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Assessment of Eco-Friendly Lightweight Interlocking Concrete Paving Units Incorporating Sawdust Waste and Laterite

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Research Article

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Abstract

This study assessed the performance of eco-friendly lightweight interlocking concrete paving units incorporating sawdust waste as a partial fine aggregate replacement and lateritic soil as a partial cement replacement. Four mixes were prepared at combined replacement levels of 0, 5, 10 and 15 percent and cured for 7, 14 and 28 days. Compressive strength, flexural strength, bulk density and water absorption were tested against EN 1338:2003 and EN 206 limits. Two-way ANOVA, Tukey's HSD, regression, response surface methodology and a desirability function were applied. Twenty-eight-day compressive strength ranged from 24.8 MPa (control) to 16.4 MPa (15 percent), all meeting the 15.0 MPa minimum. Strength and density decreased with replacement while water absorption increased; the 15 percent mix exceeded the absorption limit. Optimisation identified 7.8–8.2 percent as the best compromise level. Moderate sawdust-laterite replacement produces structurally adequate, lighter paving units suited to sustainable pavement production in Nigeria.

1. Introduction

Concrete Paving Units (CPUs) are widely used for pedestrian ways, driveways, parking areas and low volume access roads, because of their durability, ease of installation and low maintenance needs. Interlocking concrete paving units are mainly made of Portland cement, river sand and crushed stone aggregate. Their production creates a number of well-known environmental problems, such as river bank erosion, high energy consumption and high production of greenhouse gases [1, 10]. However, in the tropical developing countries where urbanization and timber processing are fast growing, two types of waste are being investigated for possible use as aggregate and as binder in CPUs, i.e. saw dust from sawmills and lateritic soils abundant in most parts of West Africa.

Abundant amounts of sawdust are generated as by-products from the processing of timber and these are often disposed of in an uncontrolled manner leading to environmental problems affecting human health [2, 5]. The density of sawdust as a lignocellulosic material is less than that of river sand; thus, its use as a partial replacement for fine aggregate in concrete would result in a reduction in the concrete’s unit weight with increased thermal insulation [3, 12]. However, due to the porous nature of sawdust and the associated organic extractives, an increase in the water required for mixing is anticipated with possible adverse effects on cement hydration. Subsequently, the mechanical properties of the concrete would decrease with increasing amounts of sawdust used as a replacement for fine aggregate at higher than moderate levels of replacement [3, 4, 31]. To improve the compatibility of sawdust with cement paste, sawdust is often treated with alkalies prior to its use in concrete, the most common being sodium hydroxide, which removes the soluble sugars and lignin fractions that would otherwise inhibit setting [4, 12].

Lateritic soils are extensive weathered soils of tropical regions. These soils are mainly composed of iron and aluminum oxides which are the end products of weathering of rocks in tropical climate. Lateritic soils have been used as building materials in the form of earth lumps in road bases, masonry blocks and

stabilized earth structures for many decades in sub-Saharan Africa [6, 20]. The soil is cheap and readily available on most construction sites. Recently, laterite has been investigated as a partial cement replacement to reduce material costs and the clinker related CO2 emissions [7, 24]. However, similar to sawdust, there are limitations in the use of laterite for cement replacement. Excessive substitution with laterite would reduce the amount of cement in concrete which would decrease the available cementitious materials and could decrease the mechanical properties of concrete needed for concrete paving units [8, 50].

The combined use of sawdust waste and laterite in a single concrete paving unit was first evaluated systematically by Sojobi [1], who demonstrated that lightweight interlocking units incorporating both materials could achieve satisfactory performance for pedestrian pavement while reducing self-weight. Subsequent work has tended to examine sawdust and laterite separately, or to substitute one waste-derived material for a single conventional constituent rather than combining two substitutions simultaneously [3, 7, 8, 9, 11]. Where studies have combined biomass-derived and lateritic materials, attention has typically concentrated on compressive strength alone, with comparatively little reporting of flexural strength, bulk density and water absorption together under a single standardised testing regime referenced against recognised paving unit standards such as EN 1338:2003 and EN 206 [17, 18, 19, 27]. This leaves an incomplete picture of how the simultaneous incorporation of these two waste-derived materials governs the full suite of properties that determine whether a paving unit is fit for service.

A further limitation of the existing literature is statistical. Many prior investigations report mean values at a single curing age, or apply one-way analysis of variance to isolate the effect of replacement level without testing whether that effect depends on curing age, and few extend beyond simple mean comparison to regression-based prediction, multi-response optimisation or multivariate analysis of the correlated property set [28, 36, 37, 46]. Because compressive strength, flexural strength, density and water absorption are governed by overlapping but not identical mechanisms, an analytical framework capable of jointly modelling these responses, testing for interaction between replacement level and curing age, and identifying a defensible optimum replacement level under competing performance criteria offers a more complete basis for mix design decisions than univariate comparison alone [34, 35, 39].

This study addresses these gaps by evaluating the physical, mechanical and durability performance of eco-friendly lightweight interlocking concrete paving units incorporating treated sawdust waste and lateritic soil at four combined replacement levels, cured for 7, 14 and 28 days, and interpreted against the requirements of EN 1338:2003 and EN 206. The specific objectives are to: (i) determine the influence of combined sawdust and laterite replacement on compressive strength, flexural strength, bulk density and water absorption; (ii) establish, through two-way analysis of variance and post-hoc comparison, whether the effect of replacement level interacts with curing age; (iii) develop regression and response surface models capable of predicting the measured properties across the tested replacement range; and (iv) determine, through desirability-based multi-objective optimisation and principal component analysis,

the replacement level that offers the most defensible compromise between structural performance, lightweight classification and durability for pedestrian and light-traffic pavement applications.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement of strength class 42.5R, conforming to BS EN 197-1, was used as the primary binder. Natural river sharp sand complying with BS EN 12620 served as the fine aggregate; it was washed to remove silt and organic matter, air-dried and sieved through a 4.75 mm mesh prior to batching. Crushed granite of nominal maximum size 10 mm, also conforming to BS EN 12620, was used as coarse aggregate. Sawdust waste was obtained from a timber processing mill in Warri, Delta State, Nigeria, air-dried for seven days, sieved through a 2.36 mm mesh, and pre-treated by soaking in a 1 percent sodium hydroxide solution to remove soluble sugars and lignin fractions that would otherwise retard cement hydration, before rinsing and re-drying. Lateritic soil was sourced from a borrow pit in the same locality, air-dried, pulverised and passed through a 2 mm sieve. Potable water conforming to BS EN 1008 was used for both mixing and curing.

