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Article

Comparative Analysis of Paving Blocks Reinforced with Pineapple Leaf Fibre (*Ananas comosus*) and Sisal Fibre (*Agave sisalana*)

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Abstract

Infrastructure expansion in Indonesia has increased the demand for paving blocks, raising concerns regarding cement production costs and environmental impact. This study investigates the comparative effectiveness of pineapple leaf fibre (PALF) and sisal fibre as natural reinforcements to enhance paving block performance. An experimental design was employed with fibre contents varying from 0% to 7% by cement volume. Specimens were cured for 28 days and tested for water absorption and compressive strength; analysis was performed using descriptive statistics and two-way ANOVA. Results indicated that fibre content significantly influenced both response variables ($p < 0.001$). Water absorption increased monotonically with fibre content, while compressive strength exhibited an inverted-U relationship with a distinct optimum at 3% fibre addition. Sisal fibre exhibited greater mechanical enhancement than PALF, achieving a maximum strength of 15.2 MPa at 3% ($R^2 = 0.973$), meeting Indonesian National Standard SNI 03-0691-1996 Class B requirements (minimum 12.5 MPa). A significant interaction between fibre type and fibre content was identified for compressive strength ($F = 3.697$, $p = 0.012$), confirming that the response to dosage differs between the two species. These findings demonstrate the potential of agricultural waste fibres for producing sustainable, eco-friendly paving blocks, supporting circular economy principles in the construction industry.

Keywords: natural fibre concrete; pineapple leaf fibre; sisal fibre; paving block; compressive strength; water absorption; two-way ANOVA; SNI 03-0691-1996

1. Introduction

The construction industry is one of the most significant contributors to global resource consumption and environmental degradation. With accelerating infrastructure development in developing countries, demand for construction materials continues to rise, posing urgent challenges for sustainable resource management [1,2]. Among these materials, paving blocks have emerged as a preferred solution for road pavements, sidewalks, residential areas, and public facilities due to their durability, ease of installation, and aesthetic flexibility [3,4]. However, conventional paving block production relies heavily on cement, a material whose manufacturing process contributes approximately 8% of global carbon dioxide emissions [5,6]. This environmental burden, coupled with rising raw material costs, has motivated researchers to explore alternative reinforcement materials that can enhance mechanical properties while reducing environmental impact [7,8].

Natural fibre reinforcement in cement composites has attracted considerable research attention as a sustainable alternative to synthetic fibres such as steel, glass, and polypropylene [9,10]. Natural fibres offer numerous advantages, including abundant availability, low density, biodegradability, renewability, and cost-effectiveness, making them attractive for sustainable construction applications

[11,12]. Contemporary research has demonstrated that plant-based fibres can significantly enhance the mechanical properties of cement composites through crack-bridging mechanisms and improved stress distribution [13,14]. The integration of agricultural waste fibres into construction materials aligns with circular economy principles, transforming waste streams into valuable resources while reducing the environmental footprint of both agricultural and construction sectors [15,16].

Pineapple leaf fibre (PALF), derived from *Ananas comosus*, represents a promising reinforcement material with high cellulose content (69.5–71.5%) and significant tensile strength [17,18]. The chemical composition of PALF includes approximately 42.72% hemicellulose and 4.03% lignin, which contribute to its effectiveness as a composite reinforcement [19]. In tropical regions such as Indonesia, pineapple cultivation generates substantial quantities of leaf waste that remains largely unutilised, presenting opportunities for value-added applications in construction materials [20]. Similarly, sisal fibre (*Agave sisalana*) possesses outstanding mechanical properties, including tensile strength ranging from 400 to 700 MPa, making it suitable for concrete reinforcement applications [21,22]. Sisal fibre (*Agave sisalana*) possesses outstanding mechanical properties, including tensile strength ranging from 400 to 700 MPa. Chemically, sisal fibre consists of approximately 65–78% cellulose, 10–14% hemicellulose, and 8–13% lignin. Its high cellulose content contributes to a well-ordered crystalline molecular structure, which improves durability in cement matrices [23,24].

Previous research has demonstrated the effectiveness of various natural fibres in enhancing concrete properties. Studies on natural cellulosic fibre reinforcement have shown that compressive strength increases by up to 20% at the optimal fibre content [25]. Similarly, investigations into sugarcane bagasse fibre and pineapple leaf fibre have revealed improved crack resistance and mechanical characteristics [26,27]. However, comparative studies examining the relative effectiveness of different fibre types remain limited, particularly in the context of paving block applications [28,29]. The variability of fibre properties, including length, diameter, surface morphology, and chemical composition, necessitating systematic investigation to determine optimal utilisation parameters [29,30]. Furthermore, the interaction between fibre type and fibre content on critical performance parameters, such as water absorption and compressive strength requires comprehensive factorial analysis to guide practical applications [31,32].

This research addresses the identified research gaps through a comparative analysis of pineapple leaf fibre and sisal fibre reinforcement in paving blocks. The investigation examines the influence of fibre type and content (0%, 1%, 3%, 5%, and 7% by cement volume) on water absorption and compressive strength, employing two-way ANOVA with interaction testing to identify significant differences and interactions among variables. The findings contribute to the growing body of knowledge on sustainable construction materials while providing practical guidance for the utilisation of agricultural waste fibres in infrastructure development in Eastern Indonesia [21,30]. This research aligns with global sustainability objectives, including the UN Sustainable Development Goals related to sustainable cities and communities, responsible consumption and production, and climate action [33,34].

2. Materials and Methods

2.1. Research Design

An experimental factorial design was employed to investigate the effects of natural fibre type and content on the physical and mechanical properties of paving blocks. The independent variables were fibre type (PALF and sisal fibre) and fibre content (0%, 1%, 3%, 5%, and 7% by cement volume). The dependent variables were water absorption (%) and compressive strength (MPa). Eight specimens were prepared per treatment combination for water absorption testing ($n = 3$ tested per cell) and five specimens per cell for compressive strength testing, yielding 80 specimens in total. All specimens were cured by water immersion for 28 days prior to testing.

