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Quantifying the Porosity–Strength Relationship of Porous Paving Blocks Containing Mechanically Processed Waste-Paper Fibre as a Partial Fine-Aggregate Replacement

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ABSTRACT: Waste paper is a large waste stream, and porous paving materials are increasingly investigated for urban stormwater management. However, quantitative information linking porosity to mechanical performance in porous paving blocks that contain waste-paper fibre remains scarce. This study quantifies how replacing fine aggregate with mechanically processed, chemically untreated waste-paper fibre affects open porosity, water absorption, dry density, compressive strength, and flexural strength, and expresses the porosity–strength relationship with confidence intervals. Paving blocks (200 × 100 × 60 mm; cement-to-sand ratio 1:3; nominal water-to-cement ratio 0.30) were produced with 0, 5, 10, 15, and 20% fibre by bulk volume of the sand replaced. Ten specimens per mixture were tested for each property at 28 days. Data were analysed using analysis of variance, Welch's test, Games–Howell and Tukey comparisons with 95% confidence intervals, effect sizes, linear regression, and Pearson and Spearman correlations. Substitution increased open porosity from 11.99% to 17.87%, reduced dry density by 13–15%, reduced compressive strength from 37.28 MPa to 18.18–25.40 MPa, and reduced flexural strength from 6.25 MPa to 3.25–4.15 MPa. Across the five mixture means, each 1-percentage-point increase in porosity corresponded to 2.78 MPa lower compressive strength (95% CI: 0.13–5.43 MPa; $p = 0.045$) and 0.43 MPa lower flexural strength (95% CI: −0.91 to +0.05 MPa; $p = 0.065$). The relationship largely vanished within the waste-paper mixtures alone ($r = −0.39$ for compressive strength), indicating that porosity is a useful indicator but not the sole determinant of strength; fibre dispersion and material heterogeneity (coefficients of variation of 19–29%) also matter. The 10% mixture (16.20% porosity, 25.40 MPa, 8.30% water absorption) is identified as a screening candidate for light-traffic porous paving, subject to infiltration, durability, and variability-control studies.

KEYWORDS: Cellulose fibre; porosity–strength relationship; stormwater management; circular economy; cement composites

1. Introduction

The increasing generation of municipal solid waste has intensified the need for effective waste prevention, recycling, and resource recovery strategies. According to the United Nations Environment Programme, global municipal solid waste generation reached approximately 2.1 billion tonnes in 2023 and is projected to increase to 3.8 billion tonnes by 2050 if current waste management practices remain unchanged [1]. This growing environmental challenge highlights the importance of developing sustainable approaches that convert residual waste into value-added materials, thereby reducing disposal requirements and supporting circular economy principles. In the construction sector, incorporating waste-derived materials into cement-based products offers opportunities to reduce the consumption of natural resources while improving waste utilization.

Waste paper represents a potentially valuable secondary resource because its cellulose fibres can be recovered and incorporated into alternative products, particularly when conventional paper recycling becomes technically or economically impractical. Previous studies have demonstrated the feasibility of incorporating waste-paper fibres into polymeric and construction materials [2]. In cement-based composites, cellulose fibres derived from paper sludge have been investigated as renewable reinforcement materials, although their high water absorption and interactions with cementitious matrices remain important challenges [3]. Recent developments have also demonstrated the potential of waste-paper-derived nanocellulose for construction applications. Alkaline treatment at relatively low temperatures has been employed to produce nanoscale cellulose particles [4], which can modify the microstructure of cement mortar [5]. Furthermore, investigations of waste-derived cellulose fibres have demonstrated their influence on mechanical properties, microstructural characteristics, durability, and environmental performance, including reductions in density, changes in moisture-related behaviour, and deterioration in mechanical strength at excessive fibre contents [6]. These findings suggest that cellulose-based waste materials offer potential benefits, although their effectiveness depends on fibre characteristics, dosage, and incorporation methods.

Paving blocks represent a promising application for waste-derived materials because they are widely used in pedestrian areas, parking facilities, and urban infrastructure, where partial replacement of conventional constituents may reduce natural resource consumption. Previous investigations have examined the incorporation of municipal solid waste incineration bottom ash into pervious concrete, demonstrating that changes in density and pore structure influence mechanical and hydraulic properties [7]. Studies on porous concrete have consistently established strong relationships among density, porosity, permeability, and compressive strength [8, 9]. These relationships are influenced not only by total void content but also by aggregate characteristics, pore size distribution, pore connectivity, and compaction conditions [8, 9, 17–20]. Consequently, understanding the relationship between pore structure and mechanical performance is essential when developing waste-modified paving materials.

Porous and permeable pavements have also received increasing attention as components of sustainable urban drainage systems because they can reduce surface runoff and promote water infiltration compared with conventional impervious surfaces [10]. However, their development involves a fundamental trade-off between mechanical strength and pore availability. Aggregate size and shape significantly influence porosity and compressive strength [9, 11], while the water-to-cement ratio and pore structure further determine the balance between hydraulic and mechanical performance [12]. Previous reviews have identified

porosity as a major factor controlling compressive strength and emphasized the importance of distinguishing total porosity, effective porosity, and pore connectivity when evaluating porous cementitious materials [13, 14]. In addition, field investigations have demonstrated that the hydraulic performance of permeable pavements can decline over time because of clogging [15], although maintenance and cleaning may partially restore permeability [16]. Therefore, laboratory measurements of porosity alone are insufficient to establish the suitability of a material for permeable pavement applications.

Despite these developments, the incorporation of waste-paper fibres into cement-based paving blocks presents several unresolved technical challenges. Cellulose fibres are hydrophilic and may increase water demand, modify pore formation, and influence bonding within the cementitious matrix. Excessive fibre incorporation may also reduce matrix continuity and mechanical strength, potentially limiting practical applications [3, 6]. These challenges become particularly important when waste-paper fibres are used to replace fine aggregates rather than being introduced as supplementary reinforcement. Aggregate replacement changes the volumetric composition of the mixture and may simultaneously affect packing density, pore distribution, water absorption, and load-bearing capacity. Consequently, the mechanical performance of waste-paper-modified paving blocks cannot be adequately predicted from conventional fibre-reinforced concrete studies alone.

Previous research has addressed different aspects of waste-derived cellulose materials and porous cementitious composites, but several important gaps remain. Studies on waste-paper nanocellulose have primarily focused on chemically processed nanoscale particles incorporated into mortar [4, 5], while investigations of cellulose fibres from paper sludge and other waste sources have generally considered their reinforcing effects in conventional cementitious matrices [3, 6]. Research on waste-modified pervious concrete has examined mineral waste materials, including incineration bottom ash, rather than hydrophilic cellulose fibres used as aggregate substitutes [7]. Meanwhile, investigations of porosity–strength relationships have largely focused on porous concrete containing conventional mineral aggregates, with particular emphasis on aggregate grading, pore characteristics, and compaction [8, 9, 12–14, 17–21, 22]. Although fibre-modified pervious concrete has been investigated, these studies have generally introduced fibres as additional reinforcement rather than as volumetric replacements for fine aggregates [17, 21]. Therefore, the combined effects of mechanically processed, chemically untreated waste-paper fibres used as fine-aggregate substitutes on the physical and mechanical properties of paving blocks remain insufficiently characterized in the cited literature. In particular, quantitative evidence describing how changes in open porosity relate to compressive and flexural strength under this replacement approach remains limited.

To address these gaps, the novelty of the present study lies in integrating mechanically processed, chemically untreated waste-paper fibres as volumetric fine-aggregate substitutes with a quantitative assessment of porosity–strength relationships in cement-based paving blocks. Unlike previous studies involving chemically treated nanocellulose or fibres added as reinforcement, this investigation considers fibre substitution based on the absolute volume of fine aggregate. This approach allows the combined effects of aggregate displacement and the porous, hydrophilic characteristics of cellulose fibres to be evaluated. Furthermore, the study integrates physical and mechanical characterization with regression analysis, confidence intervals, and sensitivity analysis to assess the magnitude and robustness of the relationships

between open porosity and mechanical strength. This analytical approach provides a basis for identifying potential mixture compositions while explicitly considering the trade-offs among porosity, water absorption, and structural performance.

Accordingly, this study aims to evaluate the effects of replacing 0–20% of the absolute volume of fine aggregate with mechanically processed waste-paper fibres on the physical and mechanical properties of cement-based paving blocks, with particular emphasis on quantifying porosity–strength relationships and identifying candidate mixtures based on predefined performance criteria. The evaluated properties include open porosity, water absorption, dry density, compressive strength, and flexural strength. The findings are expected to contribute to the understanding of waste-paper fibre utilization in cementitious paving materials and provide preliminary guidance for developing resource-efficient construction products. However, the study does not establish full permeable pavement performance because infiltration capacity and long-term durability were not evaluated.