The physical properties of the four principal solid constituents, determined from sieve analysis (BS EN 933-1) and standard bulk density, specific gravity and water absorption tests, are

summarised in Table 1.

Table 1
Physical properties of concrete constituent materials

Property	River sand	Sawdust waste	Laterite	Crushed granite
Loose bulk density (kg/m³)	1,520	185	1,380	1,490
Specific gravity	2.62	1.21	2.48	2.65
Water absorption (%)	1.2	18.4	3.6	0.8
D10 (mm)	0.18	0.30	0.09	4.10
Fineness modulus	2.81	2.09	1.82	6.24
Note. Bulk density determined per EN 1097-3. Sieve analysis performed per BS EN 933-1.				

The markedly lower bulk density of sawdust relative to river sand and laterite is the principal physical basis for the lightweight behaviour reported in Section 3, while the high water absorption of sawdust (18.4 percent) underlines the importance of the alkali pre-treatment and of maintaining a constant water-to-cement ratio across mixes so that any change in engineering performance can be attributed to the replacement materials themselves rather than to variation in mix water [3, 10].

2.2 Mix proportions and specimen preparation

A nominal mix ratio of 1:2:4 (cement:fine aggregate:coarse aggregate) was adopted with a constant water-to-cement ratio of 0.50. Four mixes were prepared by simultaneously replacing river sand with sawdust waste and cement with laterite, in fixed equal proportion, at combined replacement levels of 0 percent (control), 5, 10 and 15 percent by weight. Because the two materials were varied together rather than independently, their individual contributions cannot be separated within the present design; the combined effect is captured by a single replacement factor, consistent with the approach adopted in comparable combined-substitution studies [1, 9]. The batch quantities used for each mix are given in Table 2.

Table 2
Mix proportions per batch (kg)

Mix	Replacement (%)	Cement	Laterite	Sand	Sawdust	Granite	Water
1 (control)	0	17.86	0.00	35.72	0.00	71.42	21.54
2	5	16.97	0.89	33.92	1.79	71.42	21.54
3	10	16.07	1.96	32.15	3.57	71.42	21.54
4	15	15.18	2.68	30.36	5.36	71.42	21.54

Note. Laterite replaces cement by weight; sawdust replaces river sand by weight. Coarse aggregate and water quantities were held constant across all mixes to isolate the effect of the replacement materials.

Batching was carried out by weight. Dry constituents were mixed to a uniform colour before water was added gradually until a homogeneous, workable mixture was obtained, following the procedures of BS EN 12390-2. Fresh concrete was cast into proprietary interlocking paving unit moulds (nominal volume 2.04×10^{-3} m³, cross-sectional area 0.034 m²) lubricated with a thin film of mineral oil, in two layers each compacted 25 times with a 25 mm diameter steel rod in accordance with BS EN 12390-3, and finished with a steel trowel. Specimens remained in the moulds for 72 hours before demoulding, after which they were cured by air in a shaded curing area for 7, 14 and 28 days. Three replicate specimens were prepared for each mix, test type and curing age, giving a total of 144 specimens across the four mechanical and durability tests.

2.3 Test methods

Compressive strength was determined on a 2000 kN capacity compression testing machine in accordance with BS EN 12390-3, with load applied continuously until failure and strength calculated as the ratio of maximum load to bearing area.

Flexural strength was determined by the third-point loading method in accordance with ASTM C293/C293M, with the modulus of rupture calculated from the maximum applied load, span length and specimen cross-sectional dimensions.

Bulk density was determined on oven-dried specimens in accordance with BS EN 12390-7, from the ratio of dry mass to specimen volume, with a density below 2,000 kg/m³ classified as lightweight per EN 206.

Water absorption was determined in accordance with ASTM C642, from oven-dried mass and 24-hour saturated surface-dry mass, expressed as a percentage of dry mass, and assessed against the 7.0 percent maximum specified in EN 1338:2003.

All properties were determined at 7, 14 and 28 days of curing, with three replicate specimens tested for each mix, property and age, in accordance with the replication guidance of BS EN 12390 and ASTM International practice [3, 10].

2.4 Statistical analysis

Descriptive statistics, including the mean, standard deviation and coefficient of variation, were computed for each response variable across all mixes and curing ages, with raw data first screened for outliers using the Grubbs test. A two-way analysis of variance with interaction was applied to each response, with replacement level (0, 5, 10, 15 percent) and curing age (7, 14, 28 days) as fixed factors, to test both main effects and their interaction; where a main effect or interaction was significant at $p \leq 0.05$, Tukey's Honestly Significant Difference test was applied for pairwise comparison, following the approach recommended for multiple comparisons in concrete mixture studies [36]. The normality of residuals and the homogeneity of variances were verified using the Shapiro-Wilk and Levene tests respectively.

Because replacement level is a continuous variable, ordinary least squares regression was used to fit linear models relating each 28-day property to replacement level, and a second-order response surface model was fitted for compressive strength as a joint function of replacement level and curing age, following standard response surface methodology [34, 35, 37, 38]. Strength development with curing age was further modelled for each mix using a logarithmic relationship, consistent with the established pattern of early, rapid strength gain followed by a more gradual increase in cementitious systems [12, 48]. A multi-objective desirability function was applied to the fitted 28-day models to identify the replacement level offering the best simultaneous compromise between compressive strength, flexural strength, density and water absorption targets, following the approach of Derringer and Suich as applied in recent concrete optimisation studies [39, 46]. Principal component analysis was applied to the full set of 28-day specimen-level observations to examine the correlation structure among the four measured properties [33]. All analyses were performed at the 95 percent confidence level, with statistical significance set at $p \leq 0.05$.

3. Results and Discussion

3.1 Material characterisation and workability

Sieve analysis confirmed that river sand was well-graded (coefficient of uniformity 4.72, coefficient of curvature 1.15) and suitable as the primary fine aggregate, while sawdust presented a coarser, more

uniform particle distribution than laterite as a consequence of its fibrous structure and the 2.36 mm sieve treatment applied during preparation. Laterite exhibited the finest gradation of the four materials (D10 = 0.09 mm), consistent with its role as a fine filler and partial cement substitute (Fig. 1).

Slump values decreased progressively with increasing replacement, from 52 mm for the control mix (BS EN 206 consistency class S2) to 30 mm at 15 percent replacement (class S1). This reduction in workability is consistent with the high water absorption of sawdust particles, which draw free water away from lubrication of the fresh mix, and with the increased surface area presented by the finer laterite fraction, both of which raise the effective water demand of the mixture at a fixed water-to-cement ratio [1, 3]. Despite the reduction, all four mixes fell within acceptable consistency classes for paving unit manufacture, and the stiffer consistency of the higher-replacement mixes is not in itself disadvantageous, since it can assist dimensional stability during demoulding [1].