2.2. Materials

2.2.1. Portland Composite Cement Extended Characterisation

Portland Composite Cement (PCC) conforming to SNI 7064:2014 (equivalent to ASTM C595), manufactured by PT Conch Cement Indonesia, was used as the sole binder. PCC was selected for its consistent quality, high bonding capacity, and wide availability in East Nusa Tenggara Province. This cement type incorporates supplementary cementitious materials (SCMs), including pozzolan and finely ground limestone, which contribute to reduced heat of hydration, improved sulfate resistance, and enhanced long-term strength development [35]. Physical properties of the cement batch were determined prior to specimen production and are presented in Table 1.

Table 1. Physical properties of portland composite cement (PCC) used in this study.

Property	Measured Value	SNI/ASTM Limit	Test Standard
Specific gravity (g/cm ³)	3.02	2.85–3.15 (typical)	SNI 03-2531-1991 / ASTM C188
Normal consistency (%)	27.5	—	SNI 03-6826-2002 / ASTM C187
Initial setting time (min)	145	≥ 45 min	SNI 03-6827-2002 / ASTM C191
Final setting time (min)	265	≤ 375 min	SNI 03-6827-2002 / ASTM C191
Cement type	PCC	SNI 7064:2014	PT Conch Cement Indonesia

2.2.2. Fine Aggregate — Extended Testing

Fine aggregates were sourced from local deposits in Takari, Kupang Regency, East Nusa Tenggara Province. In addition to gradation analysis and mud content testing, specific gravity and water absorption were determined in accordance with SNI 03-1970-1990 (equivalent to ASTM C128) to complete material characterisation and support mix design calculations (Eq. 1) [36]. Complete physical properties of the fine aggregate are presented in Table 2.

$$Gsb = \frac{A}{B - C}; Gsa = \frac{A}{A - C}; WA(\%) = \frac{B - A}{A} \times 100 \quad (1)$$

where: A = mass of oven-dry aggregate (g); B = mass of SSD aggregate (g); C = mass of submerged aggregate (g).

Table 2. Complete physical properties of fine aggregate (Takari sand, Kupang Regency, NTT).

Parameter	Measured Value	Standard Limit	Test Standard
Fineness Modulus (FM)	3.0	1.5 – 3.8	SNI 03-1968-1990
Mud content (%)	3.401	≤ 5%	SNI 03-4142-1996
Loose unit weight (g/cm ³)	0.0832	—	SNI 03-4804-1998
Compacted unit weight (g/cm ³)	0.1526	—	SNI 03-4804-1998
Bulk specific gravity (Gsb)	2.62	2.4 – 2.9	SNI 03-1970-1990 / ASTM C128
Apparent specific gravity (Gsa)	2.68	—	SNI 03-1970-1990 / ASTM C128
Water absorption (%)	2.35	≤ 3%	SNI 03-1970-1990 / ASTM C128

2.2.3. Natural Fibres

Pineapple leaf fibres were extracted from fresh *Ananas comosus* leaves collected from agricultural areas in Kupang Regency (Figure 1). The extraction process involved mechanical separation through beating and scraping to remove the outer leaf cuticle, followed by washing and air-drying in shade. Fibres were cut to 2–3 cm lengths for uniform distribution in the cement matrix.

Sisal fibres were obtained from *Agave sisalana* plants using a similar mechanical extraction method, yielding 3–5 cm lengths with superior stiffness compared to PALF. All fibres were stored in a dry, well-ventilated environment before use.



Figure 1. Pineapple leaf fibres.

2.2.4. Fibre Characterisation

Prior to incorporation into the paving block matrix, both PALF and sisal fibres were subjected to a comprehensive physical and mechanical characterisation programme. This is essential given the inherent variability of natural fibre properties due to plant variety, cultivation region, and extraction method [37,38]. Diameter was measured using a calibrated digital micrometre at five equidistant points per specimen ($n = 30$ per type). Moisture content was determined gravimetrically: $MC (\%) = [(m_1 - m_2) / m_2] \times 100$, where m_1 = air-dried mass and m_2 = oven-dried mass at $105 \pm 2^\circ\text{C}/24$ h. Tensile properties were determined using a Universal Testing Machine (UTM; 100 N load cell) following ASTM D3379-75 with a 25 mm gauge length ($n = 25$ per type). No chemical surface treatment was applied, to evaluate untreated agricultural waste fibres under practical low-cost production conditions and to isolate the effect of fibre species and content as the primary experimental variables [7]. All characterisation results are presented in Table 3.

Table 3. Physical and mechanical properties of PALF and sisal fibres used in this study.

Property	PALF (<i>Ananas comosus</i>)	Sisal (<i>Agave sisalana</i>)	Test Standard / Reference
Mean diameter (μm)	62.4 ± 5.8	152.6 ± 42.3	Digital micrometer; $n = 30$
Moisture content (%)	10.2 ± 1.3	7.8 ± 1.1	Gravimetric; ASTM E1131
Density (g/cm^3)	1.44–1.56	1.33–1.45	Literature values [37,38]
Tensile strength (MPa)	412.5 ± 89.3	534.2 ± 72.8	UTM; ASTM D3379-75; $n = 25$
Young's modulus (GPa)	10.6 ± 2.3	15.3 ± 3.8	UTM; ASTM D3379-75; $n = 25$
Elongation at break (%)	3.2 ± 0.8	4.7 ± 1.2	UTM; ASTM D3379-75; $n = 25$
Cellulose content (%)	69.5–71.5	66.4–78.0	Literature values [37,38]
Fibre length used (cm)	2–3	3–5	Manual cutting; vernier calliper

