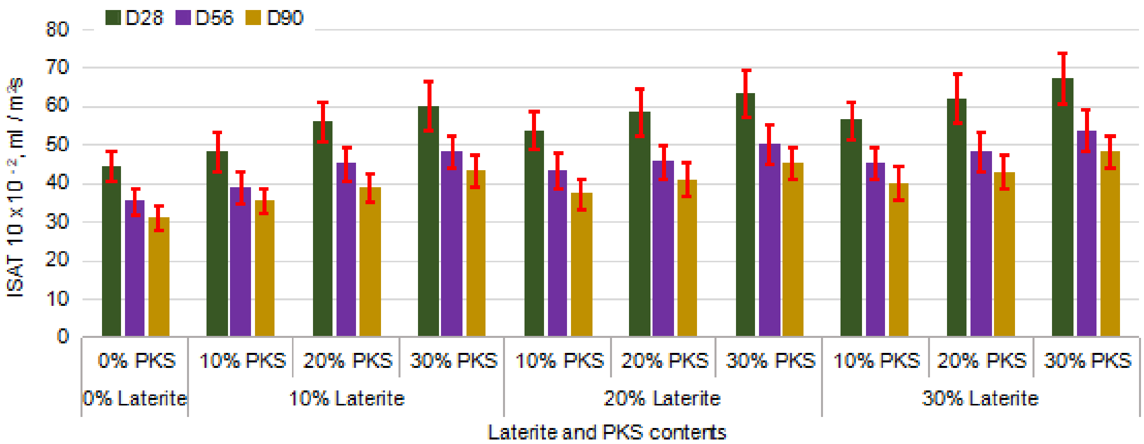
Fig. 2. Variation of void content with laterite content, PKS content, water-cement ratio, and curing age (Error bars in all figures represent standard deviation.)

At equal laterite levels, void content rises with increasing PKS content, with the highest values observed at 30% PKS. This increase is likely due to the lower density and higher porosity of PKS, which disrupts the concrete matrix. These findings align with prior research [43], which reported that incorporating PKS as a coarse aggregate in laterized concrete led to increased porosity and void content. The study provided microstructural evidence from SEM analysis, showing that PKS creates a progressively porous internal structure as its content increases. This confirms that the lightweight and porous nature of PKS contributes significantly to void formation in concrete, consistent with the trends observed in this study. Similarly, at equal PKS levels, void content increases with more laterite, particularly at 30% laterite. At a 0.4 water-cement ratio, void content increased from 9.36% (10% laterite) to 9.90% (30% laterite) at 10% PKS, from 9.95% (10% laterite) to 10.79% (30% laterite) at 20% PKS, and from 10.69% (10% laterite) to 11.53% (30% laterite) at 30% PKS, after 90 days of curing. Previous research [58] reported a similar trend, where void content increased with laterite replacement. For specimens cured in water with a 0.5 water-cement ratio, void content rose from 9.6% at 10% laterite to 10.5% at 30% laterite after 98 days of curing. Although that study did not include PKS as a coarse aggregate replacement, the trend aligns with the findings of this study, where void content similarly increased with laterite content. The consistency in results suggests that laterite replacement contributes to higher void content regardless of the presence of PKS, though differences in water-cement ratio and curing duration may influence the absolute values. The combined effect of PKS porosity and the fine structure of laterite results in a more permeable concrete with increased void content. Additionally, **Fig. 2** shows that PKS leads to higher void content than laterite in concrete. Extended curing reduces void content across all mixes, yet all laterite and PKS mixes exhibit higher void content than the control, as shown in **Table 3**.

