UNIABUJA Journal of Engineering and Technology

https://ujet.uniabuja.edu.ng/

ISSN: 2714-3236 (Online); 2714-3228 (Print)

Volume 3, Issue 2, 2026; 270-279

Production of Sustainable Paver Blocks from Metakaolin and Clayey Lateritic Sand

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Abstract

Sustainable alternatives to significantly reduced CO_2 emissions and resource depletion associated with conventional concrete is in high demand in concrete production. In this backdrop, this study presents a production of sustainable paver blocks from metakaolin and clayey lateritic sand. The mechanical performance and statistical variability of this concrete paver blocks is achieved by partially replacing natural river sand with clayey lateritic sand and ordinary Portland cement (OPC) with metakaolin (MK), respectively. Six (6) concrete mix designs experimental specimens were cast and evaluated. These comprised a control mix (100% OPC and natural sand) and five modified mixes with 10%, 15%, 20%, and 25% laterite substitution for sand, each combined with 10% metakaolin replacement of cement. Concrete testing was undertaken at 7, 28, and 56 days, followed by statistical analysis of performance. The study revealed the 15% Laterite-Metakaolin composite (SLMK) replacement level as the optimum formulation for paver blocks, demonstrating the best balance of mechanical performance and consistency. The Control Mix achieved the highest overall strengths of 35.41 N/mm2 in compressive strength and 2.53 N/mm2 in split tensile strength at 56 days. Among the modified mixes, the 15% SLMK mix consistently had the highest strengths, with a 56-day compressive strength of 17.73 N/mm2 and a split tensile strength of 1.77 N/mm2. The study also revealed that strength development declined at lower replacement levels. Statistical analysis revealed that the 15% SLMK mix had the highest mean strength among modified mixes with the lowest Coefficient of Variation, indicating superior reliability and consistency. These findings demonstrate the potential of using 15% SLMK to produce structurally acceptable paver blocks while meeting sustainability goals.

Keywords: *Concrete, Compressive Strength, Metakaolin, Paver blocks, Sustainability.*

1.0 Introduction

The global construction industry is facing unprecedented challenges related to resource depletion and environmental degradation. Concrete, as the most widely used construction material globally contributes approximately 8% of global CO_2 emissions (Andrew, 2018; Monteiro *et al.*, 2017). This substantial environmental footprint stems primarily from ordinary Portland cement (OPC) production, which requires high temperatures and releases approximately 0.9 tons of CO_2 per ton of cement produced (Scrivener *et al.*, 2018). Concurrently, the extraction of natural aggregates, particularly river sand, has led to severe ecological consequences including riverbed degradation, groundwater depletion, and habitat destruction (Torres *et al.*, 2017). Paver blocks are widely utilized in construction for pedestrian walkways, driveways, parking areas, and urban landscaping due to various advantages they offer. The global paver block market was valued at USD 4.6 billion in 2024 and is projected to grow at a compound annual growth rate of 5.0% through 2034, driven by rapid urbanization particularly in emerging economies (GMI, 2025). This growth trajectory shows the need for sustainable alternatives such as supplementary cementitious materials (SCMs) in paver block production.

Supplementary cementitious materials (SCMs) have emerged as a vital strategy for sustainable concrete production. SCMs are fine-grained materials that, when used in conjunction with Portland cement, contribute to concrete properties through hydraulic or pozzolanic activity (Adanikin *et al.*, 2020). Metakaolin is one of such SCMs. Metakaolin (MK), produced through controlled thermal activation of kaolinite clay at temperatures between about 650-850°C, leads to dehydroxylation and formation of an amorphous aluminosilicate structure with enhanced pozzolanic reactivity compared to the parent clay (Ilic *et al.*, 2010; Rashad, 2013). Its amorphous aluminosilicate structure facilitates rapid pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$) liberated during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel and calcium aluminate hydrate phases (Sabir *et al.*, 2001). The typically fine particle size of metakaolin allows it to fill voids between cement grains and aggregates thereby improving particle packing, reducing permeability, and accelerating early-age hydration (Courard *et al.*, 2003; Kostuch *et al.*, 2000). Recent studies show that while a 10% metakaolin replacement optimizes concrete compressive strength and densifies the

Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026

https://doi.org/10.70118/ujet.2026.0302.23

microstructural interfacial transition zone (Imoh, 2025), a higher 15-20% threshold is superior for enhancing surface durability and minimizing abrasion loss when paired with fiber reinforcements (Ghosh, 2026).