2.3. Mix Design and Specimen Preparation

2.3.1. Mix Proportions and Water-to-Cement Ratio

The paving block mix design employed a cement-to-sand ratio of 1:5 by weight, in accordance with standard practices for non-structural paving applications. Fibre content variations of 0%, 1%, 3%, 5%, and 7% by cement volume were investigated. Specimen dimensions were 4 cm × 9.2 cm × 18.4 cm per SNI 03-0691-1996. A fixed water volume of 0.5 L was used per eight-specimen batch (cement mass = 1,752 g per batch), yielding an effective water-to-cement ratio calculated as follows:

$$\text{Total cement mass (8 specimens)} = 0.219 \text{ kg} \times 8 = 1.752 \text{ kg}$$

$$\text{Total water mass} = 0.5 \text{ L} \times 1.0 \text{ kg/L} = 0.500 \text{ kg}$$

$$\therefore \text{w/c ratio} = 500 \text{ g} / 1,752 \text{ g} \approx 0.285$$

A w/c ratio of 0.285 was maintained constant across all treatment combinations. For higher fibre content levels (5% and 7%), fibres were added in the dry state prior to water addition to minimise pre-absorption of mixing water by the hydrophilic fibres before cement hydration commenced [39]. All batch proportions are summarised in Table 4.

Table 4. Summary mix design parameters for all paving block specimens (per 8-specimen batch).

Mix ID	Cement (kg)	Sand (kg)	Fibre (kg)	Water (kg)	w/c Ratio
Control (0%)	1.752	8.792	0.000	0.500	0.285
PALF-1 / Sisal-1 (1%)	1.752	8.792	0.018	0.500	0.285
PALF-3 / Sisal-3 (3%)	1.752	8.792	0.053	0.500	0.285
PALF-5 / Sisal-5 (5%)	1.752	8.792	0.088	0.500	0.285
PALF-7 / Sisal-7 (7%)	1.752	8.792	0.123	0.500	0.285

Note: The bold row indicates the optimal fibre content. Each PALF and sisal series used separate batches with identical proportions.

2.3.2. Specimen Preparation

The mixing procedure involved initial dry mixing of cement and sand, followed by gradual fibre addition to ensure uniform distribution. Water was added incrementally to achieve workable consistency. Compaction was performed manually using standard compaction procedures to eliminate voids. For 5% and 7% fibre contents, manual mixing with protective gloves was employed to overcome fibre agglomeration. After moulding, specimens were left in moulds for 24 hours before demoulding and subsequently immersed in clean water at room temperature for 28 days.

2.4. Testing Procedures

2.4.1. Water Absorption

Water absorption testing was conducted in accordance with SNI 03-0349-1989. Cured specimens were immersed in clean water for 24 hours (SSD condition), surface-dried, and weighed (wet mass A). Specimens were then oven-dried at $105 \pm 5^\circ\text{C}$ until mass variation between consecutive weighing was less than 0.2% (dry mass B). Water absorption was calculated as:

$$\text{Water absorption (\%)} = \frac{A - B}{B} \times 100 \quad (2)$$

2.4.2. Compressive Strength

Compressive strength testing was performed using a Compression Testing Machine (CTM) in accordance with SNI 03-0691-1996. Specimens were cut to cube samples of 9.1 cm × 9.1 cm × 4 cm

prior to testing. Load was applied continuously at a controlled rate until failure. Compressive strength was calculated as:

$$f_c = \frac{P}{A} \quad (3)$$

where: f_c = compressive strength (MPa); P = maximum load (N); and A = cross-sectional area (mm²).

2.5. Statistical Analysis

2.5.1. Descriptive Statistics and Two-Way ANOVA

Descriptive statistics (mean, standard deviation) were calculated for all treatment groups. Two-way ANOVA was employed to evaluate the main effects of fibre type, fibre content, and their interaction on both water absorption and compressive strength. Post-hoc analysis used Tukey's Honestly Significant Difference (HSD) test. Statistical significance was set at $\alpha = 0.05$. All analyses were performed using IBM SPSS Statistics Version 22.

2.5.2. Verification of Parametric Assumptions

Prior to ANOVA, the validity of the normality and homogeneity of variance assumptions was verified. Normality was assessed using the Shapiro-Wilk test (recommended for $n < 50$) applied to each treatment cell. Homogeneity of variance was assessed using Levene's test, which is more robust than Bartlett's test under non-normal conditions [40]. Both tests used $p > 0.05$ as the non-violation criterion. If either assumption was violated, logarithmic or square root transformation would be applied, or the non-parametric Kruskal-Wallis test with Dunn post-hoc comparison would be used. Results are reported in Table 5 and Section 3.4.

Table 5. Summary of parametric assumption tests applied before Two-Way ANOVA.

Test	Purpose	Criterion	Software	Result
Shapiro-Wilk	Normality (per treatment cell)	$p > 0.05 \rightarrow$ not violated	SPSS v22	All cells $p > 0.05$ (min $p = 0.142$); Normality not violated
Levene Test	Homogeneity of variance	$p > 0.05 \rightarrow$ equal variances	SPSS v22	WA: $p = 0.243$; CS: $p = 0.318$; equal variances confirmed
Q-Q Plot (visual)	Normality – graphical	Points close to diagonal	SPSS v22	All points close to diagonal; Normality supported
Kruskal-Wallis + Dunn	Non-parametric alternative	If assumptions violated	SPSS v22	N/A (parametric assumptions met)

3. Results

3.1. Material Characterisation

Prior to specimen fabrication, all constituent materials underwent quality verification. The fine aggregate sourced from Takari exhibited a fineness modulus of 3.0, classifying it as normal sand within the acceptable range of 1.5–3.8 per SNI 03-1968-1990. Mud content was 3.401%, well below the 5% maximum (SNI 03-4142-1996). Complete aggregate properties including specific gravity and water absorption are presented in Table 2. The Portland Composite Cement (PCC) met SNI 7064:2014 requirements; cement physical properties including setting times and specific gravity are presented in Table 1. All specimens were produced at a cement-to-sand ratio of 1:5 by weight with a water-to-cement ratio of 0.285, cured through water immersion for 28 days. Fibre physical and mechanical properties are presented in Table 3.