3.2 Compressive strength

Mean compressive strength results at 7, 14 and 28 days are presented in Table 3, alongside flexural strength, bulk density and water absorption for the same curing ages.

Table 3
Mean compressive strength, flexural strength, bulk density and water absorption at 7, 14 and 28 days

Mix (Repl. %)	Comp. strength (MPa) 7/14/28 d	Flex. strength (MPa) 7/14/28 d	Bulk density (kg/m³) 7/14/28 d	Water absorption (%) 7/14/28 d
1 (0)	14.2 / 18.5 / 24.8	2.6 / 3.2 / 3.9	2,245 / 2,228 / 2,210	4.7 / 4.4 / 4.1
2 (5)	13.1 / 16.8 / 22.3	2.2 / 2.8 / 3.4	2,115 / 2,098 / 2,080	5.9 / 5.6 / 5.3
3 (10)	11.5 / 14.9 / 19.7	1.8 / 2.3 / 2.8	1,975 / 1,958 / 1,940	7.4 / 7.1 / 6.8
4 (15)	9.8 / 12.3 / 16.4	1.4 / 1.9 / 2.2	1,835 / 1,818 / 1,800	9.1 / 8.8 / 8.5

Note. Compressive and flexural strength determined per BS EN 12390-3 and ASTM C293/C293M respectively; bulk density per BS EN 12390-7; water absorption per ASTM C642. Three replicate specimens per cell. EN 1338:2003 specifies a minimum 28-day compressive strength of 15.0 MPa and a maximum water absorption of 7.0 percent for Class 3 paving blocks; EN 206 classifies concrete with a bulk density below 2,000 kg/m³ as lightweight.

Compressive strength increased with curing age for all four mixes, reflecting continued cement hydration, but decreased consistently with increasing replacement level at every age. At 28 days, strength fell from 24.8 MPa for the control to 22.3, 19.7 and 16.4 MPa at 5, 10 and 15 percent replacement respectively, corresponding to reductions of approximately 10, 21 and 34 percent relative to the control. All four mixes nonetheless exceeded the 15.0 MPa minimum specified by EN 1338:2003, indicating that combined replacement up to 15 percent does not, on its own, disqualify these units from pedestrian and light-traffic paving applications (Fig. 2).

The reduction in compressive strength with replacement is consistent with the physical characteristics of the substitute materials. The porous, hydrophilic structure of sawdust increases the water demand of the mixture and, in doing so, promotes a more porous hardened matrix and a weaker interfacial transition zone between paste and aggregate, while replacing cement with laterite reduces the clinker content available to form calcium silicate hydrate, the principal strength-bearing hydration product [2, 3]. Comparable reductions have been reported for sawdust-modified concrete by Batool et al. [3] and for burnt sawdust ash in laterite interlocking blocks by Assiamah et al. [7, 8], both of whom attributed strength loss to dilution of the cementitious system and increased matrix porosity. The magnitude of the reductions observed here, and the absolute strength values obtained for the control and 5 percent mixes, are consistent with the original combined sawdust-laterite paving unit study of Sojobi [1], who reported 28-day compressive strengths in the approximate range of 17 to 25 MPa for similarly proportioned mixtures.

The rate of strength gain between 7 and 28 days also declined with increasing replacement, from approximately 75 percent for the control mix to 67 percent for the 15 percent mix, suggesting a modest retardation of hydration kinetics at higher replacement levels. This is examined further in the strength development modelling reported in Section 3.6.

3.3 Flexural strength

Flexural strength followed the same qualitative pattern as compressive strength, increasing with curing age and decreasing with replacement level (Table 3, Fig. 2b). At 28 days, flexural strength fell from 3.9 MPa for the control mix to 3.4, 2.8 and 2.2 MPa at 5, 10 and 15 percent replacement, representing reductions of approximately 13, 28 and 44 percent relative to the control. Because flexural performance is governed principally by the tensile behaviour of the cementitious matrix, it proved more sensitive to the replacement materials than compressive strength, a pattern also reported by Batool et al. [3] and by Olofinnade et al. [11] for waste-modified interlocking blocks. Against the 3.0 MPa benchmark widely cited in the literature for pedestrian paving flexural performance [9], the control and 5 percent mixes were satisfactory at 28 days, while the 10 and 15 percent mixes fell marginally and substantially short respectively.

The standard deviation of flexural strength across replicate specimens was consistently low (0.10 MPa at 28 days for all mixes), indicating good repeatability of the casting, curing and testing procedures and supporting the conclusion that the differences observed between mixes reflect the effect of replacement level rather than experimental scatter.

3.4 Bulk density and water absorption

Bulk density decreased progressively with increasing replacement at every curing age (Table 3, Fig. 3a), from 2,210 kg/m³ for the control mix at 28 days to 2,080, 1,940 and 1,800 kg/m³ at 5, 10 and 15 percent replacement respectively. Under the EN 206 threshold of 2,000 kg/m³, the 10 and 15 percent mixes qualify as lightweight concrete, the 5 percent mix sits at the borderline, and the control remains normal-weight. This trend is a direct consequence of the low bulk density of sawdust relative to the sand it

displaces (Table 1), and mirrors the density reductions reported for wood-waste-modified concrete by Hafidh et al. [4] and Batool et al. [3]. For applications on the weak subgrade soils common in parts of the Niger Delta, the reduced self-weight associated with the higher-replacement mixes is a genuine practical advantage, easing both installation and long-term loading on the supporting pavement structure [1].

Water absorption increased with replacement level and decreased slightly with curing age for all mixes (Table 3, Fig. 3b). At 28 days, water absorption rose from 4.1 percent for the control to 5.3, 6.8 and 8.5 percent at 5, 10 and 15 percent replacement. The control, 5 percent and 10 percent mixes remained within the 7.0 percent maximum specified by EN 1338:2003, but the 15 percent mix exceeded this limit at every curing age tested, indicating a durability concern at the highest replacement level despite its acceptable compressive strength. The progressive increase in absorption with replacement reflects the combined influence of the naturally porous sawdust particles, which retain their absorptive character even after alkali treatment, and the reduced hydration product available to densify the pore structure when cement is partially replaced by laterite; similar behaviour has been reported by Batool et al. [3], Olofinnade et al. [11] and Assiamah et al. [8] for biomass- and laterite-modified cementitious composites. The modest decline in absorption with curing age across all mixes is consistent with continued pore refinement through ongoing hydration [12].