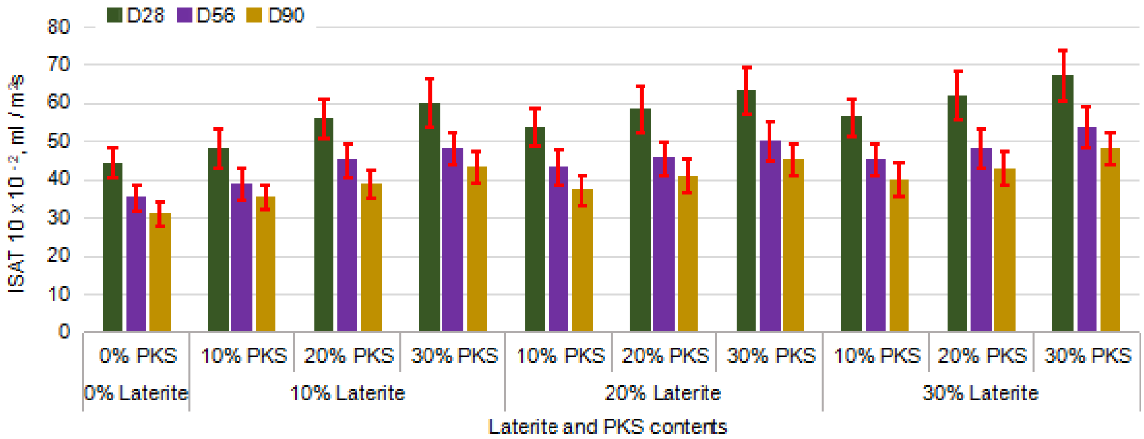
The ISAT 10 values for the concrete mixes were measured at 28, 56, and 90 days for three different water/cement (w/c) ratios (0.40, 0.45, and 0.60) and various percentages of laterite and palm kernel shell (PKS) replacements, as depicted in **Figs 3a – 3c**.



a. Change in ISAT 10 with laterite content, PKS content, and curing age at a 0.4 water-cement ratio



b. Change in ISAT 10 with laterite content, PKS content, and curing age at a 0.45 water-cement ratio



b. Change in ISAT 10 with laterite content, PKS content, and curing age at a 0.45 water-cement ratio

Fig. 3. Change in ISAT values with laterite content, PKS content, water-cement ratio, and curing age (Error bars in all figures represent standard deviation.)

The results indicate that increasing the water-cement (w/c) ratio leads to higher ISAT 10 values across all curing periods, reflecting greater surface absorption and permeability. For instance, at 28 days, the control mix exhibits ISAT 10 values of 42, 44, and 53 (x 10^{-2} ml/m^{2}s) for w/c ratios of 0.4, 0.45, and 0.6, respectively. This trend persists across different mix combinations and is attributed to reduced cement content and increased porosity at higher w/c ratios. The greater porosity at higher w/c ratios results from the increased volume of capillary pores left behind after water evaporation during hydration [59]. A higher w/c ratio also weakens the bond between the cement paste and aggregates [60], leading to reduced density and strength. The effect is further amplified by the porous nature of PKS, which absorbs additional water, contributing to microvoid formation. Consequently, higher w/c ratios result in greater permeability due to increased porosity and weaker interfacial bonding.

At equal laterite levels, increasing PKS content results in higher ISAT 10 values. This trend aligns with findings from existing literature [14], which report that PKS incorporation increases permeability and absorption in concrete due to its high porosity. The replacement of conventional aggregates with PKS introduces more voids, leading to increased water penetration, a trend consistent with the findings of this study.

Sieve analysis results show that PKS has a narrower particle size distribution than granite, as indicated by its lower coefficient of uniformity (C_u = 0.94) compared to granite (1.55). This suggests less efficient packing in the concrete matrix. While the coefficient of curvature (C_c = 1.55) falls within the acceptable range ($1 < C_c < 3$), indicating a reasonable distribution of intermediate particle sizes, PKS particles are more porous and irregularly shaped than granite, further contributing to increased voids.