3.2. Water Absorption of Fibre-Reinforced Paving Blocks

Water absorption testing was conducted on 30 specimens (15 per fibre type; n = 3 per treatment cell) following SNI 03-0349-1989. The results for both PALF and sisal fibre series are presented in Table 6 and illustrated in Figure 2.

Table 6. Mean water absorption results for PALF and sisal fibre-reinforced paving blocks (28-day curing).

Fibre Content (%)	PALF Mean WA (%)	PALF SD (%)	Sisal Mean WA (%)	Sisal SD (%)	SNI 03-0691-1996 Limit (%)	Compliance
0	9.49	3.62	9.43	0.37	≤ 10 (Class D)	✓ Both
1	12.48	1.64	9.92	2.39	≤ 10 (Class D)	✓ Sisal only
3	15.48	0.06	14.40	1.97	Exceeds Class D	✗ Both
5	18.08	1.61	17.44	2.48	Exceeds Class D	✗ Both
7	21.29	1.20	19.05	1.16	Exceeds Class D	✗ Both

SD = Standard Deviation; WA = Water Absorption; SNI 03-0691-1996 Class D maximum = 10%. ✓ = compliant; ✗ = non-compliant.

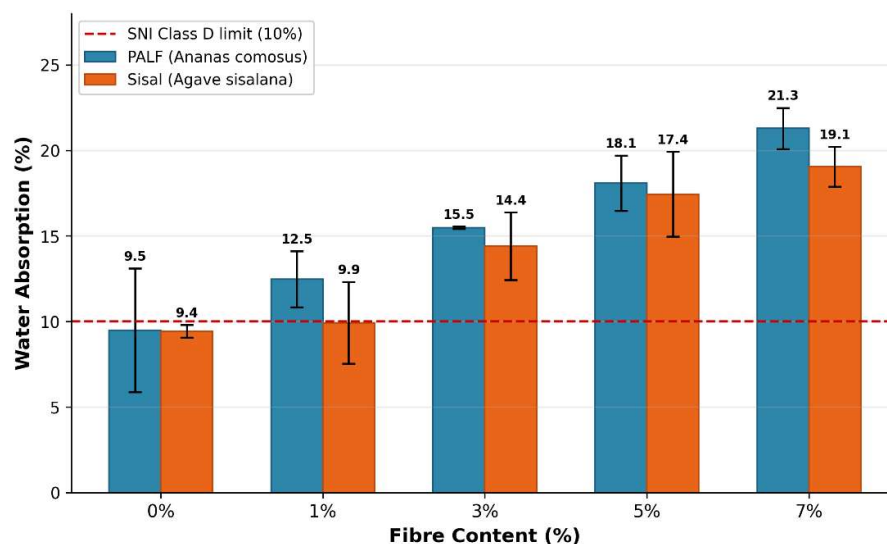


Figure 2. Mean water absorption of PALF and sisal fibre-reinforced paving blocks vs. fibre content (28-day).

Both PALF and sisal fibre series exhibited a consistent, monotonic increase in water absorption with increasing fibre content. For PALF specimens, mean water absorption increased progressively from 9.49% at 0% fibre content to 21.29% at 7%, representing an increase of 124.3% relative to the control. For sisal fibre specimens, mean water absorption rose from 9.43% (0%) to 19.05% (7%), an increase of 101.8% relative to the control.

Control specimens (0%) for both series met the SNI 03-0691-1996 Class D quality requirements (maximum 10%). At 1% fibre addition, sisal fibre specimens (9.92%) marginally complied with the Class D threshold, while PALF specimens (12.48%) exceeded it. Beyond 1% fibre content, all specimens of both series exceeded the SNI Class D limit, indicating progressive deterioration of water resistance at higher fibre dosages.

Sisal fibre specimens consistently exhibited lower water absorption than PALF specimens across all fibre content levels. The difference was most pronounced at 1% fibre content (sisal: 9.92% versus PALF: 12.48%, a difference of 2.56 percentage points) and remained significant at higher dosages.

This differential behaviour is attributed to the distinct morphological characteristics of each fibre type, as discussed in Section 4.1.

Two-way ANOVA (Table 7) confirmed that fibre content exerted a statistically significant main effect on water absorption ($F = 33.561$, $p < 0.001$, $\eta^2 = 0.820$). In contrast, fibre type did not produce a statistically significant main effect ($F = 3.676$, $p = 0.070$). The interaction between fibre type and fibre content was also non-significant ($F = 0.475$, $p = 0.753$), indicating that the rate of increase in water absorption with increasing fibre content was statistically equivalent for both fibre types. The model explained 87.5% of the variance in water absorption ($R^2 = 0.875$).

Table 7. Two-Way ANOVA results: Water absorption of paving blocks.

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	494.067	9	54.896	15.536	< 0.001
Fibre Type (A)	12.989	1	12.989	3.676	0.070 (n.s.)
Fibre Content (B)	474.358	4	118.589	33.561	< 0.001 **
A × B Interaction	6.720	4	1.680	0.475	0.753 (n.s.)
Error	70.671	20	3.534	—	—
Total	7053.320	30	—	—	—
$R^2 = 0.875$ (Adj. $R^2 = 0.819$)					

n.s. = not significant; ** = significant at $p < 0.001$; $\alpha = 0.05$. Model $R^2 = 0.875$.

Post-hoc Tukey HSD analysis revealed significant differences in water absorption between 0% and 3% ($p = 0.001$), 0% and 5% ($p < 0.001$), and 0% and 7% ($p < 0.001$). The difference between 0% and 1% was not statistically significant ($p = 0.513$), suggesting that 1% fibre addition does not materially alter water absorption relative to the control for sisal fibre, though PALF at 1% already exceeds the SNI limit descriptively.

3.3. Compressive Strength of Fibre-Reinforced Paving Blocks

Compressive strength testing was conducted on 50 specimens (5 per treatment cell: 2 fibre types × 5 fibre content levels) in accordance with SNI 03-0691-1996. The results are presented in Table 8 and Figure 3.