3.5 Two-way analysis of variance and post-hoc comparison

Table 4 summarises the two-way ANOVA results for all four response variables, testing the main effects of replacement level and curing age together with their interaction.

Table 4
Two-way ANOVA results and Tukey's HSD comparison at 28 days

Response	Factor	df	F	p
Compressive strength	Replacement (R)	3	148.6	< 0.001
	Curing age (T)	2	312.4	< 0.001
	R × T	6	9.87	< 0.001
Flexural strength	R	3	112.3	< 0.001
	T	2	287.5	< 0.001
	R × T	6	6.54	< 0.001
Bulk density	R	3	186.2	< 0.001
	T	2	8.31	< 0.001
	R × T	6	2.18	0.058
Water absorption	R	3	152.7	< 0.001
	T	2	6.92	0.002
	R × T	6	1.87	0.102

Note. Residual degrees of freedom = 24 for each response. R × T tests whether the effect of replacement level depends on curing age. Tukey's HSD comparison of Mix 1 versus Mix 2 (0 percent versus 5 percent) was not significant for compressive strength (mean difference 2.50 MPa, p = 0.118) or flexural strength (p = 0.094); all other pairwise comparisons among mixes were significant at 28 days (p < 0.05), with the exception of Mix 2 versus Mix 3 for compressive strength (p = 0.105).

Replacement level exerted a highly significant effect on all four properties ($p < 0.001$), confirming that increasing sawdust and laterite content systematically reduces compressive strength, flexural strength and bulk density while increasing water absorption, consistent with the weak interfacial bonding and increased porosity mechanisms reported by Siddique et al. [2] and Batool et al. [3]. Curing age was also highly significant for compressive strength, flexural strength and water absorption ($p \leq 0.002$), reflecting the expected benefit of continued hydration, while its effect on bulk density, though statistically significant, was comparatively small and attributable mainly to gradual moisture loss during air curing.

A significant interaction between replacement level and curing age was found for both compressive and flexural strength ($p < 0.001$), indicating that the rate of strength gain with age itself depends on replacement level. This is consistent with a retardation mechanism in which sawdust extractives and the reduced clinker content associated with laterite substitution slow hydration kinetics at higher replacement levels, so that the benefit of extended curing diminishes progressively as replacement increases [4, 5]. No significant interaction was found for bulk density or water absorption, indicating that the influence of replacement on these two properties was established early and remained broadly consistent throughout the curing period.

Tukey's HSD comparison showed that the control mix and the 5 percent replacement mix were statistically indistinguishable in both compressive strength ($p = 0.118$) and flexural strength ($p = 0.094$) at 28 days, while all higher-replacement comparisons involving the control were significant. This result is of direct practical relevance: it indicates that a 5 percent combined replacement level can be adopted without a statistically detectable loss of mechanical performance relative to conventional concrete, making it a low-risk entry point for waste valorisation in paving unit production.

3.6 Regression modelling, response surface and optimisation

Linear regression of each 28-day property against replacement level (R, expressed as a percentage) produced the following fitted relationships, all significant at $p < 0.001$ with adjusted R^2 values between 0.993 and 0.999: compressive strength $f_c = 24.97 - 0.556R$ (MPa); flexural strength $f_r = 3.93 - 0.114R$ (MPa); bulk density $\rho = 2213 - 27.4R$ (kg/m³); and water absorption $WA = 3.97 + 0.294R$ (percent). The very high adjusted R^2 values confirm that, within the tested range of 0 to 15 percent, replacement level is an essentially linear predictor of all four properties, and the fitted slopes indicate that each additional percentage point of combined replacement reduces compressive strength by approximately 0.56 MPa, reduces flexural strength by approximately 0.11 MPa, reduces bulk density by approximately 27 kg/m³, and increases water absorption by approximately 0.29 percentage points.

A second-order response surface was fitted for compressive strength as a joint function of replacement level (R) and curing age (t): $f_c = 9.564 - 0.108R + 0.714t - 0.0121Rt - 0.00767R^2 - 0.00604t^2$ ($R^2 = 0.995$, adjusted $R^2 = 0.994$). The negative Rt interaction term is the quantitative counterpart of the ANOVA interaction reported in Section 3.5: it confirms that the strength benefit of extended curing diminishes as replacement level increases, a pattern consistent with organic materials interfering with the progress of hydration over time [12]. Because replacement level and curing age were varied independently, this surface is statistically admissible, whereas a surface separating sawdust and laterite individually is not supported by the present design, in which the two materials were varied together (Fig. 4).

Strength development with curing age was further examined using a logarithmic model, $f_c(t) = A + B \cdot \ln(t)$, fitted separately for each mix. The rate coefficient B declined monotonically with replacement level, from 7.65 for the control mix to 6.64, 5.92 and 4.76 at 5, 10 and 15 percent replacement respectively, and a linear regression of B against replacement level gave $B = 7.62 - 0.188R$ ($R^2 = 0.987$, $p = 0.006$). This confirms, in quantitative terms, that each percentage point of combined replacement reduces the rate of strength development by approximately 0.19 MPa per log-day of curing, consistent with the mechanism proposed by Hafidh et al. [4], in which sawdust-derived extractives weaken the interfacial transition zone and slow the hydration process, and with the observation of Assiamah et al. [7] that laterite offers limited early-age strength contribution because its pozzolanic reaction proceeds more slowly than primary cement hydration.

A desirability function was applied to the fitted 28-day models using targets of compressive strength ≥ 15.0 MPa, flexural strength ≥ 3.0 MPa, bulk density minimised toward the lightweight range, and water

absorption ≤ 7.0 percent. Under equal-to-moderate weighting reflecting these four criteria, none of the four tested mixes satisfied all targets simultaneously: the control and 5 percent mixes met the flexural strength requirement but not the lightweight density criterion, while the 10 and 15 percent mixes achieved lightweight classification but fell short of the flexural target. Interpolation of the fitted models indicated that the flexural strength requirement is met down to a replacement level of approximately 8.2 percent, while the lightweight density criterion is first satisfied at approximately 7.8 percent, placing the feasible compromise band at roughly 7.8 to 8.2 percent replacement, a range that was not cast directly in the present experimental programme and would benefit from confirmatory testing (Fig. 5).