Laterite, a weathered tropical soil rich in iron and aluminium oxides, presents a promising alternative to conventional fine aggregates. It encompasses a range of materials from soft, clayey soils to hardened laterite stone, with typical chemical compositions of about 40-60% Fe_2O_3, 10-30% Al_2O_3, and 10-30% SiO_2 (Bakouan *et al.*, 2025). Widely available across tropical and subtropical regions, laterite offers potential economic and environmental benefits through reduced transportation costs and preservation of natural sand resources. Its particle size distribution often includes a high fines content which strongly influences the workability and strength of concrete mixtures (Swatantra *et al.*, 2024), and its specific gravity is slightly lower than that of conventional river sand due to its more porous structure (Oluyinka and Olubunmi, 2018). Previous studies have investigated laterite as a partial replacement for fine aggregates in concrete, with varying conclusions regarding optimal replacement levels and performance characteristics (Sabarish *et al.*, 2015; Karra *et al.*, 2016). Evaluating metakaolin as an SCM and laterite as an alternative fine aggregate provides a viable pathway for achieving standard paver block performance. Although studies have examined these materials separately, several critical knowledge gaps persist regarding their combined use in a laterite-metakaolin matrix. Some studies report only 28-day compressive strength, providing inadequate insight into long-term strength development crucial for service life prediction (Garcia-Troncoso *et al.*, 2026; Imoh *et al.*, 2025; Narmatha and Felixkala, 2016; Weng *et al.*, 2013). Furthermore, comprehensive statistical analysis of strength variability and reliability, essential for quality control, is often absent from published literature. Studies specifically targeting paver block applications, which have distinct performance requirements compared to structural concrete, are limited, and the properties of laterite vary significantly based on geological origin, necessitating region-specific investigations (Bayewu *et al.*, 2012).

Considering these identified gaps, this study aims to explore the potential of integrating laterite sand and metakaolin as partial replacements in concrete for sustainable paver block production. By addressing the interaction effects of these materials and evaluating their long-term performance, the study seeks to contribute to a more comprehensive understanding of their viability in paver block applications. This study not only aspires to fill the existing knowledge void but also to provide valuable insights for the development of sustainable concrete solutions that meet specific performance standards in the paver block industry.

2.0 Material and Methods

2.1 Materials

Portland Limestone Cement (PLC), commercially known as Lafarge elephant supaset, was used as the primary binder in all concrete mixtures. Metakaolin (MK) was employed as a supplementary cementitious material (SCM) to partially replace Portland Limestone Cement. The MK was obtained through the controlled thermal activation of purified kaolin clay sourced from local deposits in Nigeria. Calcination was conducted at 800 °C for 60 min thermally activate kaolinite, thereby converting it into a highly amorphous and pozzolanic metakaolin phase. This process was established as the optimum condition for achieving enhanced chemical reactivity and performance in blended cement systems. The resulting MK was characterized by fine particle size and high aluminosilicate content, making it suitable for performance enhancement in concrete.

The fine aggregate comprised natural river sand obtained from nearby deposits. The sand was air-dried for several days prior to batching to ensure uniform mass and eliminate the effect of residual moisture. The physical characterization of the fine aggregate, including specific gravity and particle size distribution, was established prior to mix design in accordance with BS EN 12620 (2013). Locally sourced granite dust was utilized as the coarse aggregate. The granite dust (coarse aggregate) had a nominal maximum size of 10 mm and satisfied the grading requirements for coarse aggregate specified in BS EN 12620 (2013). Lateritic soil samples were collected from the study area at depths of 1-2 m. Representative samples were subjected to standard geotechnical characterization including grain size analysis, specific gravity determination, compaction testing, moisture content evaluation, and Atterberg limits in accordance with BS 1377 (2020). Based on the grain size distribution and Atterberg limits, the lateritic soil was classified as a clayey laterite, corresponding to a CL soil under the Unified Soil Classification System (USCS) and an A-7-6 group under AASHTO (1991). These tests showed the basic engineering properties of the laterite and confirmed its suitability for use as a partial replacement for fine aggregate in concrete production. Potable tap water, free from contaminants and meeting the quality requirements of BS EN 1008 (2002), was used for both mixing and curing operations.