2. Materials and Methods

2.1. Research design.

This study used a laboratory experimental design with five waste-paper substitution levels: 0%, 5%, 10%, 15%, and 20%. The control mixture contained no waste-paper fibre. The substitution level was defined by the bulk volume of fibre placed in an equal absolute volume of the fine aggregate removed, not by the mass of cement. The substitution levels were selected as an evenly spaced series that increases the replaced volume in equal steps up to 20%. The upper limit of 20% corresponds to a loose-fibre volume of 0.104 m^3 per m^3 of mixture (Table 1), which was considered the practical upper limit for two reasons. First, the loose fibre volume then equals one fifth of the sand skeleton, and with manual mixing and a low water content any further increase would make uniform dispersion and compaction in a 60 mm mould increasingly difficult. Second, published work on cellulose-fibre concrete shows that excessive fibre incorporation reduces strength [6], so levels above 20% were expected to fall below the strength classes relevant to paving blocks. The experimental programme consisted of waste-paper processing, fine-aggregate characterisation, mixture proportioning, specimen fabrication, curing, physical-property testing, mechanical testing, and statistical analysis (Figure 1).

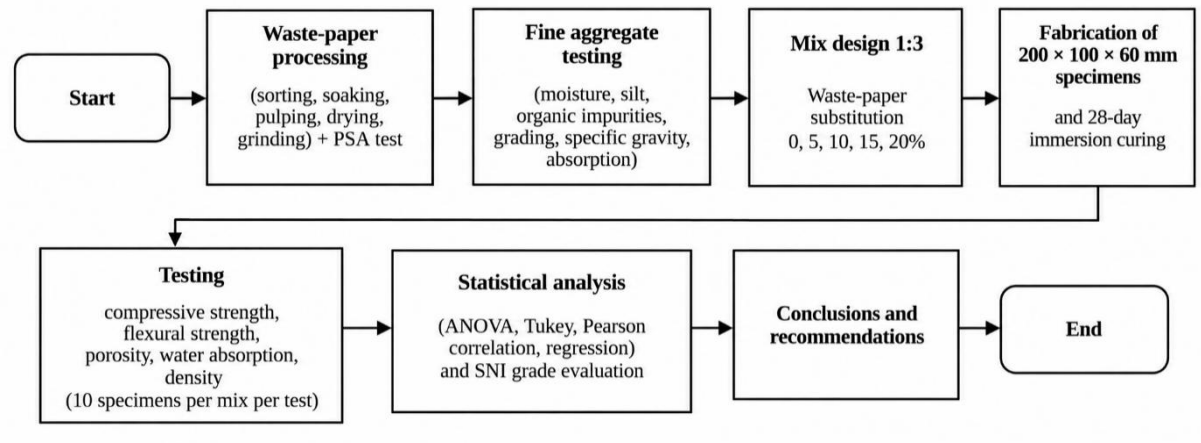


Figure 1. Research Flowchart.

2.2. Materials and waste-paper processing.

The primary materials used in this study were Portland cement, natural fine aggregate (sand), clean water, and waste office paper. Printed waste office paper was selected as the cellulose source because of its availability as a common post-consumer material and its potential for reuse in cement-based construction products. The waste paper underwent six processing stages: contaminant removal, shredding, soaking, mechanical pulping, drying, and grinding. Initially, visible contaminants, including plastics, staples, metallic components, and other foreign materials, were manually removed to minimize impurities. The cleaned paper was subsequently shredded into smaller pieces and soaked in water to facilitate fibre separation. Mechanical stirring was then performed to produce a relatively homogeneous pulp, followed by draining and sun-drying to reduce moisture content. Finally, the dried material was ground using a blender to obtain mechanically processed waste-paper fibres suitable for incorporation into the paving block mixtures.

The main stages of waste-paper preparation are illustrated in Figure 2, showing the transformation of discarded paper into processed fibre. The resulting material was incorporated into the mixtures in an air-dry condition, with a measured moisture content of approximately 5%. No chemical treatment was applied during preparation, allowing the study to evaluate mechanically processed waste-paper fibres without chemical modification. This distinction is important because chemically treated waste-paper nanocellulose may exhibit substantially different particle characteristics, surface properties, and interactions with cementitious matrices [4, 5]. Furthermore, the moisture condition of the processed fibres was considered relevant because cellulose is hydrophilic and may influence water absorption, mixture consistency, and pore formation in the hardened paving blocks.



Figure 2. Waste-paper Processing Stages: (a) Shredding; (b) Soaking; (c) Mechanical Pulping; (d) Drying; (e) Grinding; and (f) Processed Fibre.

Particle-size analysis was conducted on the dispersed fine fraction of the processed waste-paper material using a particle size analyser at the PPNN Laboratory, Institut Teknologi Bandung, Indonesia. As presented in Figure 3, two measurements produced mean particle sizes of 1,584.9 and 1,073.5 nm, respectively, with prominent particle-size ranges of approximately 200–300 nm and 2,300–2,700 nm. These results indicate a heterogeneous particle-size distribution within the analysed fine fraction, potentially reflecting variations in fibre fragmentation and particle dispersion during mechanical processing. However, the measurements characterize only the dispersed fine fraction and should not be interpreted as representing the dimensions of the entire bulk fibre material incorporated into the paving block mixtures.

The particle-size distributions shown in Figure 3 also suggest that mechanical processing produced fine particles with different characteristic sizes. Such variations may influence particle packing, water retention, and interactions with the cementitious matrix, although these mechanisms were not directly evaluated in the present study. Importantly, the presence of nanoscale particles in the analysed fraction does not establish that the processed material is nanocellulose, as its bulk morphology and nanoscale structural characteristics were not independently confirmed. Therefore, the material is consistently referred to as mechanically processed waste-paper fibre rather than nanocellulose.

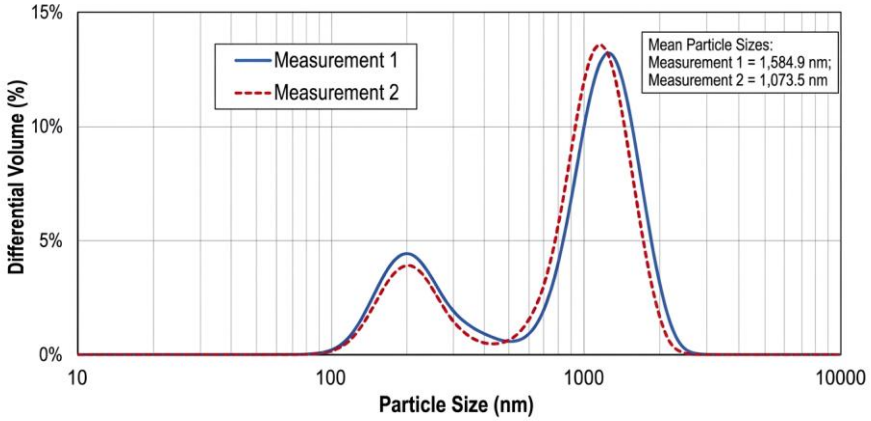


Figure 3. Particle-size Distributions of the Dispersed Fine Fraction of the Processed Waste-Paper Fibre (Two Measurements).

The natural fine aggregate was characterized before mixture preparation to evaluate its suitability for paving block production. The laboratory tests included moisture content, silt content, organic impurities, particle-size distribution, fineness modulus, specific gravity, and water absorption, following applicable ASTM procedures where available. These properties were evaluated because aggregate grading, cleanliness, and moisture characteristics can influence mixture workability, particle packing, pore formation, and the mechanical performance of cement-based products. The aggregate characterization provided baseline information for assessing the effects of replacing part of the fine aggregate volume with processed waste-paper fibres.

2.3. Mixture Proportioning And Specimen Preparation.

The control mixture was prepared using a cement-to-fine-aggregate mass ratio of 1:3, with a cement content of 450 kg/m³ and a sand content of 1,350 kg/m³. A nominal water-to-cement ratio of 0.30 was maintained across all mixtures, corresponding to 135 kg/m³ of mixing water. This relatively low ratio is commonly adopted in semi-dry paving block mixtures and porous cementitious materials to limit paste drainage and preserve void structures [8, 12]. The fine aggregate exhibited low water absorption (0.67%), indicating limited additional water demand. The mixing water was not adjusted for fibre moisture or absorption to maintain consistent nominal mixture conditions. The processed waste-paper fibre was introduced in an air-dry condition with approximately 5% moisture content. Although the fibre mass was relatively small (0.66–2.65 kg/m³), its hydrophilic characteristics could influence local water availability and cement hydration. Therefore, the actual effective water-to-cement ratio may have varied locally depending on fibre distribution and moisture absorption.

The absolute volume of fine aggregate was calculated using its mass and specific gravity. The measured oven-dry specific gravity was 2.62, while a design value of 2.60 was adopted for mixture proportioning, representing a difference of less than 1%. Waste-paper fibre replaced 0%, 5%, 10%, 15%, and 20% of the calculated sand volume. The replacement quantities were determined using the loose bulk density of processed fibre (25.46 kg/m³), which includes inter-fibre void spaces rather than representing the true solid volume of cellulose. Consequently, the substitution primarily involved reducing the sand content while introducing a relatively small mass of lightweight, porous fibre. This distinction is important because the resulting changes in packing density and void structure may influence the physical and mechanical properties of the paving blocks. The detailed mixture proportions and specimen quantities are presented in Table 1.