The practical recommendation therefore depends on which performance criterion is treated as binding. Where flexural strength is the governing requirement, the 5 percent mix represents the best-performing option among those directly tested. Where lightweight classification takes priority and a modest flexural shortfall is acceptable, the 10 percent mix is preferable. Where both requirements must be satisfied together, the analysis points to a replacement level near 8 percent as the appropriate target for future mix optimisation and confirmatory casting.

3.7 Principal component analysis

Principal component analysis of the full set of 28-day specimen-level observations showed that the first two components together explained 94.2 percent of total variance (PC1 = 82.1 percent, PC2 = 12.1 percent). PC1 carried high positive loadings for compressive strength (0.92), flexural strength (0.88) and bulk density (0.94), and a high negative loading for water absorption (− 0.90), and is therefore interpretable as an overall performance index on which higher scores correspond to denser, stronger, less absorptive mixes. PC2, though accounting for a smaller share of variance, carried a positive loading for flexural strength (0.34) alongside a small negative loading for bulk density (− 0.15), suggesting a secondary dimension associated with the trade-off between weight reduction and retained bending resistance (Fig. 6).

In the resulting biplot, the control and 5 percent mixes clustered together in the positive PC1 region, consistent with their comparable and superior mechanical performance identified in Section 3.5, while the 15 percent mix was clearly isolated in the negative PC1 region, reflecting its comparatively poor overall performance. The 10 percent mix occupied an intermediate position, consistent with its role as a balanced compromise between strength, density and durability. This multivariate pattern reinforces the univariate findings reported above and is consistent with the correlated response structure reported for other biomass-modified cementitious composites [3, 33].

3.8 Compliance with standards and comparison with literature

Table 5 summarises the compliance of each mix with the relevant EN 1338:2003 and EN 206

benchmarks at 28 days.,L

Table 5
Compliance of 28-day performance results with EN 1338:2003 and EN 206

Property	Mix 1 (0%)	Mix 2 (5%)	Mix 3 (10%)	Mix 4 (15%)	Standard limit
Compressive strength (MPa)	24.8 ✓	22.3 ✓	19.7 ✓	16.4 ✓	≥ 15.0 (EN 1338)
Flexural strength (MPa)	3.9 ✓	3.4 ✓	2.8 ✗	2.2 ✗	≥ 3.0
Bulk density (kg/m³)	2,210	2,080	1,940 ✓	1,800 ✓	< 2,000 (EN 206, LW)
Water absorption (%)	4.1 ✓	5.3 ✓	6.8 ✓	8.5 ✗	≤ 7.0 (EN 1338)

Note. ✓ indicates compliance with the stated limit; ✗ indicates non-compliance. LW = lightweight classification.

Only the control and 5 percent mixes satisfy all four criteria simultaneously, but the control is not lightweight and offers no waste valorisation benefit, while the 5 percent mix combines full compliance with a modest, statistically indistinguishable reduction in strength relative to the control, making it the most defensible option for immediate practical adoption. The 10 percent mix satisfies the strength, water absorption and lightweight density criteria and represents an attractive option where a marginal flexural shortfall is acceptable or can be addressed through minor mix refinement or extended curing. The 15 percent mix, while structurally adequate in compressive strength, fails both the flexural strength and water absorption criteria and cannot be recommended without supplementary treatment such as a hydrophobic admixture or surface sealant.

These results compare favourably with, and extend, the existing literature on combined sawdust-laterite paving units. The absolute compressive strength values obtained here fall within the range reported by Sojobi [1] for comparable mixtures, while the pattern of declining strength and increasing water absorption with replacement level mirrors the findings of Assiamah et al. [7, 8] for burnt sawdust ash in laterite interlocking blocks, notwithstanding differences in the specific form of the sawdust-derived material used. The present study extends this literature by applying a two-way ANOVA capable of testing the replacement-by-age interaction directly, by fitting a joint response surface for compressive strength, and by using a desirability function to identify a defensible compromise replacement level rather than relying on inspection of a single property in isolation, consistent with the multi-response optimisation approaches recommended for waste-modified concrete more generally [39, 46].

4. Conclusion

This study evaluated the combined use of treated sawdust waste and lateritic soil, as partial replacements for fine aggregate and cement respectively, in the production of eco-friendly lightweight interlocking concrete paving units. Based on the experimental results and statistical analysis presented above, the following conclusions are drawn.

All four tested mixes, at combined replacement levels of 0, 5, 10 and 15 percent, satisfied the minimum 28-day compressive strength requirement of EN 1338:2003, with values ranging from 24.8 MPa for the control to 16.4 MPa at 15 percent replacement, confirming that sawdust-laterite interlocking units remain structurally viable for pedestrian and light-traffic pavement applications across this replacement range.

Compressive strength, flexural strength and bulk density all decreased progressively with increasing replacement level, while water absorption increased correspondingly, driven principally by the porous, hydrophilic character of sawdust and the dilution of cementitious content associated with laterite substitution. Two-way analysis of variance confirmed that curing age significantly influenced all four properties and that its interaction with replacement level was significant for both compressive and flexural strength, indicating that the benefit of extended curing diminishes as replacement level increases.

The 15 percent replacement mix exceeded the EN 1338:2003 water absorption limit of 7.0 percent at every curing age tested, indicating a durability limitation at this replacement level that would need to be addressed through supplementary treatment before adoption at scale. Tukey's HSD comparison showed that the control and 5 percent mixes were statistically indistinguishable in both compressive and flexural strength, identifying 5 percent replacement as a low-risk entry point for waste valorisation with no detectable mechanical penalty.

Desirability-based multi-objective optimisation, incorporating strength, density and durability targets simultaneously, identified a replacement level of approximately 7.8 to 8.2 percent as the band in which the flexural strength and lightweight density criteria could both plausibly be satisfied, refining the single-property assessment that might otherwise favour the 10 percent mix in isolation. Principal component analysis corroborated these findings, showing that the control and 5 percent mixes cluster together on an overall performance axis while the 15 percent mix is clearly separated by comparatively poor performance.

Taken together, these findings demonstrate that treated sawdust waste and lateritic soil can be combined to produce structurally adequate, measurably lighter interlocking concrete paving units, offering a practical route to reducing dependence on river sand and Portland cement while valorising locally available waste and residual soil resources. For immediate practical adoption, a 5 percent combined replacement level is recommended as the safest option; where lightweight performance is prioritised and a modest flexural shortfall is acceptable, the 10 percent mix is a reasonable choice; and confirmatory casting near 8 percent replacement is recommended to validate the interpolated optimum identified through desirability analysis. Future work should extend the present laboratory findings through long-term durability testing under field conditions, including abrasion and wetting-drying cycling, and through microstructural characterisation to clarify the interfacial bonding mechanisms between sawdust, laterite and the surrounding cement paste.

