International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V73I1P122

Volume 73 Issue 1, 255-265, January 2025

Original Article

Enhancing Mechanical and Physical Properties of Plastic Waste-Based Paving Stones through Recycled Plastic Bottle Fiber Addition

Guy Oyéniran Adeoti*[1], Bio Chéissou Koto Tamou[2], Edem Chabi[3], Peace Sèna Hounkpe[4]

[1,2,4]Laboratoire d'Essais et d'Études en Génie Civil (L2EGC), Département de Génie Civil, Ecole Nationale Supérieure des Travaux publiques, Université Nationale des Sciences, Technologies, Ingénierie et Mathématiques, République du Bénin.
[3]National University of Agriculture (UNA), Department of Plateau, Republic of Benin.

[*]Corresponding Author : adeotiguy@unstim.bj

Received: 12 February 2024 Revised: 02 August 2024 Accepted: 03 January 2025 Published: 31 January 2025

Abstract - *This study investigates the enhancement of mechanical and physical properties of paving stones manufactured from plastic waste, targeting potential applications as road surface materials. Initially, paving stones were produced using an artisanal method with varying plastic content ranging from 20% to 40% to identify the optimal plastic-to-sand ratio. The results indicated that a plastic content of 25% provided the best performance, achieving compressive and tensile strengths of 4.85 MPa and 1.38 MPa, respectively. In the subsequent phase, polyethylene terephthalate (PET) fibers derived from recycled plastic bottles were introduced in proportions of 0.5%, 1%, 1.5%, and 2% (relative to sand weight). These fibers, measuring 5 mm in diameter and 6 cm in length, significantly enhanced the mechanical properties of the paving stones, with compressive strength increasing to 10.68 MPa (over 120%) and tensile strength reaching 2.48 MPa (an improvement of 79%) at an optimal fiber incorporation rate of 1.5%. Furthermore, water absorption rates decreased with higher fiber content, reaching a minimum of 0.24%. Despite these advancements, the paving stones did not fully comply with the NF EN 1338 standard requirements for road applications. These findings emphasize the potential of recycled plastic waste in sustainable construction while highlighting the need for further research to optimize material properties and achieve industry standards.*

Keywords - *Fiber from plastic bottles, Mechanical properties, Paving stones, Plastic waste, Road surface, Sustainable construction materials.*

1. Introduction

Managing non-biodegradable plastic waste represents a significant environmental challenge, necessitating innovative solutions to mitigate its adverse impacts. One promising approach lies in repurposing plastic waste as an alternative material in the construction industry. However, previous studies on paving stones produced from melted plastic bags have highlighted subpar mechanical properties, particularly in terms of tensile strength, which limits their viability as structural components. Plastics, once celebrated as revolutionary materials in the 19th century, now dominate scientific discussions due to their substantial environmental footprint. Global plastic waste generation exceeds 353 million tons annually, with only 9% being recycled and 22% ending in natural ecosystems [1]. Notably, plastic packaging for agricultural and food products, such as bags and bottles, accounts for approximately 40% of global plastic consumption [2]. Innovative solutions such as incorporating plastic waste into paving stone production have emerged in response to this growing issue. Despite these advancements, a critical gap persists: the inadequate tensile strength of paving stones made from plastic waste. Most studies in this domain have not sufficiently addressed this aspect, resulting in tensile strength values below 3.6 MPa, which falls short of the requirements outlined in the NF EN 1338 standard [3]. This shortcoming presents a significant barrier to the widespread adoption of such paving stones in road construction. Recent research has demonstrated that incorporating fibers from recycled plastic bottles, such as polyethylene terephthalate (PET), into concrete significantly enhances its mechanical properties, particularly tensile and compressive strengths. This raises a key question: can similar improvements be achieved by integrating plastic bottle fibers into paving stones derived from plastic waste? The primary objective of this study is to improve the mechanical and physical performance of paving stones produced from plastic waste, focusing on their potential application as road surface materials. Specifically, the research aims to (1) identify the optimal plastic-to-sand ratio for the manufacturing process and (2) evaluate the impact of integrating polyethylene terephthalate

(PET) fibers, derived from recycled plastic bottles, into these optimized paving stones on their mechanical and physical properties.

2. Literature Review

The increasing environmental impact of plastic waste has prompted significant research into its potential use in construction materials, particularly paving blocks. This growing interest stems from the dual objectives of mitigating environmental pollution and creating sustainable alternatives to traditional materials. While previous studies have explored diverse aspects such as manufacturing methods, mechanical properties, and environmental benefits, critical challenges persist, including the optimization of material composition and compliance with performance standards. In 2019, B. Traore [4] introduced a method to recycle plastic waste into paving blocks suitable for roads and flooring.