Table 1. Mixture Proportions and Experimental Specimens.

Waste-paper fibre (%)	Cement (kg/m³)	Sand (kg/m³)	Sand volume (m³/m³)	Fibre volume (m³/m³)	Fibre mass (kg/m³)	Specimens per property
0	450	1,350.00	0.519	0.000	0.00	10
5	450	1,282.50	0.493	0.026	0.66	10
10	450	1,215.00	0.467	0.052	1.32	10
15	450	1,147.50	0.441	0.078	1.99	10
20	450	1,080.00	0.416	0.104	2.65	10

As shown in Table 1, the cement content remained constant at 450 kg/m³, while the sand content decreased progressively with increasing waste-paper fibre substitution. At the maximum replacement level of 20%, the sand content decreased to 1,080 kg/m³, corresponding to a nominal fibre bulk volume of 0.104 m³/m³ and a fibre mass of 2.65 kg/m³. Because the replacement was calculated using loose bulk density, the reported fibre volume includes inter-fibre air and should not be interpreted as the absolute solid volume of cellulose. The resulting mixture proportions may therefore influence pore formation through changes in aggregate packing, fibre distribution, and matrix continuity. Furthermore, the loose bulk density of processed fibre can vary with moisture content, particle characteristics, and packing conditions, which should be considered when reproducing the mixture design.

The materials were weighed according to the specified proportions and mixed until the waste-paper fibres appeared visually distributed throughout the mixture. The fresh mixtures were subsequently placed into rectangular moulds measuring 200 × 100 × 60 mm and manually compacted using five blows per specimen. A consistent number of blows was applied to standardize the nominal compaction procedure across all mixtures while limiting excessive densification of the semi-dry material. However, manual compaction may introduce variability because the actual energy delivered to individual specimens was not precisely controlled. Following demoulding, the specimens were cured by water immersion until 28 days to support cement hydration and strength development.

For each mixture, 10 specimens were prepared for compressive strength testing, 10 for flexural strength testing, and 10 for physical property characterization. Accordingly, five mixture compositions were evaluated using a total of 150 specimens, comprising 50 specimens for each testing category. Separate specimens were used for physical and mechanical testing; therefore, porosity and strength measurements could not be directly paired at the individual-specimen level. Subsequent analyses of porosity–strength relationships were consequently based on mixture-level mean values rather than paired specimen measurements.

2.4. Physical-property Testing.

Open porosity, water absorption, and dry density were determined using an immersion-based procedure derived from the principles of ASTM C642. Specimens were oven-dried at 105 °C to constant mass, weighed to obtain the dry mass, immersed in water until saturation, and weighed in the saturated surface-dry condition. Open porosity was calculated from the volume of water-accessible voids relative to the specimen volume. Water absorption was expressed as the mass increase between the dry and saturated surface-dry states. Dry density was obtained from the dry mass and external specimen volume. The specimen volume was 0.0012 m^3 and the density of water was taken as 1,000 kg/m^3. The tests were performed at the Construction Laboratory of the Civil Engineering Study Program, Pradita University.

2.5. Mechanical Testing.

Compressive strength was measured at 28 days using a hydraulic compression machine with a capacity of 2,000 kN. Specimens were tested on the 200 × 100 mm face, and strength was calculated as the maximum load divided by the loaded area. Flexural strength was determined using centre-point loading on the intact 200 mm specimen supported over a 120 mm span (each support 40 mm from the specimen end), with the load applied at midspan of the 100 mm wide face. The modulus of rupture was calculated from the maximum load, span, specimen width, and thickness. The 120 mm span and 60 mm thickness give a span-to-depth ratio of 2, which differs from the conventional beam geometry used in standard concrete flexural testing. The flexural values were therefore used primarily for relative comparison among mixtures, not for direct specification compliance. All flexural specimens failed in the midspan region.

2.6. Statistical Analysis.

For each mixture, the mean, standard deviation, and coefficient of variation (CoV) were calculated. Differences among the five mixtures were assessed by one-way analysis of variance (ANOVA) at a significance level of 0.05, with homogeneity of variance evaluated by Bartlett's test. Where unequal variances were detected (compressive strength and porosity), Welch's ANOVA and Games–Howell post-hoc comparisons were used; where variances were homogeneous (flexural strength), Tukey's procedure was used. Pairwise mean differences are reported with 95% confidence intervals (n = 10 per mixture; computed from the mixture means and standard deviations). The magnitude of the mixture effect was expressed as eta-squared (η^2), interpreted using the conventional benchmarks of 0.01 (small), 0.06 (medium), and 0.14 (large).

The relationship between open porosity and strength was evaluated at the mixture-mean level using linear regression, Pearson correlation, and Spearman rank correlation. Slope confidence intervals were calculated from the t-distribution with 3 degrees of freedom. Because physical and mechanical tests used different specimens, specimen-level regression was not possible. Robustness was assessed in two ways: (i) a leave-one-out sensitivity analysis, in which each mixture was omitted in turn; and (ii) a separate analysis restricted to the four waste-paper mixtures (5–20%) to determine whether the association was driven mainly by the contrast between the control and waste-paper mixtures. Linear and exponential models were compared descriptively.

Results were also interpreted against the compressive-strength and water-absorption classes of SNI 03-0691-1996. This standard defines four classes by mean compressive strength, minimum individual strength, and maximum mean water absorption: A (40 MPa, 35 MPa, 3%), B (20 MPa, 17 MPa, 6%), C (15 MPa, 12.5 MPa, 8%), and D (10 MPa, 8.5 MPa, 10%), intended respectively for roads, parking areas, pedestrian walkways, and parks or other light uses. Because this standard was developed for conventional paving blocks rather than purpose-designed porous materials, the classification is reported only as a comparative benchmark and not as evidence of compliance for permeable-pavement applications.

3. Results and Discussion

3.1. Material Characteristics.

The natural fine aggregate exhibited a moisture content of 0.26%, silt content of 0.53%, and water absorption of 0.67%. The fineness modulus was 2.96, while the oven-dry, saturated-surface-dry, and apparent specific gravities were 2.62, 2.64, and 2.67, respectively. The organic impurity test corresponded to plate No. 1, indicating a low level of detectable organic contamination. These characteristics suggest that the sand was relatively clean, moderately coarse, and exhibited low water absorption, making it suitable for cement-based paving block production. Because the same aggregate source was used throughout the experiment, variations in the resulting physical and mechanical properties were more likely associated with waste-paper fibre substitution than with differences in aggregate quality. Furthermore, replacing part of the relatively coarse sand with lightweight, porous fibres may reduce aggregate packing efficiency and increase void formation, particularly under the low-water mixing conditions adopted in this study.

The processed waste-paper fibre exhibited mean particle sizes of 1,584.9 and 1,073.5 nm in two measurements of its dispersed fine fraction. As illustrated in Figure 3, the particle-size distributions showed prominent ranges of approximately 200–300 nm and 2,300–2,700 nm, indicating the presence of particles with different characteristic sizes. These results suggest that mechanical grinding generated a heterogeneous mixture of fine particles and larger fibre fragments. In comparison, chemically treated waste-paper nanocellulose has been reported to exhibit particle sizes of approximately 100–500 nm following low-temperature alkaline processing [4]. However, the presence of nanoscale particles in the analysed fraction does not establish that the bulk material was nanocellulose. The processed material also contained larger, millimetre-scale fibre aggregates, which may have influenced its dispersion and interaction with the cementitious matrix.

The preparation procedure presented in Figure 2 involved mechanical processing without chemical modification. This approach preserved the characteristics of untreated waste-paper fibres while potentially producing variations in fibre size, morphology, and dispersion. Fibre agglomeration may occur when mechanically processed fibres are incorporated into semi-dry cementitious mixtures, particularly when insufficient mixing water is available to promote uniform distribution. Such agglomerates can act as low-density inclusions, potentially creating localized voids and reducing the effectiveness of bonding between fibres and the cement paste. Similar observations have been reported in fibre-modified pervious concrete, where fibre agglomeration contributed to localized weaknesses within the porous matrix [17].

Nevertheless, the extent of fibre agglomeration and its influence on interfacial bonding were not directly quantified in the present study.

Particle-size variation may also influence the microstructure of the cementitious matrix. Fine cellulose particles could potentially occupy small voids or modify local particle packing, as demonstrated in previous investigations of waste-paper-derived nanocellulose incorporated into mortar [5]. However, the proportion of nanoscale particles within the bulk processed fibre was not determined, preventing a quantitative assessment of their contribution to pore refinement or cement hydration. Conversely, larger fibre fragments and aggregates may contribute to increased void formation by disrupting the continuity of the sand–cement matrix. Therefore, the observed particle-size distribution provides preliminary information about the processed material but does not independently establish the mechanisms responsible for changes in paving block properties.