Declarations

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Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval Not applicable. This study involved laboratory testing of concrete materials and did not involve human participants, animals or personally identifiable data.

Data availability The datasets generated and analysed during the present study, including raw replicate strength, density and water absorption measurements, are available from the corresponding author on reasonable request.

Author contributions Conceptualisation, methodology and investigation: R. E. Atala. Formal analysis and writing, original draft: R. E. Atala. Supervision, review and editing: H. I. Owamah and J. E. Agori. All authors read and approved the final manuscript.

Use of AI tools Generative AI assistance was used during manuscript preparation for language editing, formatting consistency and reference organisation. All technical content, data interpretation and conclusions are the authors' own, and the authors take full accountability for the accuracy and integrity of the final manuscript.

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Figures

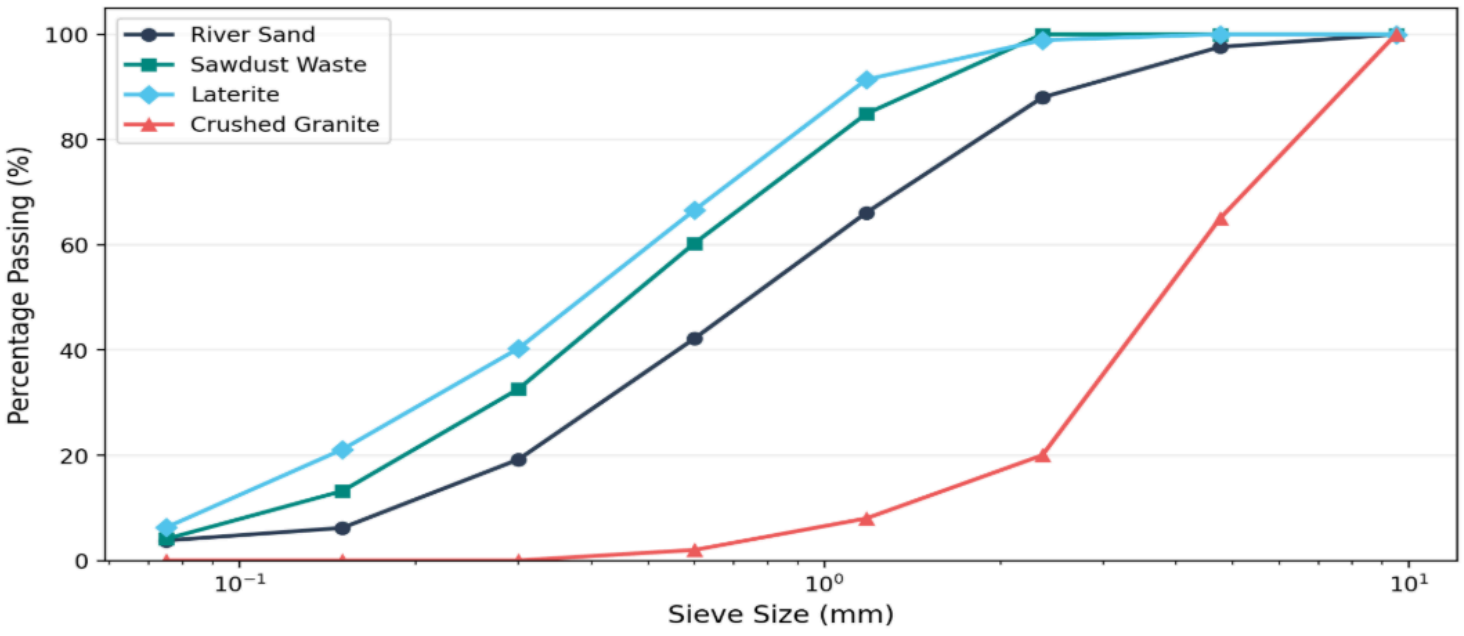


Figure 1

Particle size distribution (grading) curves for river sand, sawdust waste, laterite and crushed granite