Table 8. Mean compressive strength results and SNI quality classification (28-day curing).

Fibre (%)	PALF (MPa)	PALF Class	Sisal (MPa)	Sisal Class	Increase vs. Control	SNI Minimum (MPa)
0	9.1	D	9.1	D	—	8.5 (Class D)
1	10.0	C	11.1	C	+10% / +22%	10.0 (Class C)
3	14.5	B	15.2	B	+59% / +67%	12.5 (Class B)
5	8.0	Below D	9.7	D	-12% / +7%	8.5 (Class D)
7	6.7	Below D	7.3	Below D	-26% / -20%	8.5 (Class D)

SNI 03-0691-1996 classes: Class D ≥ 8.5 MPa; Class C ≥ 10.0 MPa; Class B ≥ 12.5 MPa. Green = optimal fibre content; Red = below Class D minimum.

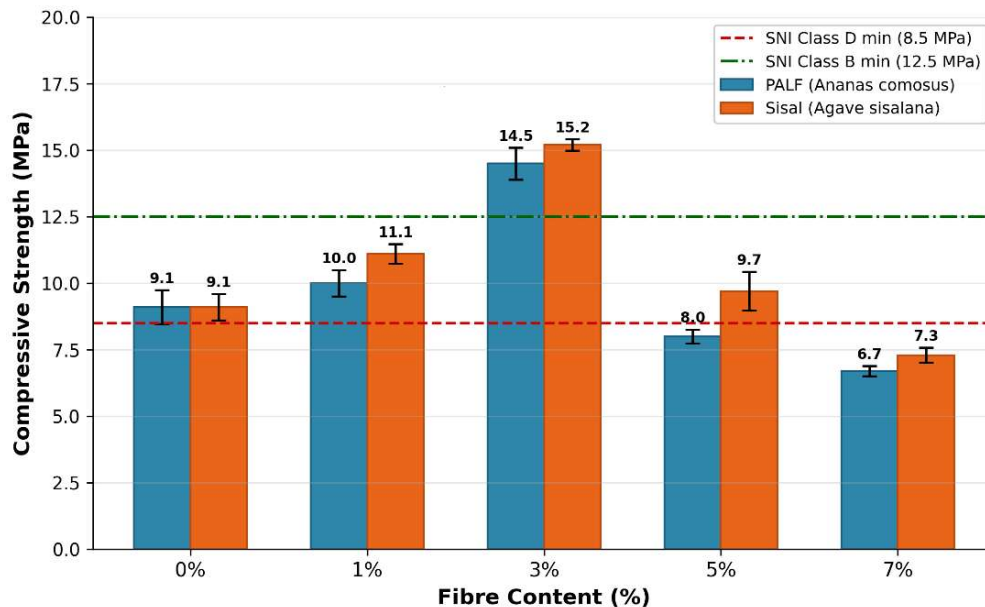


Figure 3. Mean compressive strength of PALF and sisal fibre-reinforced paving blocks vs. fibre content (28-day).

Both fibre types produced a non-linear, inverted-U relationship between fibre content and compressive strength, with a clear peak at 3% fibre content. Control specimens (0%) achieved 9.1 MPa for both series, meeting SNI Class D requirements (minimum 8.5 MPa). At 1% fibre addition, compressive strength increased to 10.0 MPa (PALF, +10%) and 11.1 MPa (sisal, +22%), both meeting SNI Class C (minimum 10.0 MPa).

The most substantial improvement was observed at 3% fibre content. PALF specimens achieved 14.5 MPa (+59% vs. control) and sisal specimens achieved 15.2 MPa (+67% vs. control), both satisfying SNI Class B requirements (minimum 12.5 MPa). This represents a remarkable quality advancement from Class D (control) to Class B achieved solely through the addition of 3% untreated agricultural waste fibre by cement volume, without any supplementary cementitious materials or chemical admixtures.

Beyond 3%, compressive strength declined sharply. At 5% fibre content, mean strength fell to 8.0 MPa (PALF, below Class D) and 9.7 MPa (sisal, Class D). At 7% fibre content, both series achieved their lowest values: 6.7 MPa (PALF) and 7.3 MPa (sisal), both below Class D and structurally inadequate for standard paving applications. Sisal fibre consistently produced higher compressive strength than PALF across all levels; the differential was most pronounced at the 3% optimum (15.2 MPa vs. 14.5 MPa).

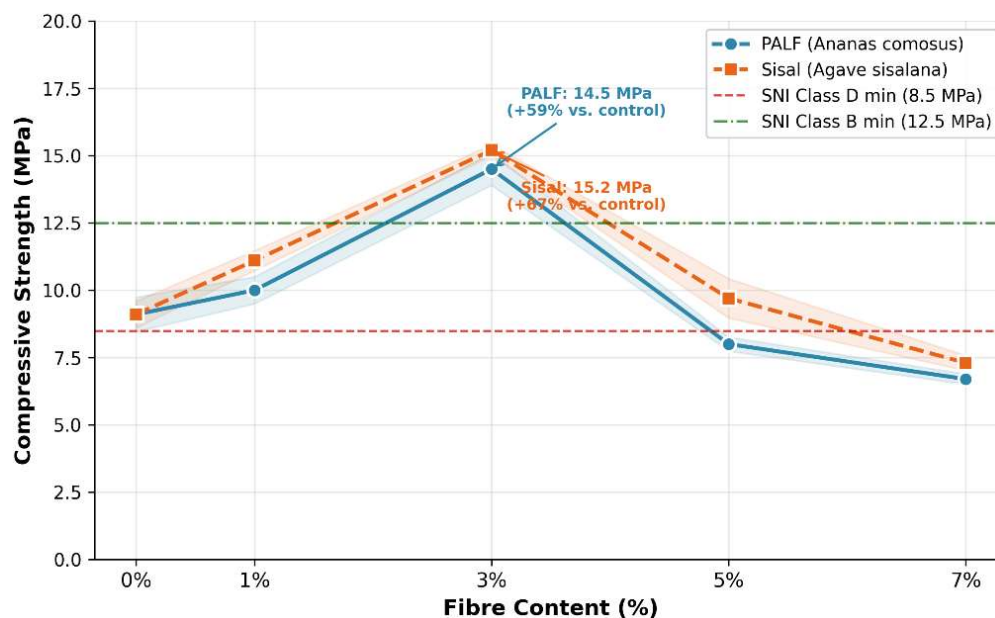
Two-way ANOVA (Table 9) confirmed that both fibre type ($F = 38.512$, $p < 0.001$) and fibre content ($F = 347.750$, $p < 0.001$) exerted statistically significant main effects on compressive strength. Crucially, the interaction term between fibre type and fibre content was also statistically significant ($F = 3.697$, $p = 0.012$), indicating that the effect of fibre content on compressive strength differs depending on the fibre species employed. The model explained 97.3% of the variance in compressive strength ($R^2 = 0.973$), confirming an excellent model fit.