Another important characteristic of waste-paper fibre is its hydrophilic nature, which may influence moisture distribution, cement hydration, and pore development. Previous studies have demonstrated that cellulose-based fibres can exhibit substantial water absorption, potentially affecting the mechanical and physical properties of cementitious composites [3, 6]. In the present study, the nominal water-to-cement ratio was maintained at 0.30 without additional correction for fibre absorption. Consequently, the fibres may have absorbed part of the available mixing water, potentially affecting local workability, compaction, and hydration conditions. Moisture exchange between the fibres and surrounding cement paste during curing and drying may also influence interfacial void formation. Conversely, retained moisture within the fibres could potentially contribute to internal curing, although this mechanism was not experimentally investigated.

Overall, the characteristics of the processed waste-paper fibres suggest that particle-size heterogeneity, fibre agglomeration, and moisture absorption may collectively influence the pore structure and mechanical performance of the paving blocks. However, these mechanisms remain hypothetical because fibre water absorption, solid density, and microstructural characteristics were not directly measured. Further investigations incorporating optical microscopy, scanning electron microscopy, fibre absorption measurements, and fractured-surface analysis would provide stronger evidence of fibre–matrix interactions and the mechanisms governing porosity and strength development.

3.2. Mechanical Performance.

The physical and mechanical results are summarised in Table 2 and Figure 4. The control mixture produced a mean compressive strength of 37.28 MPa with an individual minimum of 35.00 MPa. Waste-paper fibre reduced the mean compressive strength to 21.28 MPa at 5%, 25.40 MPa at 10%, 22.53 MPa at 15%, and 18.18 MPa at 20%. Flexural strength decreased from 6.25 MPa for the control to 4.00, 3.53, 3.25, and 4.15 MPa at 5%, 10%, 15%, and 20%. the control mixture achieved the highest mean compressive strength (37.28 MPa), with a minimum individual value of 35.00 MPa. Incorporating waste-paper fibre reduced the mean compressive strength to 21.28, 25.40, 22.53, and 18.18 MPa at substitution levels of 5%, 10%, 15%, and 20%, respectively. These values represent reductions of approximately 32–51% relative to the control, indicating a substantial decrease in compressive resistance following fibre incorporation. Flexural strength exhibited a similar overall reduction, decreasing from 6.25 MPa in the control mixture to 4.00, 3.53, 3.25, and 4.15 MPa at the corresponding

substitution levels. However, the response was not strictly monotonic, suggesting that fibre content alone did not fully explain the observed differences in mechanical performance.

Table 2. Physical and Mechanical Properties of Paving Blocks at 28 Days (Mean Values; N = 10 Per Property and Mixture).

Mix	Compressive strength (MPa)	SD (MPa)	CoV (%)	Flexural strength (MPa)	SD (MPa)	CoV (%)	Porosity (%)	Water absorption (%)	Dry density (kg/m³)
0%	37.28	1.84	4.9	6.25	0.76	12.2	11.99	5.31	2,262
5%	21.28	6.12	28.8	4	0.74	18.4	14.96	7.83	1,926
10%	25.4	5.68	22.4	3.53	0.61	17.2	16.2	8.3	1,966
15%	22.53	5.86	26	3.25	0.67	20.5	17.41	8.86	1,974
20%	18.18	3.44	18.9	4.15	0.52	12.4	17.87	9.23	1,941

The distributions of compressive and flexural strength measurements are illustrated in Figure 4, which presents specimen-level variability and statistical groupings for the five mixtures. The boxplots indicate differences in median strength, interquartile ranges, and overall dispersion, providing additional information beyond the mean values. The control mixture exhibited comparatively consistent compressive strength, whereas the fibre-containing mixtures showed greater variability, particularly at substitution levels of 5–15%. This pattern suggests that incorporating mechanically processed waste-paper fibre may increase heterogeneity within the cementitious matrix, potentially affecting the consistency of mechanical performance.

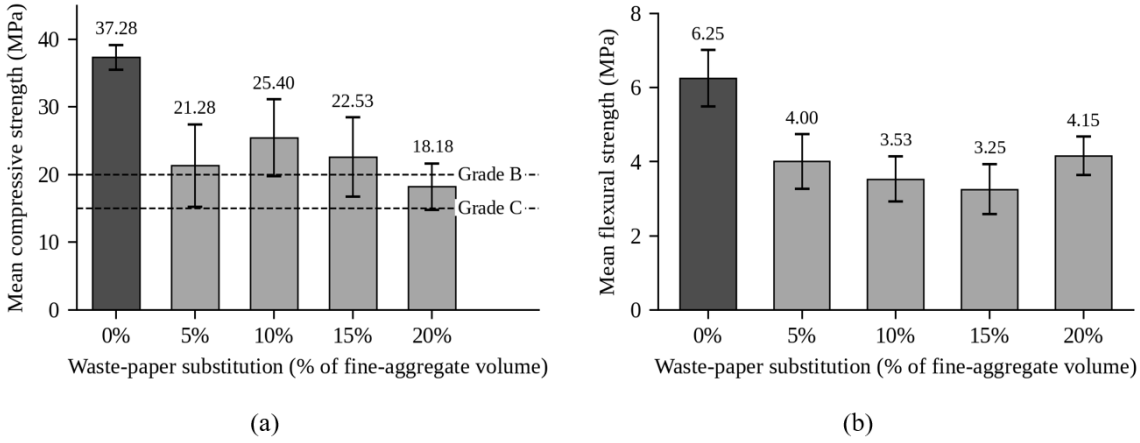


Figure 4. (a) Compressive strength and (b) flexural strength of paving blocks at 28 days. Boxes show the median and interquartile range, whiskers the range, diamonds the mean, and dots the individual specimens (n = 10). Letters above the boxes denote homogeneous groups ($p > 0.05$) from Games–Howell (compressive) and Tukey (flexural) comparisons.

To determine whether the observed differences among mixtures were statistically significant, analysis of variance (ANOVA) was performed for compressive strength, flexural strength, and open porosity. The results are presented in Table 3, together with eta-squared effect sizes, Bartlett's tests for homogeneity of variance, and Welch's ANOVA results. the mixture composition had a statistically significant effect on compressive strength, flexural strength, and open porosity ($p < 0.001$). The eta-squared values were 0.67, 0.74, and 0.57, respectively, indicating large effects and suggesting that mixture composition accounted for

approximately 57–74% of the observed variation in these properties within the experimental dataset. Bartlett's tests indicated unequal variances for compressive strength ($p = 0.010$) and open porosity ($p = 0.025$), supporting the use of Welch's ANOVA as a more robust assessment. Welch's ANOVA confirmed statistically significant differences among mixtures for both properties ($p < 0.001$). In contrast, flexural strength satisfied the homogeneity-of-variance assumption (Bartlett $p = 0.816$), supporting the application of conventional ANOVA and Tukey's post hoc procedure.

Table 3. Statistical Analysis of Differences Among Mixtures.

Property	ANOVA F	p-value	Eta-squared	Bartlett p-value	Welch F	Welch p-value
Compressive strength	22.78	<0.001	0.67	0.01	70.97	<0.001
Flexural strength	31.75	<0.001	0.74	0.816	24.11	<0.001
Open porosity	15.09	<0.001	0.57	0.025	34.56	<0.001

Pairwise comparisons were subsequently conducted to identify differences between individual mixtures. Table 4 presents the mean differences, 95% confidence intervals, and adjusted p-values obtained using Games–Howell comparisons for compressive strength and Tukey's procedure for flexural strength. The pairwise comparisons in Table 4 demonstrate that every fibre-containing mixture exhibited significantly lower compressive and flexural strength than the control ($p < 0.001$). The control exceeded the modified mixtures by 11.88–19.10 MPa in compressive strength and 2.10–3.00 MPa in flexural strength. However, differences among the fibre-containing mixtures were less consistent. For compressive strength, only the comparison between 10% and 20% substitution was statistically significant (mean difference = 7.22 MPa; 95% CI: 0.73–13.71 MPa; $p = 0.026$). Similarly, the only significant flexural strength difference among fibre-containing mixtures occurred between 15% and 20% substitution (mean difference = −0.90 MPa; 95% CI: −1.75 to −0.05 MPa; $p = 0.032$). These results indicate that the most robust mechanical response was the reduction in strength following fibre incorporation, whereas the differences among individual fibre substitution levels were comparatively uncertain.

Table 4. Pairwise comparisons of mixture means (mean difference = first mix − second mix; 95% confidence intervals computed from the mixture means and standard deviations; n = 10 per mixture). Compressive strength: Games–Howell; flexural strength: Tukey.

Comparison	Δ Compressive (MPa)	95% CI (MPa)	p	Δ Flexural (MPa)	95% CI (MPa)	p
0% − 5%	16	9.42 to 22.58	<0.001	2.25	1.40 to 3.10	<0.001
0% − 10%	11.88	5.76 to 18.00	<0.001	2.72	1.87 to 3.57	<0.001
0% − 15%	14.75	8.44 to 21.06	<0.001	3	2.15 to 3.85	<0.001
0% − 20%	19.1	15.25 to 22.95	<0.001	2.1	1.25 to 2.95	<0.001
5% − 10%	−4.12	−12.11 to 3.87	0.539	0.47	−0.38 to 1.32	0.519
5% − 15%	−1.25	−9.35 to 6.85	0.989	0.75	−0.10 to 1.60	0.104
5% − 20%	3.1	−3.81 to 10.01	0.64	−0.15	−1.00 to 0.70	0.987
10% − 15%	2.87	−4.93 to 10.67	0.798	0.28	−0.57 to 1.13	0.88
10% − 20%	7.22	0.73 to 13.71	0.026	−0.62	−1.47 to 0.23	0.246
15% − 20%	4.35	−2.31 to 11.01	0.303	−0.90	−1.75 to −0.05	0.032

The reduction in mechanical strength is consistent with previous studies on waste-derived cellulose fibre concrete, which reported strength deterioration at higher fibre contents [6].