Beyond gradation effects, PKS's lightweight and porous nature significantly increases water absorption and permeability. At 20% PKS, ISAT rose from 52 × 10^{-2} ml/m^{2}s (10% laterite) to 58 × 10^{-2} ml/m^{2}s (30% laterite) at a 0.4 w/c ratio, highlighting the link between void content and absorption. The lower density of PKS compared to granite further reduces packing efficiency, creating interconnected voids that facilitate water ingress.

Additionally, the organic nature of PKS weakens the interfacial transition zone (ITZ) with cement paste, leading to microcracks and additional pathways for water absorption. These factors collectively contribute to the observed increase in ISAT 10 values with higher PKS content. However, since PKS already has a relatively uniform particle size distribution, further reducing size variation may not improve packing efficiency. Instead, a well-graded PKS with a broader range of particle sizes would enhance particle interlock, reduce void content, and improve overall performance. While PKS enhances sustainability by reducing reliance on natural aggregates, its increased permeability could affect durability unless measures such as optimized packing and admixture use are implemented.

Similarly, at equal PKS levels, increasing laterite content raises ISAT 10 values, as its finer clay-like particles and higher water demand contribute to interparticle voids and reduced packing efficiency.

At a 0.4 water-cement ratio, ISAT 10 values ($\times10^{-2}$ ml/m²s) at 20% PKS replacement increased from 52 (10% laterite) to 55 (20% laterite) and further to 58 (30% laterite) after 28 days. A study [58] observed a similar trend at a 0.35 water-cement ratio, where ISAT values increased from 36.5 (10% laterite) to 40.0 (30% laterite) after 42 days of water curing. Although the absolute values differ due to variations in water-cement ratio and curing duration, both studies confirm that higher laterite replacement leads to increased surface absorption, reinforcing the trend observed in this research.

Sieve analysis results further explain this behavior. Laterite is poorly graded compared to sand, as indicated by its lower coefficient of uniformity (Cu), which is 3.20 compared to 4.88 for sand. This narrower range of particle sizes in laterite reduces its ability to fill voids effectively. Similarly, the coefficient of curvature (Cc) for laterite is 0.94, slightly higher than sand's 0.92, but still below the ideal range of 1 - 3, indicating an imbalance in the distribution of intermediate-sized particles.

At larger sieve sizes (e.g., 2.36 mm and 1.18 mm), laterite has a much higher percentage passing (95.85% and 71.92%) than sand (80.70% and 61.09%), indicating a greater proportion of finer particles at these sizes. However, at intermediate sieve sizes (0.425 mm - 0.3 mm), laterite has noticeably fewer passing particles (20.35% and 9.16%, respectively) compared to sand (24.82% and 15.48%). This deficiency in intermediate particles reduces packing efficiency and increases void content in the concrete matrix. Although laterite has slightly more very fine particles at 0.063 mm (1.47% vs. 0.61% for sand), this marginal increase is insufficient to compensate for the grading gap.

Overall, laterite's poorer gradation, lower Cu, and deficiency in intermediate-sized particles contribute to its reduced packing efficiency and higher void content, ultimately leading to increased permeability. In contrast, sand's well-graded nature allows for better particle interlock and lower permeability, enhancing concrete durability.

Given that the laterite sample is deficient in intermediate-sized particles as evident from its lower passing percentages at the 0.425 mm and 0.3 mm sieves, introducing a controlled range of smaller particles could improve the overall gradation. A more continuous particle size distribution would likely enhance packing efficiency, reduce void content, lower binder demand, and improve the overall strength and durability of the concrete mix. This highlights the potential benefits of optimizing laterite gradation in future mix designs.

Across all tested water-cement ratios, the concrete mix containing 10% Laterite and 10% PKS consistently exhibits ISAT and VPV values that fall within the acceptable range compared to the control mixes. Other mixes with higher percentages of Laterite or PKS replacements exceed the comparable ranges for either ISAT, VPV, or both, indicating that they may not possess properties as favorable as the control.