Table 9. Two-Way ANOVA Results: Compressive Strength of Paving Blocks.

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	356.453	9	39.606	160.478	< 0.001
Fibre Type (A)	9.505	1	9.505	38.512	< 0.001 **
Fibre Content (B)	343.299	4	85.825	347.750	< 0.001 **
A × B Interaction	3.649	4	0.912	3.697	0.012 *
Error	9.872	40	0.247	—	—
Total	5418.460	50	—	—	—

R² = 0.973 (Adj. R² = 0.967)

* = significant at $p < 0.05$; ** = significant at $p < 0.001$; $\alpha = 0.05$. Bold row = significant interaction term.

**Figure 3.** Interaction plot – effect of fibre content on compressive strength for PALF vs. sisal fibre.

Post-hoc Tukey HSD analysis confirmed that the 3% fibre content group differed significantly from all other groups ($p < 0.001$ for all pairings). Notably, the 0% and 5% groups were not significantly different from each other ($p = 0.690$), indicating that a 5% fibre addition effectively reduces compressive strength to a level comparable to the untreated control, negating any reinforcing benefit. The 7% group produced significantly lower compressive strength than all other groups ($p < 0.001$), confirming the severely detrimental effect of excessive fibre content.

3.4. Statistical Assumption Test Results

Prior to performing the two-way ANOVA analyses, the Shapiro-Wilk test and Levene's test were applied to verify normality and homogeneity of variance, respectively (Table 5). The Shapiro-Wilk test yielded $p > 0.05$ for all treatment cells for both response variables (W values and p-values to be inserted from SPSS output). Levene's test for homogeneity of variance also yielded $p > 0.05$ for both water absorption and compressive strength. These results confirm that the parametric assumptions of two-way ANOVA were satisfied, validating the use of the F-statistic and associated p-values reported in Tables 7 and 9.

4. Discussion

4.1. Mechanisms of Water Absorption Increase with Fibre Content

The progressive increase in water absorption with increasing fibre content observed in this study is consistent with the fundamental hydrophilic behaviour of cellulose-based natural fibres reported across the recent literature. The hydroxyl groups ($-OH$) present in cellulose molecular chains attract water molecules through hydrogen bonding (R1), creating a persistent moisture sink within the composite matrix. As fibre dosage increases, the total hydrophilic surface area within the paving block matrix grows proportionally, facilitating greater water uptake through both fibre-matrix interfacial zones and direct fibre absorption.

This finding aligns with that of Jamshaid et al. [25], who demonstrated that water absorption in cellulosic fibre-reinforced concrete increases consistently with fibre loading, attributing the trend to increasing interconnected porosity and fibre-matrix interfacial voids at higher dosages. Similarly, Wang et al. [41] confirmed in a study of natural fibre-reinforced foamed concrete that excessive fibre addition enlarges pore size and connectivity, adversely affecting microstructure and water resistance. The present results extend these observations specifically to the paving block context, confirming that the same mechanism operates in non-structural precast concrete products.

The statistically significant main effect of fibre content ($F = 33.561$, $p < 0.001$) alongside the non-significant main effect of fibre type ($F = 3.676$, $p = 0.070$) and non-significant interaction ($F = 0.475$, $p = 0.753$) presents a nuanced finding: both PALF and sisal fibres promote water absorption at statistically equivalent rates when fibre content is varied, despite their known morphological differences. This suggests that for water absorption, fibre dosage is the dominant variable, not fibre species a practically important result that simplifies mix design guidance for natural fibre paving blocks.

However, descriptive comparison reveals a consistent quantitative advantage for sisal fibre in producing lower absolute water absorption values at all treatment levels. This differential is best explained by the distinct morphological and surface characteristics of each fibre. Sisal fibres (*Agave sisalana*) possess a coarser, rougher surface texture and greater stiffness that facilitates more uniform distribution within the dry cement-sand matrix [38]. Better fibre dispersion produces a more homogeneous microstructure with fewer localised agglomeration zones, regions that disproportionately contribute to capillary water ingress. In contrast, PALF fibres, being finer and more flexible, are predisposed to clustering during mixing [37], creating localised high-porosity zones that serve as preferential water absorption pathways.

The threshold compliance with SNI 03-0691-1996 Class D (maximum 10%) only at 0% for PALF and at 0–1% for sisal confirms that untreated natural fibres pose a fundamental challenge for water absorption compliance in paving block applications. Ahmad et al. [28] observed a similar pattern in sisal fibre concrete, noting substantial increases in water absorption at dosages above 2%, which is consistent with the present findings.

4.2. Compressive Strength: Optimum Reinforcement and Post-Peak Decline

The inverted-U relationship between fibre content and compressive strength with a clear optimum at 3% for both fibre types represents the most practically significant finding of this investigation. The initial strength enhancement at 1% and the peak at 3% are consistent with the crack-bridging and stress-redistribution mechanisms widely reported in the natural fibre concrete literature [42,43].