Similar trends have been observed in porous cementitious materials, where increased void content reduces matrix continuity and load-bearing capacity [8, 12, 13]. Several mechanisms may explain the observed reductions. Replacing dense mineral aggregates with lightweight cellulose fibres may weaken the aggregate skeleton, while fibre absorption may alter local moisture availability and compaction conditions [3, 6]. In addition, incomplete fibre–paste bonding, fibre shrinkage, and localized agglomeration may contribute to interfacial void formation and stress concentration. Previous investigations of fibre-modified pervious concrete have similarly suggested that fibre agglomeration can offset potential reinforcement benefits [17]. However, these mechanisms remain plausible interpretations because direct microstructural and interfacial measurements were not performed.

An interesting observation was the higher mean compressive strength of the 10% mixture (25.40 MPa) compared with the 5% (21.28 MPa) and 15% (22.53 MPa) mixtures, despite its greater porosity relative to the 5% mixture. Nevertheless, Table 4 indicates that these differences were not statistically significant ($p = 0.539$ and 0.798, respectively). The relatively large within-mixture standard deviations, ranging from 5.68 to 6.12 MPa for the 5–15% mixtures, further suggest that the apparent strength increase at 10% substitution may partly reflect experimental variability rather than a consistent improvement. Differences in fibre dispersion, local moisture distribution, pore arrangement, and manual compaction may have contributed to this variability. Previous research has emphasized that pore size, distribution, and connectivity can influence mechanical performance independently of total porosity [17, 19], while fibre agglomeration may affect local stiffness and failure initiation [17, 21].

A different response was observed in flexural strength, where the 20% mixture achieved a higher mean value (4.15 MPa) than the 10% (3.53 MPa) and 15% (3.25 MPa) mixtures despite having the highest porosity. The difference between the 15% and 20% mixtures was statistically significant ($p = 0.032$), whereas the difference between the 10% and 20% mixtures was not ($p = 0.246$). One possible explanation is fibre bridging, whereby fibres crossing developing cracks transfer tensile stresses and delay crack propagation. Such behavior has been discussed in previous studies of fibre-reinforced pervious concrete [17, 21]. However, the relatively short testing span of 120 mm, corresponding to a span-to-depth ratio of 2, may introduce substantial shear contributions. Therefore, the measured flexural strengths should primarily be interpreted as comparative experimental values rather than pure bending resistance. Fracture-surface observations, fibre pull-out tests, and load–deflection measurements would be necessary to verify the proposed bridging mechanism.

The variability of mechanical performance also has important implications for practical manufacturing. As indicated in Table 2, the compressive strength CoV increased from 4.9% in the control mixture to 18.9–28.8% in the fibre-containing mixtures. Flexural strength variability was also generally higher, with CoV values of 12.4–20.5%, compared with 12.2% for the control. Assuming an approximately normal strength distribution, the indicative fifth-percentile compressive strength, estimated as the mean minus 1.645 standard deviations, would be approximately 31–47% lower than the mean for the fibre-containing mixtures, compared with approximately 8% for the control. These estimates are illustrative rather than validated characteristic strengths. Nevertheless, they highlight the potential difficulty of achieving consistent production quality when using mechanically processed waste-paper fibres.

Overall, the findings demonstrate that waste-paper fibre substitution substantially reduced the mechanical strength of paving blocks while increasing variability among

specimens. Although some non-monotonic responses were observed, particularly at 10% substitution for compressive strength and 20% for flexural strength, most differences among fibre-containing mixtures were not statistically significant. The results suggest that practical applications would require improved control of fibre moisture, particle size, mixing sequence, dispersion uniformity, and compaction energy. Further microstructural investigations are also necessary to distinguish the effects of fibre agglomeration, pore characteristics, and fibre–matrix interactions on mechanical performance.

3.3. Porosity, Water Absorption, and Density.

Open porosity increased from 11.99% in the control to 14.96%, 16.20%, 17.41%, and 17.87% at 5%, 10%, 15%, and 20% substitution (Table 2, Figure 5), a statistically significant effect ($\eta^2 = 0.57$; Table 3). Porosity was approximately linear in substitution level within the investigated range ($R^2 = 0.91$), but this relationship rests on five levels and should not be extrapolated beyond 0–20%. The largest relative increase (+2.97 percentage points) occurred at the first 5% of fibre; subsequent 5% steps added 1.24, 1.21, and 0.46 points. Water absorption rose from 5.31% to 7.83–9.23%, and dry density fell from 2,262 kg/m³ to 1,926–1,974 kg/m³, a reduction of about 13–15%.

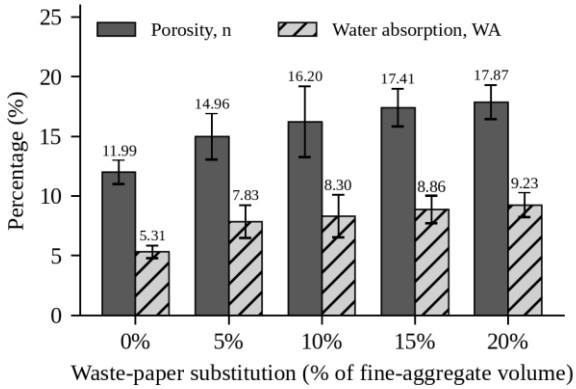


Figure 5. Mean (a) Open Porosity, (B) Water Absorption, and (C) Dry Density of Paving Blocks at 28 Days. Error Bars Show the Standard Deviation of the Ten Specimens Per Mixture.

Porosity, absorption, and density are not independent measurements. In an immersion test, the saturated uptake defines both porosity (water volume per specimen volume) and absorption (water mass per dry mass), so absorption ≈ porosity × water density / dry density. Applying this identity to the mixture means reproduces the reported absorption within 0.1 percentage points (for example, 14.96 × 1,000 / 1,926 = 7.77% against 7.83% measured at 5%; 17.87 × 1,000 / 1,941 = 9.21% against 9.23% at 20%). The rise in absorption from 5.31% to 9.23% (+74%) is therefore larger than the rise in porosity (+49%) because the denominator, dry mass, simultaneously decreases. Absorption does not add independent information on pore structure; its practical value is in relating to durability classes and to the moisture demand of the fibre.

Four contributions to the higher porosity can be distinguished, although their individual shares were not measured. (i) Aggregate displacement: removing sand reduces particle packing and leaves space that paste cannot fill in a semi-dry, manually compacted mixture. (ii) Bulk-volume substitution: because the replacing volume is loose-fibre volume, most of the replaced volume is air held between fibres (Section 2.3), and the effective paste volume fraction is

increased only slightly. (iii) Fibre clumps: clumps that are not completely surrounded by paste retain interior and boundary voids. (iv) The fibre itself: cellulose cell walls and lumens take up water during immersion, so some water recorded as "open porosity" is imbibed within the fibre rather than held in voids of the cement matrix. Consequently, open porosity in these blocks mixes true matrix voids with fibre-bound water, which has implications for interpreting the porosity–strength relationship (Section 3.4) and hydraulic function (below). Higher porosity also coincides with higher absorption, consistent with the water sensitivity reported for cellulose-fibre composites [3, 6].

Dry density did not decrease monotonically with fibre content: it dropped by 336 kg/m³ (−14.9%) at 5%, then rose to 1,966 and 1,974 kg/m³ at 10% and 15% before falling to 1,941 kg/m³ at 20%. Three observations help to interpret this. First, the fibre mass is negligible (at most 2.65 kg/m³), so density is controlled by the sand removed and by how well the remaining solids are packed, not by the fibre mass itself. Removing sand alone would lower density by only about 3% for each 5% step if the moulded volume were constant, whereas the observed first-step reduction (≈15%) is five times larger, implying that the first fibre increment sharply disrupts packing and compaction. Second, the differences among the 5–20% mixtures (up to 48 kg/m³, about 2.4% of the mean) are an order of magnitude smaller than the drop from the control, and they are likely to lie within the specimen-to-specimen variation of manually compacted blocks. Third, porosity continues to increase through 10–20% while density does not, showing that porosity and density respond to different aspects of the structure (water-accessible void volume versus total mass per volume, which also depends on moulded volume and moisture state). The data do not allow the non-monotonic density trend to be resolved into compaction, moisture, or fibre-distribution effects; specimen-level density standard deviations and tests under controlled compaction energy would be needed.