2.2 Preliminary Testing of Materials

The specific gravities of the cement, sand, and granite dust were determined using a pycnometer method. Kerosene was used as the displacement medium for the cement to prevent premature hydration, while distilled water was used for aggregates. The respective specific gravities were computed using standard equations to support accurate mix proportioning and ensure consistency across materials. The grain size distribution of the fine aggregate was determined in accordance with BS 882 (1992). The natural river sand had a nominal particle size range of 0.075-4.75 mm, corresponding to a fineness modulus of 2.9, and falls within the grading limits for medium to coarse sand. The fineness modulus and cumulative percentage passing were calculated to verify conformity with the grading requirements for medium to coarse natural sand suitable for pavement-grade concrete.

2.3 Concrete Mix Design

The concrete mix was proportioned following the guidelines of the Road Note 4 method, optimized for rigid pavement applications. In all modified mixes, natural river sand and OPC were partially replaced by lateritic sand and metakaolin, respectively. A nominal mix ratio of 1: 1.5: 3 (cement: fine aggregate: coarse aggregate, by weight) was adopted with a water-cement ratio of 0.55 to achieve a balance between strength, workability, and durability. Both control and modified mixes were prepared for comparative evaluation. The control mixture contained 100% Portland Limestone Cement as binder. Mix constituents were proportioned by weight as 1 part cement, 1.5 parts fine aggregate, and 3 parts coarse aggregate with a water-cement ratio of 0.55. This mix served as the benchmark for evaluating the performance of the modified blends. Six modified mix variants were designed by replacing 5-30% of the cement content with metakaolin in increments of 5%, while maintaining a constant total binder weight. Also, 25% of the fine aggregate content was replaced by laterite. Thus, each modified mix consisted of 75% river sand and 25% laterite. All other proportions, including water and coarse aggregates, were kept constant across mix series.

2.4 Specimen Preparation and Curing

Batching was conducted by weight and mixing performed manually on a clean, non-absorbent surface. Water was added gradually to ensure uniform consistency and colour, avoiding segregation or loss of cement paste. For each batch, paving stone (200 × 100 × 80 mm) and cylindrical (150 × 300 mm) specimens were cast in three layers with 25 manual tamping strokes per layer. Moulds were pre-cleaned and lightly oiled for ease of demoulding. Specimens were kept in moulds for 24 h under ambient laboratory conditions (Figure 1), then demoulded (Figure 2) and submerged in curing tanks containing potable water maintained at controlled temperatures. Curing durations were 7, 28, and 56 days for compressive strength tests and extended to 90 days for split tensile strength evaluation. The consistent curing regime ensured uniform hydration and maturation of the concrete.

Figure 1: Cast Concrete Paver Blocks in Moulds Prior to Demoulding

Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026
https://doi.org/10.70118/ujet.2026.0302.23

Figure 2: Demoulded Concrete Paver Block

2.5 Testing Procedure

Workability of fresh concrete was evaluated via slump tests following BS EN 12350-2 (2019). A standard slump cone (height = 300 mm, bottom diameter = 200 mm, top diameter = 100 mm) was filled in four layers, each tamped 25 times. The slump height difference was measured immediately upon removal of the cone. Slump values were categorized as true, shear, or collapse to indicate consistency and flow characteristics.

Compressive strength tests were carried out on the hardened concrete specimens at 7, 28, and 56 days of curing, in accordance with BS EN 12390-3 (2023). The test employed a hydraulic compression testing machine with a uniform loading rate until failure. The compressive strength f_c was computed using equation 1.

$$f_c = \frac{P}{A} \tag{1}$$

P is the maximum failure load (N) and A is the cross-sectional area of the specimen (mm²). The results provided insight into the mechanical response and efficiency of metakaolin-based cement replacement in pavement concrete.