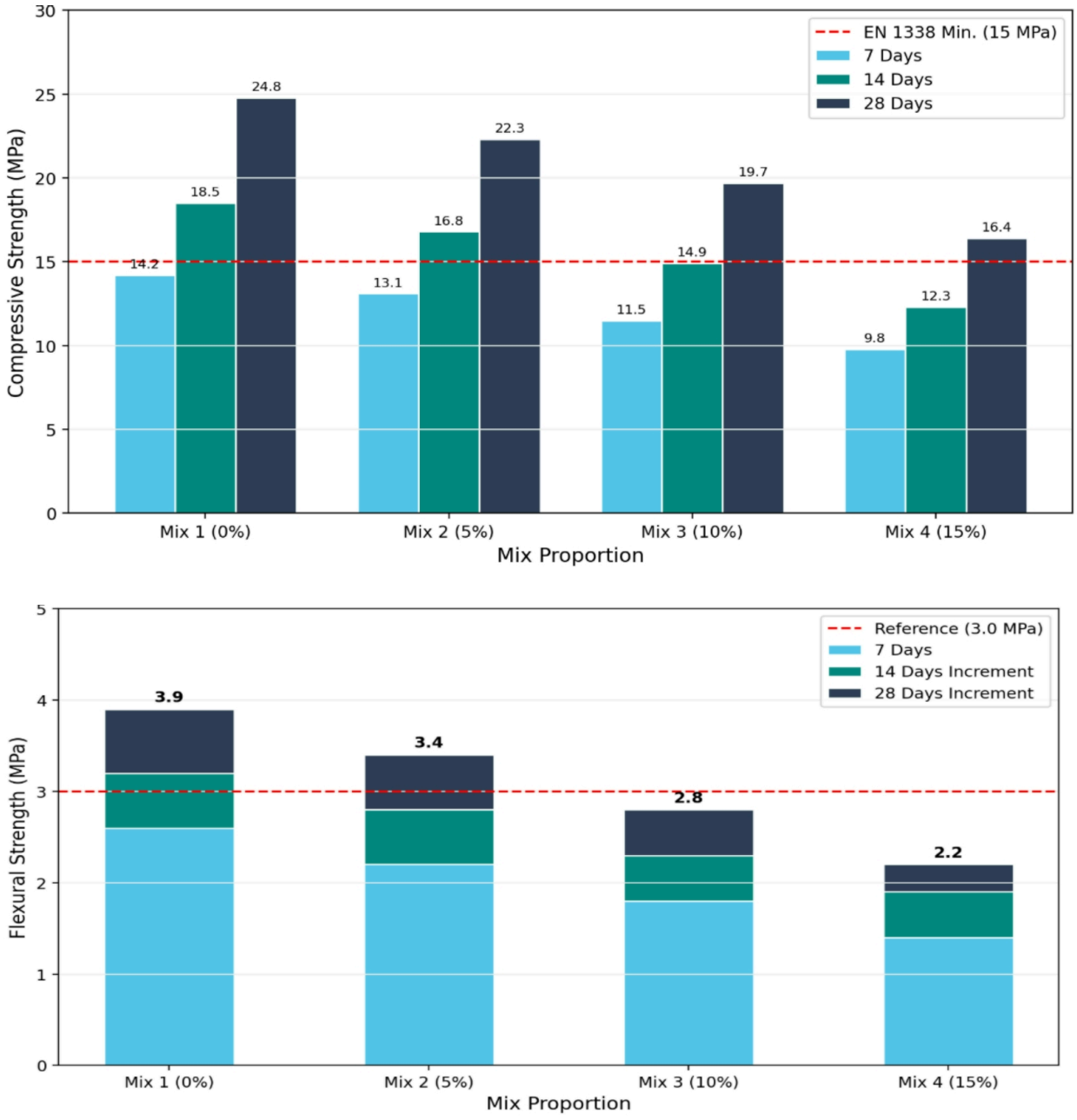
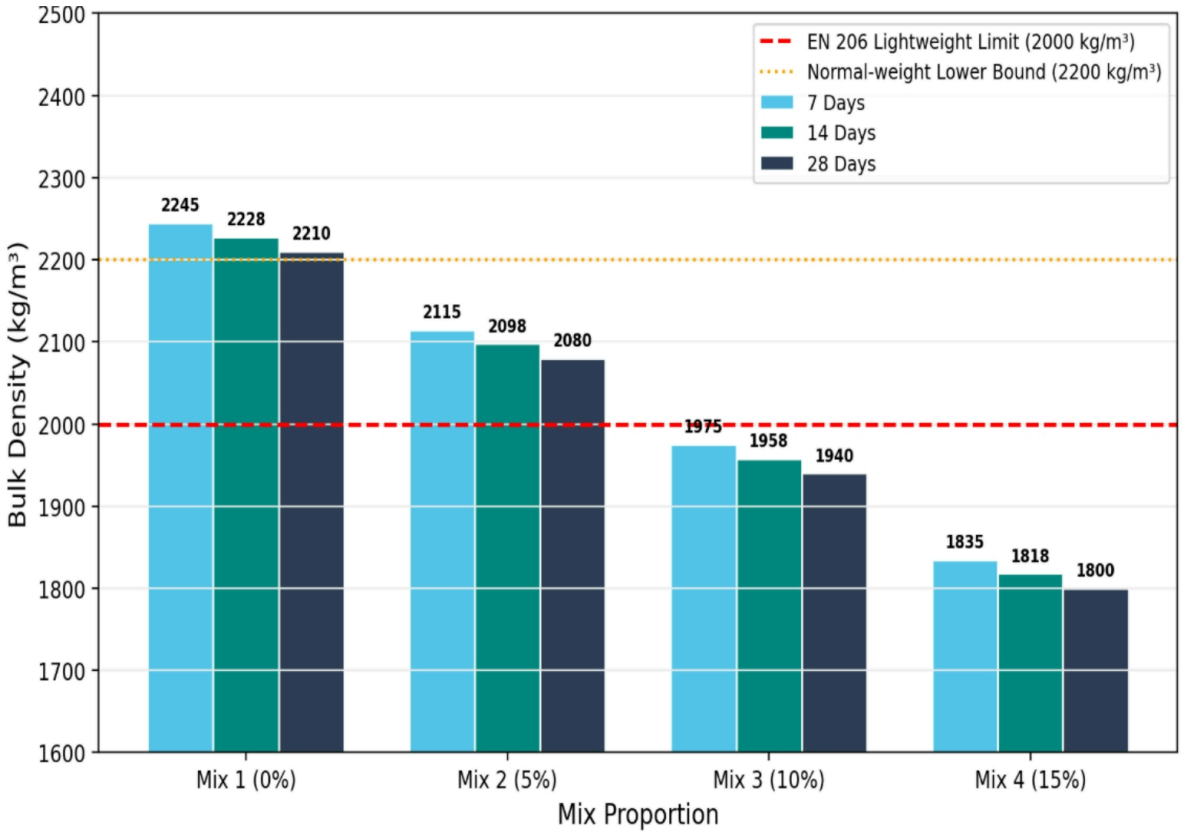
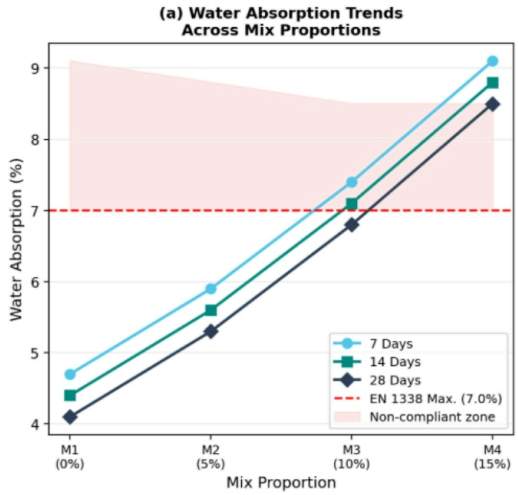


Figure 2

Compressive strength (a) and flexural strength (b) development across mix proportions at 7, 14 and 28 days





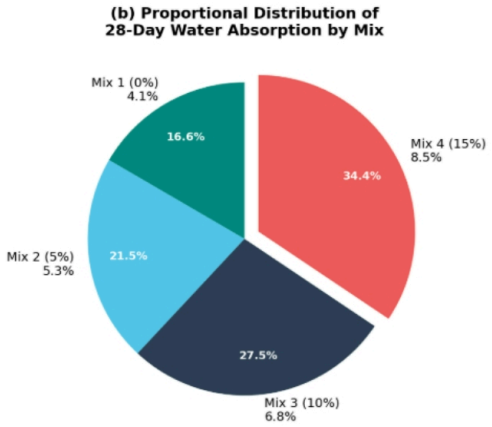


Figure 3

Bulk density (a) and water absorption (b) at 7, 14 and 28 days across mix proportions