Durability assessments based on ISAT and VPV classifications were used to evaluate the concrete mixes. These classifications draw upon foundational research on ISAT values and VPV values, enabling a targeted application of each mix's resistance to chloride ingress, carbonation, and general permeability across various environmental exposure categories [60,61]. For the concrete mixes with a 0.4 water-cement ratio, both ISAT and VPV values indicate suitability for high-durability environments. All the mixes, regardless of laterite or PKS content, demonstrated VPV values below 14%, aligning with the criteria for severe coastal and marine environments (Class C). The control mix (0% laterite, 0% PKS) and the mix with 10% laterite and 10% PKS achieved ISAT values that further confirm their high resistance to chloride ingress. This makes them especially suitable for chloride-rich conditions, such as marine or coastal structures and bridge decks, where resistance to aggressive salt exposure is critical. The dense matrix of these mixes provides effective impermeability, minimizing moisture ingress and enhancing durability in saline conditions.

Other mixes with this water-cement ratio, containing higher percentages of laterite or PKS, also meet the durability requirements for Class C environments, though their optimal application may be in less direct marine settings, where the presence of saltwater spray is more moderate. This classification underscores the suitability of the 0.4 water-cement ratio for high-durability applications where impermeability is essential.

The concrete mixes with a 0.45 water-cement ratio generally align with Class C environmental standards, suitable for severe coastal and marine environments. However, the mix with 30% laterite and

30% PKS has a VPV value of 14.21%, slightly above the Class C threshold. This marginally higher void content suggests that this mix is better suited to moderate coastal or humid environments (Class B2), where exposure is less aggressive. The ISAT results further differentiate durability for these mixes, with the control mix and the 10% laterite, 10% PKS mix being highly suitable for chloride-rich environments due to their low permeability.

For urban or moderate CO_2-exposed structures (carbonation-prone settings), the 10% laterite with 20-30% PKS, 20% laterite with 10-30% PKS, and 30% laterite with 10-30% PKS mixes are appropriate. As per the ISAT results, these mixes exhibit moderate carbonation resistance, making them ideal for structures like parking garages and industrial or urban buildings where atmospheric CO_2 is the primary durability concern.

Table 4. ISAT factor and percentage increase across different water-cement ratios with laterite and PKS replacement levels

% Laterite Replacement Level	% PKS Replacement Level	ISAT Factor - D28	ISAT Factor - D56	ISAT Factor - D90	Overall Mean	% Increase in ISAT Value
			0.35 Water-cement ratio			
0	0	100	100	100	100	0
	10	108	110	112	110	10.0
10	20	125	127	126	126	26.0
	30	136	137	138	137	37.0
	10	120	122	119	120.3	20.3
20	20	132	131	134	132.3	32.3
	30	142	144	145	143.7	43.7
	10	129.0	126.0	131.0	128.7	28.7
30	20	137.0	136.0	139.0	137.3	37.3
	30	148.0	147.0	146.0	147.0	47.0
			0.45 Water-cement ratio			
0	0	100.0	100.0	100.0	100.0	0.0
	10	109.0	110.0	114.0	111.0	11.0
10	20	126.0	128.0	125.0	126.3	26.3
	30	135.0	136.0	139.0	136.7	36.7
	10	121.0	123.0	119.0	121.0	21.0
20	20	131.0	129.0	132.0	130.7	30.7
	30	142.0	143.0	145.0	143.3	43.3
	10	127.0	128.0	129.0	128.0	28.0
30	20	140.0	136.0	138.0	138.0	38.0
	30	152.0	152.0	154.0	152.7	52.7
			0.60 Water-cement ratio			
0	0	100.0	100.0	100.0	100.0	0.0
	10	107.0	109.0	114.0	110.0	10.0
10	20	120.0	120.0	123.0	121.0	21.0
	30	132.0	134.0	136.0	134.0	34.0
	10	119.0	119.0	120.0	119.3	19.3
20	20	131.0	134.0	135.0	133.3	33.3
	30	141.0	141.0	142.0	141.3	41.3
	10	127.0	125.0	129.0	127.0	27.0
30	20	138.0	138.0	139.0	138.3	38.3
	30	149.0	150.0	152.0	150.3	50.3