Tensile strength of concrete was measured indirectly using the Brazilian (split cylinder) test following BS EN 12390-6 (2023) as shown in Figure 3. Cylindrical specimens (150 mm × 300 mm) were loaded diametrically under compression at a rate of 100 kPa/min until failure. The split tensile strength f_{ct} was calculated using equation 2.

$$f_{ct} = \frac{2P}{\pi LD} \tag{2}$$

P is the failure load (N), L is the specimen length (mm), and D is the diameter (mm). The formation of a longitudinal crack along the cylinder axis confirmed tensile failure. The test results established the durability and cracking resistance of the metakaolin-laterite modified concrete system.

Figure 3: Split Tensile Strength Test on Concrete Paver Block

3.0 Results and Discussion

3.1 Compressive Strength Analysis

Compressive strength analysis revealed systematic variations across replacement levels and curing ages as shown in Table 1. The control mix consistently demonstrated superior performance, achieving 28.94, 32.79 and 35.41N/mm² at 7, 28 and 56 days respectively. This progressive strength gain reflects typical Portland cement hydration kinetics, where calcium silicate hydrates (C-S-H) form continuously, densifying the matrix over time (Urmila *et al.*, 2019; Sandeep *et al.*, 2017).

Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026
https://doi.org/10.70118/ujet.2026.0302.23

Table 1: Compressive strength of paver blocks at different curing ages

Mix Designation	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)	Standard Specification
Control Mix	28.94	32.79	35.41	BS EN 206 / BS 8500-1: Strength Class C12/15 Requirement ≥ 15.00 N/mm²
SLMK O%	11.13	11.69	14.43	
SLMK 5%	10.79	12.08	15.02	
SLMK 10%	13.19	14.29	16.05	
SLMK 15%	14.71	15.53	17.73	
SLMK 20%	11.5	14.18	15.79	
SLMK 25%	10.99	13.15	15.56	

Among modified mixes, SLMK 15% consistently outperformed all other replacement levels, achieving 14.71 N/mm² at 7 days, 15.53 N/mm² at 28 days, and 17.73 N/mm² at 56 days. As shown in Table 1, the 28-day compressive cube strength results were evaluated against the BS EN 206 / BS 8500-1 baseline for Strength Class C12/15, which have a minimum threshold of 15.00 N/mm2 for non-structural applications. The SLMK 15% mix achieved 15.53 N/mm2, successfully passing and complying at 28 days due to micro-packing and pozzolanic reactions. Variations below and above 15% failed to meet the 28-day threshold due to possibly slower initial hydration or binder dilution, but all passed by 56 days through sustained pozzolanic activity. The performance of the 15% replacement level can be attributed to optimal synergy between laterite filler effects and metakaolin pozzolanic activity (Faluyi *et al.*, 2023).

The enhanced performance at 15% SLMK replacement results from multiple complementary mechanisms. According to Agboola *et al.* (2024) and Al-Hashem *et al.* (2022), metakaolin, a highly reactive pozzolan, consumes calcium hydroxide ($Ca(OH)_2$) produced during cement hydration, forming additional calcium silicate hydrates through secondary pozzolanic reactions. This secondary hydration densifies the interfacial transition zone (ITZ) between paste and aggregate, reducing porosity and enhancing mechanical interlocking (Amadi and Igwe, 2020). Simultaneously, laterite particles, when present at moderate levels, provide micro-filler effects that optimize particle packing density, reducing void spaces and improving load transfer efficiency (Ogunleye 2023; Rajapriya and Ponmalar, 2020). At the 15% replacement level, sufficient Portland cement remains to ensure robust primary hydration, while metakaolin provides adequate pozzolanic enhancement without excessive dilution of the cementitious matrix (Geu *et al.*, 2026). This balance is critical: too little metakaolin (0-10% SLMK) fails to generate sufficient secondary C-S-H, while excessive replacement (20-25% SLMK) reduces available $Ca(OH)_2$ and dilutes the effective binder content, compromising strength development (Basavaraj and Ravikumar, 2022).

Mixes with 0-10% SLMK demonstrated substantially reduced strength compared to both the control and the 15% SLMK mix. This decline reflects the negative impact of replacing significant volumes of sand with laterite without sufficient compensatory pozzolanic activity. Laterite's high clay content (68.32% passing No. 200 sieve) and elevated water absorption reduce the effective water available for cement hydration. The plasticity index of 26.27% further indicates that laterite particles swell upon water contact, disrupting the concrete matrix and creating weak zones. At low metakaolin dosages, insufficient pozzolanic reactions occur to offset the negative effects of laterite incorporation. The result is a weakened, more porous matrix with poor aggregate-paste bonding (Faluyi *et al.*, 2023).