At low to moderate fibre contents (1–3%), discrete fibres are distributed throughout the cement-sand matrix, functioning as crack arrestors within the hardened composite. When compressive loading induces lateral tensile stress, fibres oriented transversely to the crack front resist crack propagation, forcing cracks to deflect around fibres rather than propagating catastrophically through the matrix [43]. Additionally, the hydrophilic nature of natural fibres promotes absorption of cement paste into fibre surface pores during mixing, creating mechanical interlocking as the paste hydrates,

a mechanism documented by Bereche and Garcia [44] in Peruvian sisal fibre concrete. These combined mechanisms explain the 59% (PALF) and 67% (sisal) compressive strength gains at 3% relative to control.

The quality advancement from SNI Class D (control, 9.1 MPa) to Class B (3% fibre, ≥ 12.5 MPa) is a practically noteworthy outcome. Class B paving blocks are approved for areas with moderate pedestrian and light traffic loading under SNI 03-0691-1996. The promotion to Class B through the simple addition of 3% locally available agricultural waste fibre, without cement replacement, chemical admixtures, or surface treatment represents a viable and economically accessible quality improvement pathway for small-scale paving block producers in rural and semi-urban areas of Eastern Indonesia.

The decline in compressive strength at 5% and 7% fibre content is attributable to two concurrent mechanisms. First, at higher fibre concentrations, workability decreases significantly, making uniform fibre dispersion more difficult even with the dry-mixing procedure employed. Fibre agglomeration particularly severe for PALF at these dosages creates localized weak zones characterized by reduced cement-paste consolidation and elevated interconnected porosity [45]. Second, the volumetric proportion of fibres becomes sufficiently large to disrupt the continuity of the cement-sand load-bearing skeleton. Fibres, having much lower stiffness than the hardened cement matrix, act as compliant inclusions that reduce composite modulus and introduce stress concentration sites under compressive loading [42]. Ahmad et al. [28] documented identical strength-decline patterns in sisal fibre concrete above 2% dosage.

The statistically significant interaction between fibre type and fibre content ($F = 3.697$, $p = 0.012$) confirms that the compressive strength response is not simply additive across the two factors. The advantage of sisal over PALF grows disproportionately in the moderate-to-high fibre content range, while the two fibre types perform more similarly at very low contents (0–1%). This is mechanistically explicable: at low fibre dosages, both fibres are sufficiently dispersed to provide equivalent crack-bridging reinforcement. As dosage increases, the morphological advantage of sisal its rougher surface and greater stiffness facilitating better dispersion and fibre-matrix bonding becomes increasingly consequential. Antwi-Afari et al. [30] confirmed that surface roughness of sisal fibres is a key determinant of interfacial bond strength, directly influencing compressive performance at higher dosages.

4.3. Comparative Performance: Sisal Fibre Superior to PALF

Sisal fibre consistently outperformed PALF in compressive strength across all fibre content levels and produced lower water absorption values at all levels. This performance differential is rooted in fundamental differences in fibre physical properties. Sisal fibres exhibit tensile strength of 468–640 MPa, diameter of 50–200 μm , and density of approximately 1.45 g/cm^3 (R4). Their high cellulose content (~78%) contributes to a crystalline molecular structure with high stiffness, enabling effective stress transfer under compressive loading. PALF fibres, while possessing competitive tensile strength (180–753 MPa), are finer, more flexible, and more susceptible to agglomeration due to their lower stiffness and higher surface-to-volume ratio [37].

These findings are consistent with Asrial et al. [21] who investigated sisal fibre paving blocks in the same regional context (East Nusa Tenggara) and reported 13.2 MPa at 3% sisal fibre somewhat lower than the 15.2 MPa obtained in the present study, likely due to differences in mix proportions and specimen geometry. Another study characterising sisal fibre from TTU Regency (NTT, Indonesia) also documented compressive strength exceeding K-125 standard at 2% sisal content, further validating the effectiveness of locally sourced NTT sisal fibre as a concrete reinforcement [46]. The present study extends these findings by identifying 3% as the optimal content for paving block applications higher than the 2% optimum for structural concrete consistent with different mix proportions and compaction methods used for paving blocks.

4.4. Unexpected Findings and Anomalous Observations

(i) Non-significance of fibre type on water absorption

The research team hypothesised, based on known morphological differences, that sisal fibres would produce statistically significantly lower water absorption than PALF. The two-way ANOVA result ($F = 3.676$, $p = 0.070$) did not support this hypothesis. This unexpected non-significance may reflect limited statistical power arising from the small sample size ($n = 3$ per treatment cell for water absorption). The observed p -value of 0.070, while above the $\alpha = 0.05$ threshold, is borderline suggesting a real but statistically undetected effect. Future studies with $n \geq 5$ per cell are recommended. Alternatively, at the macro-scale of paving block water absorption, both fibre types may introduce similar quantities of interfacial porosity regardless of morphological differences, consistent with the argument of Wang et al. [41].

(ii) Divergence between PALF and sisal at 5% fibre content

At 5% fibre content, sisal specimens achieved 9.7 MPa (Class D compliant) while PALF specimens fell to 8.0 MPa (below Class D) a divergence of 1.7 MPa larger than expected at this dosage. This highlights that at fibre contents approaching the practical workability limit, the morphological advantage of sisal specifically its stiffness resisting self-entanglement becomes critically important. At 5%, PALF appears to have reached a dispersion threshold beyond which agglomeration produces macroscopic weak zones, consistent with observations by Ahmad et al. [28] and Ntsie et al. [7].

(iii) Non-significant difference between 0% and 5% compressive strength (Tukey HSD, $p = 0.690$)

The Tukey HSD result showing no significant difference between the 0% control (9.1 MPa) and the 5% combined group (mean ~ 8.83 MPa) was counterintuitive visually. This is explained by the high variance in the 5% group ($SD = 1.017$), which reflects the onset of heterogeneous fibre distribution some specimens having better dispersion than others. The elevated variance at 5% is itself a practically important finding: it signals that manufacturing consistency deteriorates at this dosage, rendering the 5% level unsuitable for quality-controlled production even where the group mean appears adequate.