At a 0.6 water-cement ratio, the durability classifications shift to less aggressive environments due to higher VPV values across mixes. Only the control mix (0% laterite, 0% PKS) achieved a VPV below 14%, rendering it suitable for severe environments (Class C). Other mixes with 10-30% laterite and 10-20% PKS exhibit VPV values within the range for moderate coastal or humid environments (Class B2), suggesting suitability for moderately aggressive conditions, such as sheltered coastal areas where the risk of direct marine exposure is reduced.

The ISAT results for these mixes indicate moderate carbonation resistance, making them suitable for urban applications exposed to CO_2 but without high chloride risks. However, mixes with 10-30%

laterite and 30% PKS, and 30% laterite and 20% PKS exceed the VPV limits for Class B2, making them more appropriate for mild outdoor or interior protected environments (Class A/B1). These environments present minimal exposure to aggressive agents, aligning well with the moderate durability these mixes offer.

The combined insights from ISAT and VPV classifications underscore how adjustments in water-cement ratios, laterite content, and PKS content can tailor concrete durability performance. This integrative analysis offers a clear guide for selecting optimal concrete mixes based on intended environmental exposure, thereby enhancing the performance and longevity of structures. Additionally, by incorporating sustainable materials like laterite and palm kernel shell (PKS), this approach promotes eco-friendly concrete production, reducing reliance on traditional materials like sand and crushed stone.

Fig. 4 illustrates the 28-day compressive strength results for concrete mixes with varying laterite and PKS replacement levels across different water-cement (w/c) ratios. Compressive strength decreases with higher w/c ratios and increasing laterite and PKS content. For example, the control mix (0% laterite, 0% PKS) achieves compressive strengths of 52.0 MPa, 47.5 MPa, and 42.0 MPa for w/c ratios of 0.4, 0.45, and 0.60, respectively. At a 0.4 w/c ratio, strength decreases from 47.0 MPa at 10% PKS to 43.3 MPa at 30% PKS with 10% laterite, with similar trends at higher w/c ratios. This reduction is linked to increased porosity and lower matrix density caused by PKS and laterite incorporation. PKS, being a lightweight and porous material, has a lower density and strength than conventional granite, while its poor interfacial bond with cement paste weakens load transfer and promotes microcracking. Laterite, with its fine clayey particles, interferes with cement hydration, reducing the formation of calcium silicate hydrate (C-S-H) gel, which is crucial for strength development. Additionally, the increased void content at higher replacement levels further compromises matrix compactness, leading to strength reductions. Consequently, the control mix consistently outperforms laterite- and PKS-modified mixes, aligning with studies documenting the weakening effects of these alternative aggregates in concrete [34, 43, 44].