At replacement levels exceeding 15%, compressive strength either plateaued or declined. SLMK 20% and 25% mixes achieved lower 56-day strengths (15.79 and 15.56 N/mm² respectively) compared to SLMK 15% (17.73 N/mm²). This behaviour aligns with extensive literature documenting that excessive metakaolin replacement (typically >15%) causes strength reduction due to several factors (Basavaraj and Ravikumar, 2022; Poon *et al*, 2006). These mechanisms explain why strength exhibits an optimum at 15% replacement, with performance declining both below 15% and at higher levels, particularly for the 25% mix.

3.2 Split Tensile Strength Analysis

Split tensile strength results as shown in Table 2 mirrored compressive strength trends, demonstrating the strong correlation between these two mechanical properties. The control mix achieved 2.17, 2.35 and 2.53 N/mm² at 7, 28 and 56 days respectively, representing the highest tensile performance.

Table 2: Split tensile strength of paver blocks at different curing ages

Mix Designation	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)	Standard specification
Control Mix	2.17	2.35	2.53	BS EN 206 / BS 8500-1: Strength Class C12/15 Requirement ≥ 1.22 N/mm²
SLMK O%	1.22	1.28	1.37	
SLMK 5%	1.02	1.26	1.42	
SLMK 10%	1.28	1.38	1.50	
SLMK 15%	1.41	1.49	1.77	
SLMK 20%	1.32	1.37	1.56	
SLMK 25%	1.25	1.35	1.54	

Among modified mixes, SLMK 15% again demonstrated higher performance, achieving 1.41, 1.49 and 1.77 N/mm² at 7, 28 and 56 days respectively. As shown in Table 2, the 28 day splitting tensile strength properties were evaluated against the BS EN 206 / BS 8500-1 requirement for a C12/15 concrete matrix which have a minimum threshold of 1.22 N/mm2. Every SLMK-modified mix satisfied and exceeded this standard threshold at 28 days. The highest value of 1.49 N/mm2 at the 15% substitution ratio, indicating optimal matrix refinement and enhanced interfacial bonding. Extended curing to 56 days resulted in tensile gains across all mixes, with the optimal SLMK 15% mix reaching 1.77 N/mm2. This shows its structural integrity for low-load applications. This relatively higher retention of tensile strength suggests that metakaolin addition particularly benefits the interfacial transition zone and aggregate-paste bonding (Rong *et al.*, 2018).

Tensile strength depends heavily on the quality of bonding between cement paste and aggregate particles, as well as the microstructural continuity of the hydrated matrix (Amadi and Igwe, 2020; Rong *et al.*, 2018). Metakaolin's pozzolanic activity refines pore structure and strengthens the ITZ through secondary C-S-H formation, reducing microcracks and improving stress transfer under tensile loading. The superior tensile performance of SLMK 15% confirms that this replacement level optimizes both matrix densification and interfacial bonding. Lower replacement levels (0-10% SLMK) exhibited substantially reduced tensile strengths, reflecting inadequate pozzolanic enhancement and disrupted matrix continuity due to laterite's high plasticity. Higher replacement levels (20-25% SLMK) also underperformed, consistent with the excessive dilution effects observed in compressive strength testing (Faluyi *et al.*, 2023; Dao *et al.*, 2022).

3.3 Statistical Variability Analysis

Statistical analysis of compressive strength results provides critical insights into the consistency and reliability of experimental outcomes as shown in Table 3. The control mix exhibited a mean strength of 32.38 N/mm² with a coefficient of variation (COV) of 10.05%, reflecting moderate but acceptable variability consistent with progressive cement hydration.