Pervious concrete is generally reported to have a porosity of about 15–25% [17]. The open porosity of the waste-paper blocks (14.96–17.87%) therefore lies in the lower part of that range, while the control (11.99%) lies below it. In a basalt-gravel pervious concrete without sand, Liu et al. measured volumetric porosities of 14.5–17.8% with compressive strengths of 40.3 MPa at 14.5% and 24.0 MPa at 17.8% [17]. At similar porosity, the present blocks were weaker: 21.3 MPa at 14.96% and 18.2 MPa at 17.87%. The difference reflects the very different systems: Liu et al. used a coarse-aggregate skeleton, a low water-to-binder ratio with supplementary cementitious materials and a superplasticiser, and 150 mm cubes, whereas the present blocks are sand–cement matrices with a hydrophilic fibre, manual compaction, and a 200 × 100 mm loaded face. The contrast illustrates that porosity alone does not define strength; the way in which the porosity is created matters. It also differs in direction from basalt fibre, which slightly reduced porosity when added to a pervious concrete [17], whereas the cellulose fibre in the present study increased it because it displaced aggregate and has a porous structure of its own.

Open porosity is not equivalent to effective, interconnected porosity: water-accessible voids may include dead-end pores, fibre-bound water, and pores that contribute little to through-flow, and permeability depends on pore size and connectivity as well as total porosity [14, 18]. Infiltration rate and permeability coefficient were not measured. The blocks are therefore described as porous paving blocks, not validated permeable pavement units. Even a block with high open porosity may clog during service [15, 16].

3.4. Porosity and mechanical performance.

Figure 6 presents the relationship between mixture-mean porosity and strength, with the fitted line and its 95% confidence band; circles are mixture means (each the mean of 10 specimens), and individual specimens are not shown because porosity and strength were measured on different specimens. Error bars give the standard deviation of strength. Across the five mixture means, compressive strength decreased as porosity increased (Pearson r = −0.89, p = 0.045; Table 5). The regression explained about 79% of the variance of the five means. Within the investigated porosity range of 11.99–17.87%, each 1-percentage-point increase in porosity corresponded to a 2.78 MPa lower mean compressive strength, but the 95% confidence interval for this slope is wide (−5.43 to −0.13 MPa per percentage point), with the upper limit almost reaching zero. The corresponding flexural analysis gave r = −0.86 (p = 0.065), $R^2 \approx 0.73$, and a slope of −0.43 MPa per percentage point (95% CI: −0.91 to +0.05), which includes zero and therefore does not meet the 0.05 significance level.

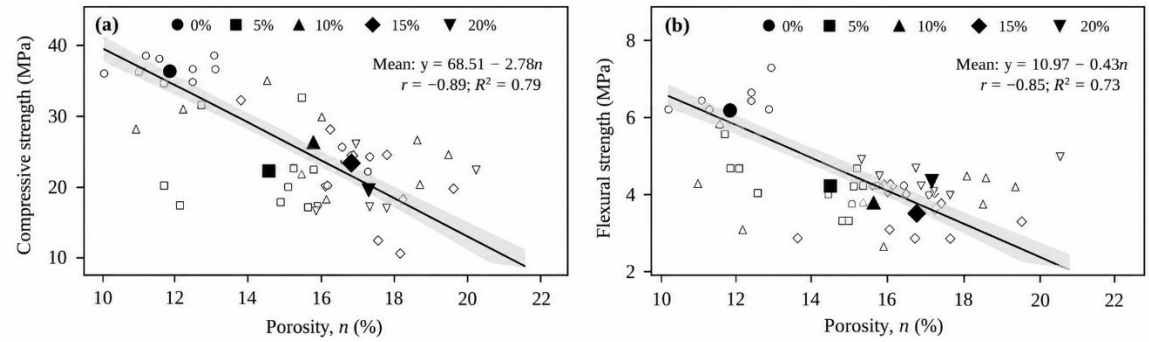


Figure 6. Figure 6. Relationship between open porosity and (a) compressive strength and (b) flexural strength of paving blocks. Solid lines indicate linear regression; shaded bands represent 95% confidence intervals.

R^2 describes how closely the five mean points lie on a line; it does not, by itself, indicate how likely such a fit is to arise by chance. That likelihood depends on the number of points. With five means the regression has only three degrees of freedom, so r must exceed 0.878 to reach $p < 0.05$. The flexural correlation (r = 0.86) lies just below this threshold, so a fit that explains 73% of the variance can still be non-significant and carry a confidence interval that includes zero. The compressive correlation (r = 0.89) is only just above it. Both results should therefore be read as suggestive rather than conclusive.

The Spearman correlations were weaker (−0.70 for compressive strength, p = 0.19; −0.40 for flexural strength, p = 0.50). The rank-based coefficients are lower because the ordering of strength among the waste-paper mixtures does not follow the ordering of porosity (the 10% mixture is stronger than the 5% mixture in compression, and the 20% mixture is stronger than the 10% and 15% mixtures in flexure). With only five observations, Spearman's coefficient also has little power, so the difference between Pearson and Spearman is a warning that the Pearson result is influenced by the large separation between the control and the other mixtures. Sensitivity analysis. Two patterns emerge from Table 5. First, when any one waste-paper mixture is omitted, the compressive slope remains similar (−2.66 to −3.06 MPa per point), but the p-value ranges from 0.012 to 0.153, so statistical significance depends on which point is removed. The same holds for flexure (slopes −0.40 to −0.57; p = 0.024 to 0.177). Second, when the control is omitted, the relationship largely disappears: for the four waste-paper mixtures, the compressive slope falls to −0.90 MPa per point (r = −0.39) with a confidence interval that

spans from −7.3 to +5.5 MPa, and the flexural correlation is only −0.13. This confirms that the strong overall relationship is mainly driven by the contrast between the control and the fibre mixtures. Within the waste-paper group, the porosity range is narrow (14.96–17.87%, 2.9 points), and the porosity-related strength change implied by even the full-data slope (about 8 MPa) is comparable with the within-mixture standard deviation (3.4–6.1 MPa), so the within-group analysis has low power to detect a porosity effect and cannot exclude one.

Table 5. Robustness of the Porosity–Strength Relationship at the Mixture-Mean Level (Slope in Mpa Per Percentage-Point of Porosity).

Data set	Property	n (means)	Slope	95% CI of slope	Pearson r	R^2	p
All mixtures (0–20%)	Compressive	5	−2.78	−5.43 to −0.13	−0.89	0.79	0.045
All mixtures (0–20%)	Flexural	5	−0.43	−0.91 to 0.05	−0.86	0.73	0.065
Waste-paper mixtures only (5–20%)	Compressive	4	−0.90	−7.31 to 5.51	−0.39	0.15	0.608
Waste-paper mixtures only (5–20%)	Flexural	4	−0.04	−1.00 to 0.92	−0.13	0.02	0.866
Leave-one-out, control retained (range over 4 subsets)	Compressive	4	−2.66 to −3.06	–	−0.85 to −0.99	–	0.012 to 0.153
Leave-one-out, control retained (range over 4 subsets)	Flexural	4	−0.40 to −0.57	–	−0.82 to −0.98	–	0.024 to 0.177

The regression represents an association across mixture means, not a causal effect of porosity. At least four limitations apply. (i) Only five mixture means are available, giving three degrees of freedom and wide confidence intervals. (ii) Porosity and fibre content are almost perfectly collinear ($R^2 = 0.91$), so the effect of void volume cannot be separated from other effects of the fibre, such as its low stiffness, its weak interface with the paste, and its moisture demand. (iii) Porosity and strength were measured on different specimens, and the regression treats mean porosity as exact, ignoring its specimen-to-specimen uncertainty; specimen-level regression was impossible. (iv) Open porosity includes fibre-bound water (Section 3.3), so "porosity" here is not identical to the matrix void fraction that governs fracture in porous concrete. The fitted equation should therefore not be used as a design relationship; it is a quantitative summary of the trend in this dataset.

The direction of the relationship agrees with research showing that porosity is a major but not exclusive determinant of strength in porous concrete, with aggregate size, pore size, pore connectivity, density, compaction, and water-to-cement ratio also modifying the response [8,9,11–14]. Pore size, spacing, and distribution were shown to influence compressive response beyond total porosity [17,19], and strength was related to porosity in mixtures proportioned for desired porosities [20]. Quantitatively, the data of Liu et al. [17] for no-sand pervious concrete imply a decline of roughly 4.9 MPa per percentage point of porosity between 14.5% and 17.8% (40.3 to 24.0 MPa), a coarser comparison than a regression but steeper than the −2.78 MPa per point found here (95% CI: −5.43 to −0.13), which falls within the same order of magnitude and includes values close to theirs. The two datasets differ in aggregate size, binder composition, and specimen geometry, so the comparison is indicative only.

An exponential relationship was also considered. Although the original-scale exponential fit produced an R^2 slightly higher than the linear model, the difference cannot be regarded as meaningful with five observations. The linear form was retained because it is simpler to interpret within the experimental range.