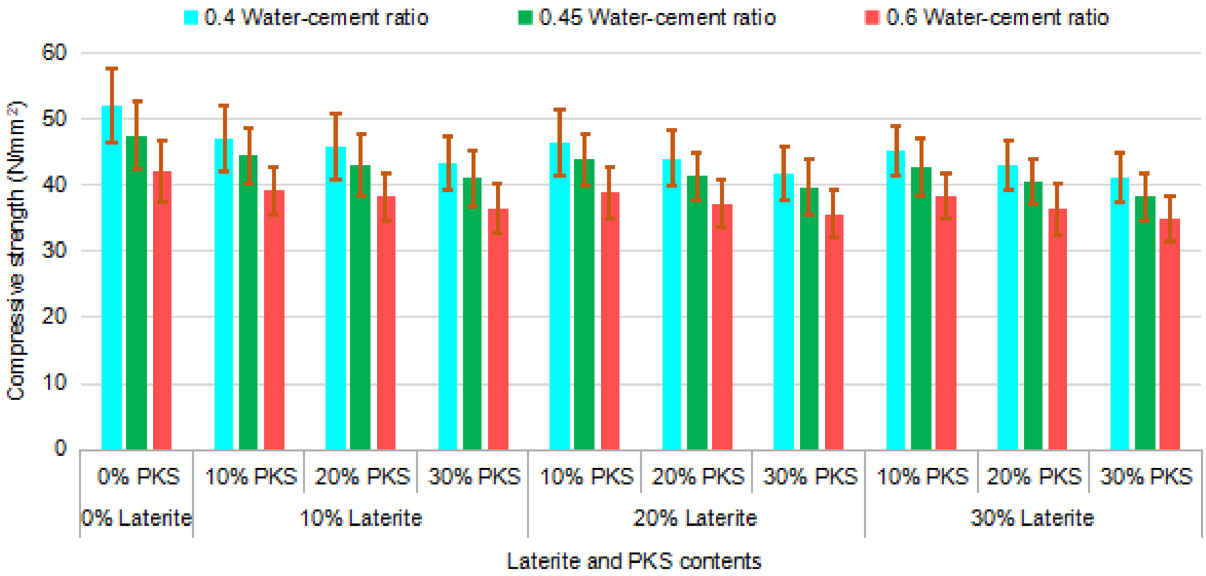


Fig. 4. Change in 28-day compressive strength with laterite content, PKS content, and water-cement ratio.

The interplay between compressive strength, void content, and initial surface absorption (ISAT 10) in the concrete reveals critical insights (**Figs. 5** and **6**). The introduction of laterite and PKS as partial replacements for sand and granite, respectively, modifies concrete properties by reducing compressive strength while increasing void content and surface absorption, particularly at higher water-cement ratios. These changes are primarily attributed to the porous nature of laterite and PKS, their finer particles, and PKS's irregular shape, which collectively increase porosity and weaken the concrete matrix. Consequently, the use of these alternative materials necessitates careful consideration in mix design to achieve a balance between strength and durability, particularly in structural applications.

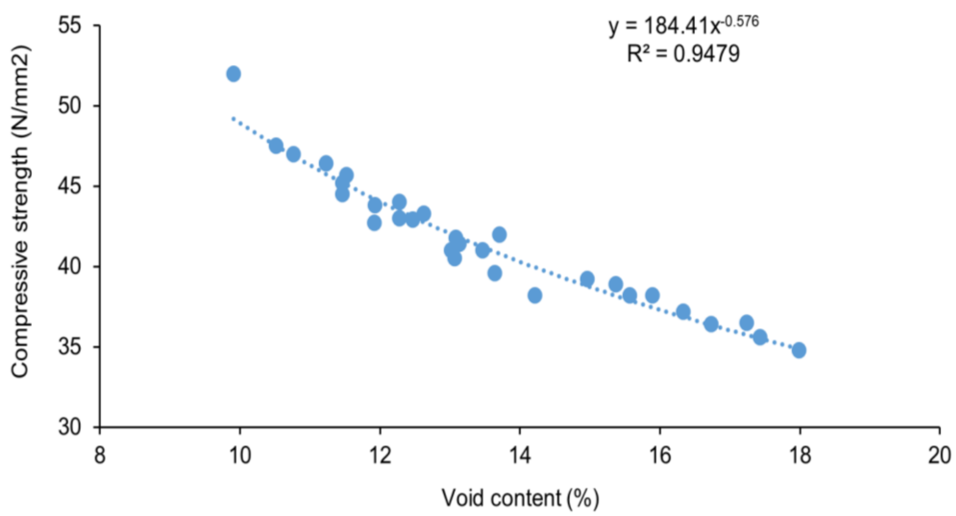


Fig. 5. Correlation between compressive strength and void content in PKS laterized concrete