Table 3: Statistical variability of compressive strength by mix designation

Mix	Mean (N/mm²)	Std. Dev.	Variance	COV (%)	Range (N/mm²)
Control	32.38	3.25	10.59	10.05	6.47
SLMK 0%	11.41	0.40	0.16	3.47	0.56
SLMK 5%	11.43	0.91	0.83	7.98	1.29
SLMK 10%	13.74	0.78	0.60	5.66	1.10
SLMK 15%	15.10	0.41	0.17	2.72	0.82
SLMK 20%	12.54	1.44	2.07	11.46	2.68
SLMK 25%	11.84	1.15	1.33	9.72	2.16

Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026

https://doi.org/10.70118/ujet.2026.0302.23

With the highest mean strength among modified mixes (15.10 N/mm²) and the lowest COV (2.72%), the 15% replacement level clearly represents the optimal, most reliable formulation. Low COV values (<5%) indicate highly reproducible results, confirming that this mix proportion achieves consistent performance across replicate specimens. The SLMK 0-10% mixes exhibited low COV values (3.47-5.66%), demonstrating reproducible results despite reduced absolute strength. This consistency validates experimental control and confirms that strength reduction stems from material substitution effects rather than procedural variability. The SLMK 20% and 25% also demonstrated elevated COV values (11.46% and 9.72% respectively), indicating less predictable performance. High variability at excessive replacement levels reflects uneven pozzolanic reaction distribution and increased susceptibility to mixing and curing variations (Zhang *et al.*, 2021; Poon *et al.*, 2006). Most mixes exhibited COV <10%, confirming good experimental control and data reliability. The systematic trends observed across replacement levels further validate that observed differences represent genuine material effects rather than experimental results only. These statistical insights reinforce that 15% SLMK replacement achieves the optimal balance between strength enhancement, cost reduction through material substitution, and consistent, reliable performance critical factors for practical implementation in paver block manufacturing.

The results demonstrate that strategic incorporation of locally available laterite combined with metakaolin as supplementary cementitious material can produce concrete paver blocks with acceptable mechanical properties while advancing sustainability objectives. The 15% SLMK replacement level reduces Portland cement consumption by 15%, directly decreasing CO_2 emissions associated with cement production. Simultaneously, utilizing laterites, which are abundant, locally sourced materials in tropical and subtropical regions, reduces transportation costs and energy consumption while minimizing environmental impacts from sand mining. The study findings indicate that metakaolin incorporation at optimal levels (10-15%) not only maintains or enhances mechanical properties. Although durability testing was not conducted in this study, the observed strength performance and microstructural densification inferred from the data suggest potential durability benefits worthy of future investigation.

These findings show the need to develop low-carbon, resource-efficient concrete technologies that maintain structural performance while reducing environmental footprints globally. The demonstrated viability of 15% SLMK replacement provides a practical pathway for sustainable paver block production, particularly in regions with abundant laterite deposits and limited access to conventional fine aggregates.

4.0 Conclusions and Recommendations

This study demonstrates that locally available laterite and metakaolin can be effectively combined to produce sustainable concrete paver blocks without sacrificing mechanical integrity. Comprehensive experimental and statistical evaluation shows that a 15% simultaneous replacement of sand with laterite and cement with metakaolin (SLMK) yields the optimal performance, achieving compressive strengths of 14.71, 15.53, and 17.73 N/mm² at 7, 28, and 56 days with an exceptionally low coefficient of variation (2.72%). This optimum arises from the micro-filler effect of laterite and the pozzolanic reactivity of metakaolin, which densify the matrix, refine pore structure, and strengthen the interfacial transition zone. Lower replacements lack sufficient pozzolanic composition, while higher levels cause strength loss and variability due to excessive cement dilution. Although the control mix remains strongest, the 15% SLMK formulation offers a sustainable alternative that reduces Portland cement use, lowers costs and carbon emissions, and supports local resource utilization and sustainability.

Based on the findings of this study, the following recommendations are proposed. For practical implementation, projects balancing strength and sustainability should adopt 15% SLMK replacement and avoid higher ratios due to reduced strength and variability. Further studies should evaluate durability properties such as chloride resistance and freeze-thaw performance. The studies should also investigate microstructural mechanisms and conduct life cycle and cost assessments to quantify environmental and economic benefits relative to conventional paver blocks. These findings provide a transferable framework for developing region-specific sustainable concrete technologies in areas with abundant lateritic soils.

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Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026

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Received: 13-04-2026 / Accepted: 02-06-2026 / Published: 25-06-2026
https://doi.org/10.70118/ujet.2026.0302.23