3.5. Comparative Performance And Candidate Composition.

The control mixture achieved a mean compressive strength of 37.28 MPa, whereas the waste-paper fibre mixtures exhibited values ranging from 18.18 to 25.40 MPa. These strengths overlap with ranges commonly reported for porous concrete in previous reviews [13, 14], although they were lower than those reported for coarse-aggregate pervious concrete at comparable porosity levels [17]. To identify potentially suitable mixture compositions, three screening criteria were established: a minimum mean compressive strength of 20 MPa, corresponding to the Grade B mean-strength requirement for parking-area paving blocks under SNI 03-0691-1996; a minimum open porosity of 15%, representing the lower range commonly reported for pervious concrete [17]; and a maximum water absorption of 10%, corresponding to the Grade D mean-absorption limit under SNI 03-0691-1996. These criteria were adopted as preliminary performance benchmarks rather than definitive design requirements because the standard primarily addresses conventional paving blocks and does not establish hydraulic performance requirements for permeable pavement materials.

The screening results are presented in Table 6, which summarizes mean compressive strength, strength variability, indicative fifth-percentile strength, flexural strength, open porosity, water absorption, and the corresponding SNI classifications. The indicative fifth-percentile compressive strength was estimated using the mean minus 1.645 standard deviations, assuming an approximately normal strength distribution. This additional parameter was included to account for the relatively high variability observed in fibre-containing mixtures, although it should not be interpreted as a formally established characteristic strength.

Table 6. Screening of Candidate Mixtures using Mechanical Properties, Porosity, and SNI 03-0691-1996 Benchmarks.

Mix (%)	Mean fc (MPa)	CoV (%)	5th-percentile fc (MPa)	Flexural (MPa)	Porosity (%)	Absorption (%)	SNI fc	SNI absorption	Screening result
0	37.28	4.9	34.25	6.25	11.99	5.31	B	B	Not selected: insufficient porosity
5	21.28	28.8	11.21	4.00	14.96	7.83	B	C	Not selected: porosity below 15%
10	25.40	22.4	16.06	3.53	16.20	8.30	B	D	Candidate
15	22.53	26.0	12.89	3.25	17.41	8.86	B	D	Candidate: lower strength than 10%
20	18.18	18.9	12.52	4.15	17.87	9.23	C	D	Not selected: strength below 20 MPa

Note: fc = compressive strength; CoV = coefficient of variation. SNI classifications are based on mean values and are provided for comparison only. The fifth-percentile estimates assume an approximately normal distribution and do not establish compliance with characteristic-strength requirements.

As shown in Table 6, the 10% and 15% waste-paper fibre mixtures satisfied all three preliminary screening criteria. The 5% mixture exhibited slightly insufficient porosity

(14.96%), whereas the 20% mixture failed to achieve the minimum mean compressive strength of 20 MPa. Among the two candidate mixtures, the 10% substitution level demonstrated a more favorable combination of mechanical and physical properties, with higher mean compressive strength (25.40 versus 22.53 MPa), lower strength variability (22.4% versus 26.0%), lower water absorption (8.30% versus 8.86%), and higher indicative fifth-percentile strength (16.06 versus 12.89 MPa). However, the differences between the 10% and 15% mixtures were not statistically significant for compressive strength ($p = 0.798$) or flexural strength ($p = 0.880$), as reported in Table 4. Therefore, the 10% mixture should be considered a promising candidate rather than a statistically confirmed optimum composition.

Based on mean compressive strength, the mixtures containing 0–15% waste-paper fibre corresponded to Grade B, whereas the 20% mixture corresponded to Grade C under SNI 03-0691-1996. However, some individual specimens from the 5–15% mixtures exhibited compressive strengths below the Grade B individual minimum of 17 MPa. The indicative fifth-percentile strength of the 10% mixture was also approximately 16.06 MPa, suggesting that consistent compliance with Grade B requirements cannot be established. Regarding water absorption, the control mixture corresponded to Grade B, the 5% mixture to Grade C, and the 10–20% mixtures to Grade D. These classifications provide comparative performance benchmarks but do not establish full compliance with the standard, particularly because other required properties and long-term performance characteristics were not comprehensively evaluated.

Overall, the findings suggest that 10% waste-paper fibre substitution offers a potentially favorable balance between mechanical strength, open porosity, and water absorption. This composition may be considered for further investigation in low-load paving applications, including pedestrian areas, residential yards, and selected parking facilities. Nevertheless, the suitability of the proposed mixture remains preliminary because open porosity alone does not establish water infiltration capacity or hydraulic connectivity. Additional investigations involving permeability, abrasion resistance, wetting–drying durability, long-term mechanical performance, and production quality control are necessary before practical implementation. Consequently, the proposed 10% substitution level should be regarded as a candidate for further optimization and validation rather than a confirmed design recommendation.

3.6. Implications for Sustainable Construction.

The incorporation of waste-paper fibres into paving blocks offers potential environmental benefits through reduced natural sand consumption and the utilization of residual paper waste. At 10% volumetric substitution, approximately 135 kg of sand per cubic metre of mixture was replaced with 0.052 m^3 of loose waste-paper fibre, corresponding to a sand reduction of approximately 8.1 kg/m^2 for a pavement thickness of 60 mm. At 20% substitution, the corresponding reductions increased to 270 kg/m^3 and 16.2 kg/m^2. However, because of the low bulk density of the processed fibre (25.46 kg/m^3), the actual quantity of waste paper incorporated remained relatively small, ranging from 1.32 kg/m^3 at 10% substitution to 2.65 kg/m^3 at 20%. These quantities correspond to approximately 0.08 and 0.16 kg/m^2 of pavement, respectively. Therefore, the primary resource-efficiency benefit is the reduction in natural sand consumption rather than substantial waste-paper diversion per unit area. Previous studies have similarly emphasized the potential of residual paper fibres for value-added construction applications while recognizing the associated mechanical and durability challenges [2, 6].

The comparative environmental and engineering implications of conventional and waste-paper-modified paving blocks are summarized in Table 7. The comparison considers material consumption, density, mechanical performance, porosity, water absorption, and practical limitations. The calculated material savings are based on nominal mixture proportions and an assumed constant pavement thickness of 60 mm, without experimental verification of actual production yields.

Table 7. Comparison of Conventional and Waste-Paper Paving Blocks: Benefits, Trade-Offs, and Limitations.

Parameter	Control (0%)	10% substitution	20% substitution	Interpretation
Cement content (kg/m³)	450	450	450	No cement reduction
Sand content (kg/m³)	1,350	1,215	1,080	Sand consumption reduced by 10–20%
Sand saved (kg/m²)	0	8.1	16.2	Reduced natural aggregate demand
Waste paper used (kg/m²)	0	0.08	0.16	Limited waste diversion per unit area
Sand saved per block (kg)	0	0.16	0.32	Based on 200 × 100 × 60 mm blocks
Dry density (kg/m³)	2,262	1,966	1,941	Approximately 13–14% reduction
Dry mass per block (kg)	2.71	2.36	2.33	Lower handling and transportation mass
Compressive strength (MPa)	37.28	25.40	18.18	Strength reductions of 32–51%
Flexural strength (MPa)	6.25	3.53	4.15	Reduced bending resistance
Compressive strength CoV (%)	4.9	22.4	18.9	Increased production variability
Open porosity (%)	11.99	16.20	17.87	Increased void content
Water absorption (%)	5.31	8.30	9.23	Increased moisture sensitivity
Infiltration, durability, and clogging	Not evaluated	Not evaluated	Not evaluated	Further testing required

As shown in Table 7, waste-paper fibre substitution reduced both sand consumption and dry density, suggesting potential benefits for natural resource conservation and material handling. At 10% substitution, the dry density decreased from 2,262 to 1,966 kg/m³, corresponding to a reduction of approximately 13%. However, these benefits were accompanied by a 32% reduction in mean compressive strength and increased water absorption. At 20% substitution, the density reduction was slightly greater, but compressive strength decreased by approximately 51% relative to the control. These findings demonstrate a clear trade-off between resource efficiency and mechanical performance. Furthermore, because cement consumption remained constant across all mixtures, the environmental benefits of sand replacement cannot be assumed to outweigh the impacts associated with cement production and fibre processing. A comparative life-cycle assessment, preferably based on equivalent mechanical performance and service life, would be necessary to establish the net environmental benefits.

The practical implementation of waste-paper fibre paving blocks also presents several manufacturing challenges. The laboratory preparation process involved shredding, soaking, mechanical pulping, sun-drying, and grinding, whereas industrial production would require more efficient processing and controlled energy and water consumption. The extremely low loose bulk density of the fibre means that approximately 39 m³ of storage volume would be required for one tonne of processed material, potentially increasing transportation, storage, and handling requirements. Densification or pelletization could improve logistical efficiency, although these processes would require additional energy and might alter fibre dispersion characteristics. Furthermore, the relatively high coefficients of variation observed in fibre-

containing mixtures indicate the need for improved quality control, particularly regarding fibre moisture content, particle size, mixing uniformity, and compaction energy.