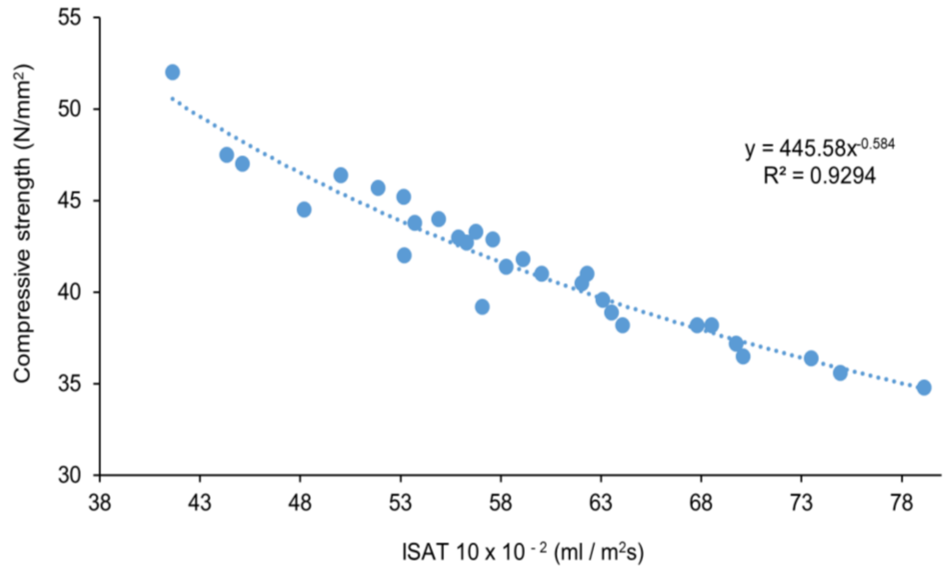


Fig. 6. Analysis of compressive strength in relation to ISAT values in PKS laterized concrete

4 Conclusions

Based on the detailed analysis of void content and initial surface absorption, this study concludes that palm kernel shell (PKS) and laterite can be effectively incorporated into concrete as partial replacements for granite and sand, respectively, offering an eco-friendly alternative to conventional materials. The experimental findings highlight that both PKS and laterite contribute to increased void content and surface absorption, with these effects amplified at higher water-cement ratios and replacement levels. However, the mix containing 10% PKS and 10% laterite displayed performance metrics close to those of the control mix, making it a promising option for practical applications where the performance of the control mix is acceptable.

This study's durability assessments, based on ISAT and VPV values, indicate that PKS-laterized concrete mixes with a 0.4 water-cement ratio, particularly the 10% PKS and 10% laterite mix, are well-suited for high-durability applications in severe coastal environments, showing strong resistance to chloride ingress. Mixes with higher replacement levels at this ratio are suitable for moderate coastal exposure. At a 0.45 water-cement ratio, durability aligns with standards for coastal settings, though higher laterite and PKS levels are best suited to less aggressive environments. For urban applications exposed to carbonation but not high chloride, mixes with up to 30% laterite or PKS proved effective. These findings underscore the viability of PKS and laterite as sustainable alternatives in concrete, enabling tailored mix designs for specific environmental conditions.

PKS-laterized concrete holds the potential for sustainable building, aligning with global environmental goals while contributing to resource conservation. Future research should assess the long-term durability of PKS-laterized concrete in severe weather conditions and aggressive chemical exposures to confirm its sustained performance over time. Additionally, investigating the use of plasticizers or alternative admixtures could help mitigate workability challenges associated with higher laterite content, improving the flowability of the mix without compromising strength. Furthermore, optimizing mix designs to enhance strength and reduce permeability could expand the applicability of PKS-laterized concrete, ensuring its suitability for a broader range of structural applications.

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All authors contributed equally to the completion of this research.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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