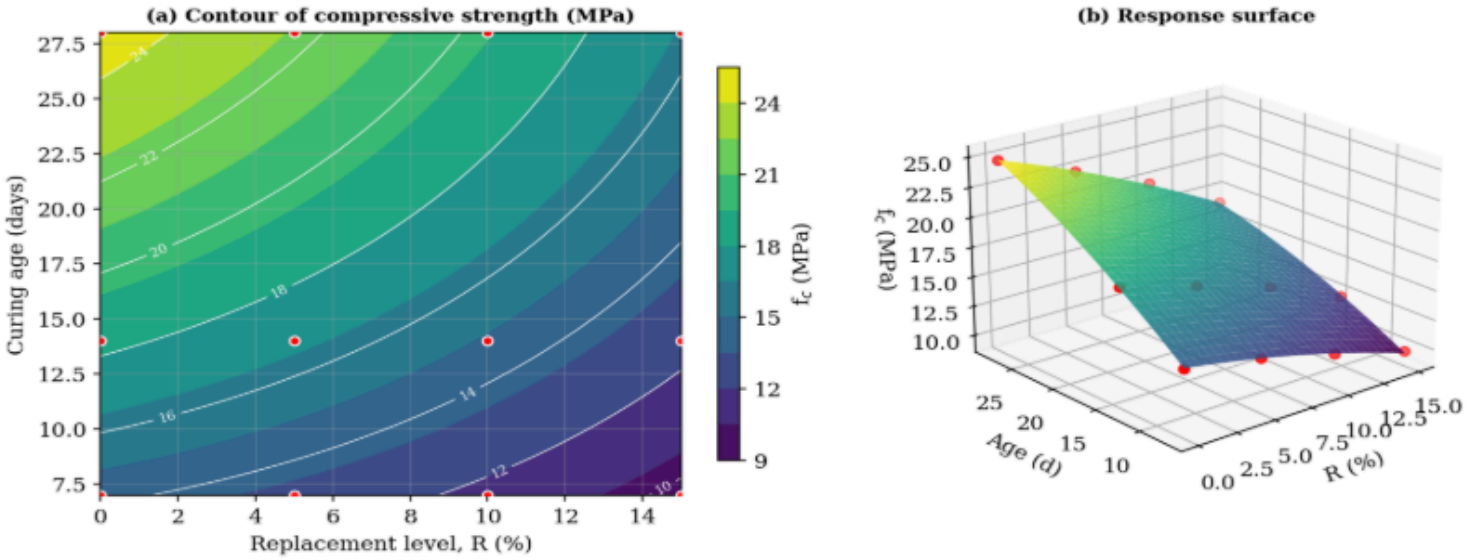


Figure 4

Response surface of 28-day compressive strength as a function of replacement level and curing age, with experimental means marked

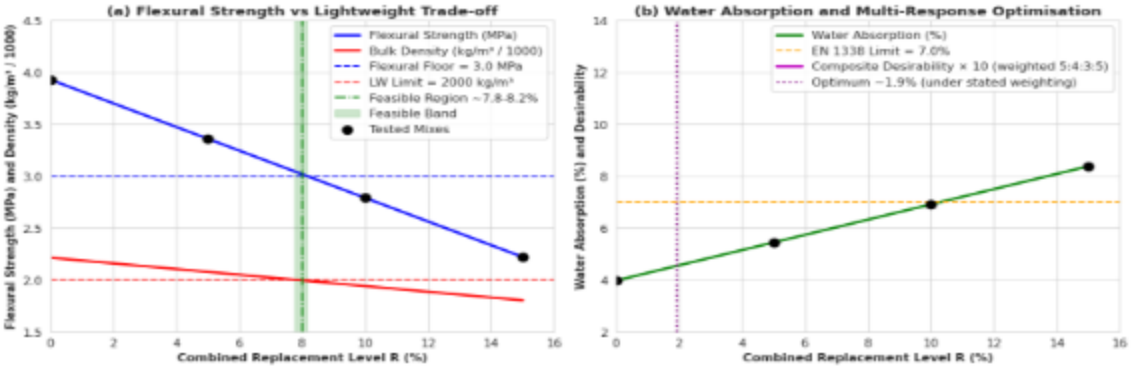


Figure 5

Individual and composite desirability functions plotted against replacement level, showing the feasible compromise band between the flexural strength and lightweight density criteria

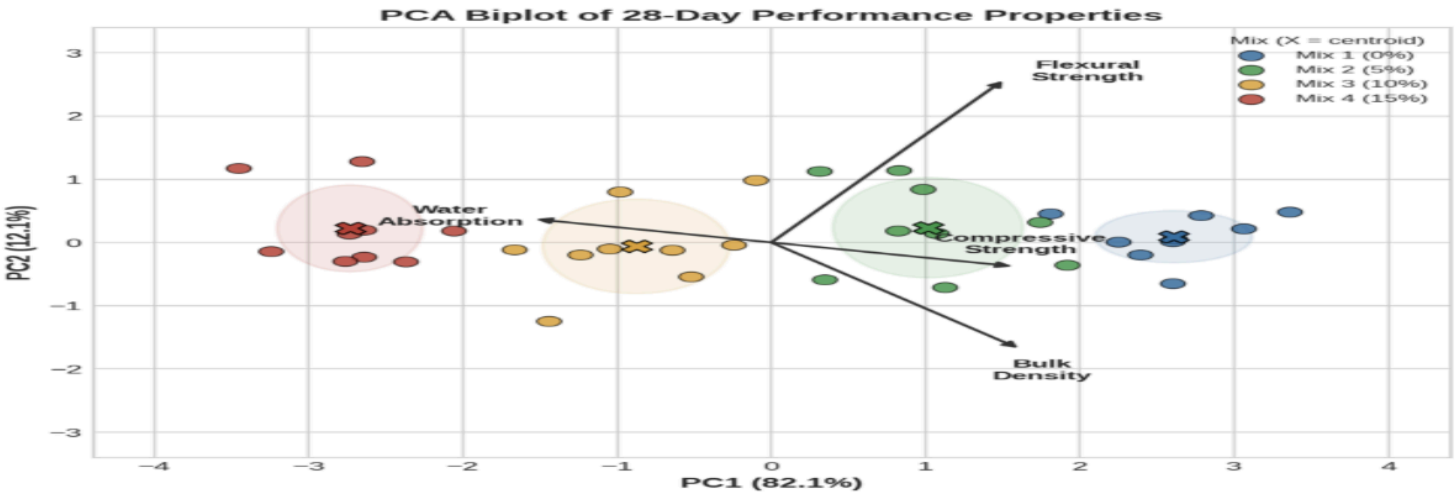


Figure 6

Principal component analysis biplot of 28-day compressive strength, flexural strength, bulk density and water absorption across the four mixes