Long-term durability and hydraulic performance remain important considerations for future applications. Cellulose fibres may undergo physical or chemical changes within the alkaline cementitious environment, while repeated wetting and drying could affect fibre–matrix bonding and pore structure. These potential degradation mechanisms require direct experimental verification through accelerated aging, wetting–drying cycles, and microstructural characterization. Similarly, although waste-paper substitution increased open porosity, the results do not establish sufficient pore connectivity or infiltration capacity for permeable pavement applications. Previous studies have demonstrated that permeable pavement performance may decline over time because of clogging, although appropriate maintenance can partially restore hydraulic functionality [15, 16]. Therefore, permeability, infiltration, abrasion resistance, and long-term durability should be evaluated before considering practical implementation. Overall, waste-paper fibre substitution represents a potentially useful resource-efficiency strategy, but its environmental and engineering feasibility depends on achieving an acceptable balance among material savings, mechanical reliability, production efficiency, and long-term performance.

4. Conclusions

This study demonstrated that replacing 5–20% of fine-aggregate volume with mechanically processed waste-paper fibres increased open porosity (11.99–17.87%) and water absorption (5.31–9.23%) while reducing dry density by approximately 13–15%. Compressive strength decreased from 37.28 to 18.18–25.40 MPa, while flexural strength declined from 6.25 to 3.25–4.15 MPa. Strength variability also increased substantially. Regression analysis revealed that each percentage-point increase in porosity was associated with a 2.78 MPa reduction in compressive strength ($p = 0.045$), whereas the relationship with flexural strength was not statistically significant ($p = 0.065$). However, these associations were primarily influenced by differences between the control and fibre-containing mixtures. Based on mechanical strength, porosity, and water absorption criteria, the 10% mixture demonstrated the most favorable preliminary balance, achieving 25.40 MPa compressive strength, 16.20% porosity, and 8.30% water absorption. Nevertheless, this composition represents a candidate rather than a statistically established optimum. Future research should prioritize fibre dispersion, moisture control, specimen-level porosity–strength relationships, microstructural characterization, infiltration performance, and long-term durability before practical application in permeable pavement systems.

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Author Contributions

Pengki Suanto: Conceptualization, Methodology, Analysis, Writing – Original Draft, Funding Acquisition. Mulyadi Sugih Dharsono: Investigation, Data Collection, Testing. Nadia Diandra: Supervision, Methodology, Writing – Review and Editing. Rayesa Bimo Pasya: Data Collection, Testing, Visualization. Randhy Ramadhan Jaenudin: Statistical Analysis, Visualization, Writing – Review and Editing. All authors reviewed and approved the final manuscript.

Competing Interests

The authors declare that they have no competing financial, personal, or professional interests that could have influenced the research presented in this manuscript.

Declaration of AI-Assisted Technologies

The authors used AI-assisted tools to improve the language, grammar, and readability of the manuscript. All AI-assisted content was critically reviewed and verified by the authors, who take full responsibility for the accuracy, originality, and integrity of the published work. AI tools were not listed as authors.

References

[1] United Nations Environment Programme; International Solid Waste Association. (2024). Global Waste Management Outlook 2024: Beyond an Age of Waste – Turning Rubbish into a Resource; UNEP: Nairobi, Kenya. https://doi.org/10.59117/20.500.11822/44939.

[2] Lei, W.; Du, J.; Li, Z.; Fang, C.; Hou, J.; et al. (2024). Waste paper recycling and its application in modification of the green biodegradable material. *Industrial Crops and Products*, *222*, 119896. https://doi.org/10.1016/j.indcrop.2024.119896.

[3] Bencardino, F.; Mazzuca, P.; do Carmo, R.; Costa, H.; Curto, R. (2024). Cement-based mortars with waste paper sludge-derived cellulose fibers for building applications. *Fibers*, *12*, 13. https://doi.org/10.3390/fib12020013.

[4] Suanto, P.; Saloma; Nurjannah, S.A.; Ngian, S.P. (2025). Synthesis of nanocellulose as a sustainable construction material from waste paper using the alkaline method at low temperature. *Civil Engineering and Architecture*, *13*, 175–192. https://doi.org/10.13189/cea.2025.130110.

[5] Saloma; Nurjannah, S.A.; Saggaff, A.; Usman, A.P.; Suanto, P.; et al. (2025). Effect of waste paper-based nanocellulose synthesized at low temperatures on the microstructural properties of mortar. *Research on Engineering Structures & Materials*, 1609–1635. https://doi.org/10.17515/resm2025-1100ma0820rs.

[6] Patrisia, Y.; Gunasekara, C.; Setunge, S.; Mendis, P.; Nanayakkara, O. (2025). Multi-perspective evaluation of waste-derived cellulose fiber concrete: Engineering performance, microstructure and sustainability. *Sustainable and Resilient Infrastructure*. https://doi.org/10.1080/23789689.2025.2561203.

[7] Song, H.; Fan, S.; Che, J.; Yao, J.; Lee, Y. (2024). Physical and mechanical properties of pervious concrete incorporating municipal solid waste incineration bottom ash. *Journal of Building Engineering*, *96*, 110599. https://doi.org/10.1016/j.jobe.2024.110599.

[8] Sánchez-Mendieta, C.; Galán-Díaz, J.J.; Martínez-Lage, I. (2024). Relationships between density, porosity, compressive strength and permeability in porous concretes: Optimization of properties through control of the water-cement ratio and aggregate type. *Journal of Building Engineering*, *97*, 110858. https://doi.org/10.1016/j.jobe.2024.110858.

[9] Ahilash, N.; Shobijan, J.; Arunan, M.; Subramaniam, D.N. (2024). Investigation and prediction of impact of aggregate size and shape on porosity and compressive strength of pervious concrete. *International Journal of Pavement Engineering*, *25*. https://doi.org/10.1080/10298436.2024.2405031.

[10] Öztürk, Ş.; Yılmaz, K.; Dinçer, A.E.; Kalpakı, V. (2024). Effect of urbanization on surface runoff and performance of green roofs and permeable pavement for mitigating urban floods. *Natural Hazards*, *120*, 12375–12399. https://doi.org/10.1007/s11069-024-06688-w.

[11] Ahmad, S.A.; Ahmed, H.U.; Rafiq, S.K.; Jafer, F.S.; et al. (2024). A comparative analysis of simulation approaches for predicting permeability and compressive strength in pervious concrete. *Low-carbon Materials and Green Construction*, *2*, 10. https://doi.org/10.1007/s44242-024-00041-x.

[12] Liu, F.; Li, Z.; Liu, B.; Yu, Z.; Li, Z.; et al. (2025). Experimental and numerical investigations on the influences of target porosity and w/c ratio on strength and permeability of pervious concrete. *Materials*, *18*, 3951. https://doi.org/10.3390/ma18173951.

[13] Abousnina, R.; Aljuaydi, F.; Benabed, B.; Almabrok, M.H.; Vimonsatit, V. (2025). A state-of-the-art review on the influence of porosity on the compressive strength of porous concrete for infrastructure applications. *Buildings*, *15*, 2311. https://doi.org/10.3390/buildings15132311.

[14] Hari, R.; Zhuge, Y.; Madhavan, M.K. (2025). Strength enhancements and quantitative paradigms in pervious concrete: A review. *Results in Engineering*, *27*, 106668. https://doi.org/10.1016/j.rineng.2025.106668.

[15] Huang, P.; Zhang, K.; Chui, T.F.M. (2025). Hydrologic performance of permeable pavements under extreme and regular rainfall conditions. *Journal of Hydrology*, *652*, 132653. https://doi.org/10.1016/j.jhydrol.2024.132653.

[16] Perez, O.; Chen, L.M.; Chen, J.W.; Lecher, T.J.; Simpson, L.A.; et al. (2025). Monitoring the permeability and evaluating the impact of cleaning on two permeable pavement systems. *Water*, *17*, 2140. https://doi.org/10.3390/w17142140.

[17] Liu, R.; Chi, Y.; Chen, S.; Jiang, Q.; Meng, X.; Wu, K.; Li, S. (2020). Influence of pore structure characteristics on the mechanical and durability behavior of pervious concrete material based on image analysis. *International Journal of Concrete Structures and Materials*, *14*, 29. https://doi.org/10.1186/s40069-020-00404-1.

[18] Neithalath, N.; Sumanasooriya, M.S.; Deo, O. (2010). Characterizing pore volume, sizes, and connectivity in pervious concretes for permeability prediction. *Materials Characterization*, *61*, 802–813. https://doi.org/10.1016/j.matchar.2010.05.004.

[19] Deo, O.; Neithalath, N. (2010). Compressive behavior of pervious concretes and a quantification of the influence of random pore structure features. *Materials Science and Engineering: A*, *528*, 402–412. https://doi.org/10.1016/j.msea.2010.09.024.

[20] Deo, O.; Neithalath, N. (2011). Compressive response of pervious concretes proportioned for desired porosities. *Construction and Building Materials*, *25*, 4181–4189. https://doi.org/10.1016/j.conbuildmat.2011.04.055.

[21] Hesami, S.; Ahmadi, S.; Nematzadeh, M. (2014). Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement. *Construction and Building Materials*, *53*, 680–691. https://doi.org/10.1016/j.conbuildmat.2013.11.070.

[22] Yang, J.; Jiang, G. (2003). Experimental study on properties of pervious concrete pavement materials. *Cement and Concrete Research*, *33*, 381–386. https://doi.org/10.1016/S0008-8846(02)00966-3.



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