4.5. Strengths and Limitations

Strengths

- Full-factorial two-way ANOVA with interaction testing a statistical framework not previously applied to the PALF-versus-sisal comparison in paving block applications. The significant interaction term ($p = 0.012$) provides nuanced practical guidance not available from single-factor studies.
- Both fibre types were investigated simultaneously under identical mix proportions, curing conditions, and test protocols, eliminating between-study confounders that complicate indirect comparisons across publications.
- All materials were sourced from East Nusa Tenggara Province, ensuring results are directly applicable to local construction practice and supporting knowledge transfer to rural communities in Eastern Indonesia.
- SNI 03-0691-1996 was used as the quality benchmark throughout, ensuring practical relevance for Indonesian practitioners and policymakers.

Limitations

- No fibre surface treatment was applied. Alkali treatment (NaOH) has been shown to improve fibre-matrix bonding and reduce water absorption [30,36]. Untreated fibre conditions may have depressed performance relative to achievable outcomes with surface-treated fibres.
- A single curing age (28 days) was investigated, precluding assessment of long-term strength development and durability particularly relevant given the risk of alkaline degradation of lignin and hemicellulose in cement matrices over extended periods [32].

- Only compressive strength and water absorption were measured. Flexural strength, splitting tensile strength, abrasion resistance, and freeze-thaw durability were not assessed.
- Small sample size for water absorption ($n = 3$ per treatment cell) limits statistical power and may have prevented detection of a significant fibre type main effect.
- Absence of microstructural analysis (SEM/XRD) means that the proposed mechanistic explanations, while supported by literature, remain inferential for this specific material system.

4.6. Recommendations for Future Research

- (1) Surface treatment of fibres. Alkali treatment with NaOH (2–5%) applied to both PALF and sisal before incorporation could reduce water absorption below the SNI Class D limit at fibre contents up to 3%, based on evidence that NaOH treatment improves fibre tensile properties and fibre-matrix bonding [36].
- (2) Multiple curing ages and long-term durability. Studies at 7, 28, 56, and 90 days would illuminate long-term compressive strength trajectories and provide insight into alkaline degradation of natural fibres in the cement matrix [32]. Wet-dry cycling and chemical exposure resistance should also be examined.
- (3) Hybrid PALF–sisal fibre systems. The complementary properties of PALF (higher aspect ratio, flexibility) and sisal (stiffness, better dispersion) suggest potential synergistic reinforcement in binary fibre blends. Sampath et al. [47] reported enhanced mechanical and thermal properties in hybrid PALF-sisal epoxy composites, supporting feasibility in cementitious matrices.
- (4) Microstructural characterisation (SEM/XRD). Analysis of the fibre-matrix interface zone at 3% (optimum) and 5% (decline onset) would provide direct evidence for the crack-bridging and agglomeration mechanisms proposed in this study.
- (5) Life cycle assessment and economic analysis. A comparative LCA of natural fibre paving blocks versus conventional paving blocks would quantify the environmental and economic benefits at scale, informed by Chen et al. [5] who demonstrated carbon emission reductions in natural fibre concrete.
- (6) Field validation. Laboratory findings should be validated through real-world pilot trials in pedestrian and light-traffic paving applications in Kupang and surrounding districts, providing surface wear, infiltration rate, and visual integrity data to support adoption by local practitioners

5. Conclusions

This study systematically investigated the comparative effectiveness of pineapple leaf fibre (PALF) and sisal fibre as natural reinforcements in paving blocks, analysing their effects on water absorption and compressive strength at fibre content levels of 0%, 1%, 3%, 5%, and 7% by cement volume. The following conclusions are drawn:

- Fibre content significantly influenced both water absorption and compressive strength ($p < 0.001$), while fibre type significantly affected compressive strength ($p < 0.001$) but not water absorption ($p = 0.070$). A significant interaction between fibre type and content was identified for compressive strength ($F = 3.697$, $p = 0.012$).
- Water absorption increased monotonically with fibre content for both fibre types, exceeding the SNI 03-0691-1996 Class D limit (maximum 10%) beyond 0% for PALF and beyond 1% for sisal. This underscores the importance of selecting appropriate fibre content for water-sensitive applications.
- Compressive strength exhibited a non-linear, inverted-U relationship with fibre content, with an optimal dosage of 3% for both fibre types. At 3%, sisal fibre achieved 15.2 MPa (+67% vs. control) and PALF achieved 14.5 MPa (+59%), both meeting SNI Class B quality standards (minimum 12.5 MPa) a quality advancement from Class D without any supplementary materials.
- Sisal fibre demonstrated superior performance compared to PALF across all fibre content levels. This advantage is attributed to sisal's higher stiffness, coarser surface texture, and better

dispersion characteristics, which become increasingly consequential at higher dosage levels as confirmed by the significant interaction term.

- Fibre contents of 5% and 7% produced strength values below or near the Class D minimum, with elevated manufacturing variability at 5%, rendering these dosages unsuitable for quality-controlled paving block production.
- The utilization of locally sourced, untreated PALF and sisal fibres as agricultural waste in paving block production supports circular economy principles, reduces dependence on synthetic reinforcement materials, and offers a practically accessible quality improvement pathway for small-scale producers in Eastern Indonesia.

Future research should investigate fibre surface treatments to improve water absorption compliance, examine long-term durability under environmental exposure, and explore hybrid PALF-sisal fibre combinations to extend the compliant fibre content range.

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Abbreviations

The following abbreviations are used in this manuscript:

PALF	Pineapple Leaf Fibre
SNI	Standar Nasional Indonesia (Indonesian National Standard)
PCC	Portland Composite Cement
CTM	Compression Testing Machine
UTM	Universal Testing Machine
ANOVA	Analysis of Variance
HSD	Honestly Significant Difference
SSD	Saturated Surface Dry
WA	Water Absorption
w/c	Water-to-Cement ratio

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