The study employed two production techniques: manual compression and thermo-pressing, incorporating clay into the mixture. The research demonstrated that low-density polyethylene (LDPE) content up to 30% improved compressive strength, but higher concentrations negatively affected mechanical properties due to a decrease in interparticle cohesion. Ndepete et al. [5] (2022) investigated the valorization of plastic waste in paving block production, highlighting a reduction in water absorption and an initial increase in compressive strength with higher plastic content. However, beyond a certain threshold, mechanical performance declined. A similar trend was observed in tensile strength, underlining the complex interplay between plastic content and overall material properties. Research by Saïfoullah et al. [6] (2020) in Cameroon examined varying sand-to-plastic ratios, revealing that optimal ratios minimized water absorption while maximizing compressive strength. These findings emphasized the need for precise control over material composition to achieve desired mechanical properties. Onimisi and Akindele [7] (2022) explored interlocking paving blocks made from recycled plastic waste in Nigeria. Their study identified an optimal plastic-to-sand ratio that enhanced compressive strength, although the lack of data on tensile performance limited its applicability for structural uses.

Bhatia et al. [8] (2019) highlighted the significant role of material composition in paving block performance. Their research showed that increasing plastic content reduced water absorption and improved both compressive and tensile strengths but at the expense of workability and long-term durability. Awodiji et al. [9] investigated using sand-cement and sand-plastic mixtures in paving block production. Their study confirmed the potential of plastic waste to enhance mechanical properties but noted that density and strength varied significantly based on material proportions. Gahané et al. [10] (2022) further emphasized the importance of sand-to-plastic ratios in determining paving block properties and identifying an optimal composition for maximizing compressive strength. Beyond paving blocks, incorporating plastic waste into concrete has been a focal point of research. Studies by Fadhil and Yaseen [11] and Ganaw et al. [12] demonstrated that reinforcing concrete with plastic fibers improved compressive and flexural strengths, providing a sustainable alternative to conventional reinforcement materials. Similarly, Alshkane [13] explored the effects of plastic powder substitution and fiber incorporation in concrete, noting improved tensile strength with fiber addition but reduced density with powder substitution.While these studies underline the potential of plastic waste in construction, several gaps remain. Few studies have investigated the simultaneous optimization of compressive and tensile strengths in paving blocks. Moreover, most research does not adequately address compliance with standards such as NF EN 1338, particularly regarding tensile performance. Additionally, the potential benefits of incorporating polyethylene terephthalate (PET) fibers, derived from recycled plastic bottles, remain underexplored in the context of paving stones. This study addresses these gaps by systematically evaluating PET fibre addition's effects on the mechanical and physical properties of paving stones made from plastic waste. Building on previous research's insights, it aims to provide a comprehensive understanding of material behavior and propose solutions for meeting industry standards.

3. Materials and Methods

3.1. Materials

The plastic waste used in this study for paving stone production was obtained from the Waste Management and Sanitation Company (SGDS Benin). It primarily consisted of low-density polyethylene (LDPE) bags, which underwent meticulous washing and drying procedures to remove impurities and ensure their suitability for processing. The sand utilized in the study was sourced from a quarry in Houéyogbé. To achieve consistency in particle size, the sand was first dried to eliminate any residual moisture and then sieved through a 1 mm mesh. These preparatory steps ensured the uniformity and quality of the raw materials, which was critical for optimizing the paving stone manufacturing process.

Fig. 1 Waste used for the manufacture of paving stones

Fig. 2 Sifted sand

Table 1. Physical and mechanical properties of sand

Property	Value	Unit
Fineness modulus	1.82	-
Uniformity coefficient	2.10	-
Apparent density	1.63	g/cm³
Density	2.60	g/cm³
Sand equivalent	63	%

3.1.1. Analysis and Interpretation of Sand Properties Fineness Modulus (1.82)

The fineness modulus, which reflects the overall granularity of the sand, indicates that the material is relatively fine. A value of 1.82 suggests that the sand is well-suited for applications requiring improved workability, such as paving stone mixtures. However, excessively fine sand may adversely affect mechanical properties if the binder proportions are not optimized. Therefore, careful attention to the sand-to-binder ratio is critical to achieving the desired performance.

Uniformity Coefficient (2.10)

The uniformity coefficient, calculated as the ratio of the particle diameters at 60% and 10% passing (D60/D10), provides insight into the gradation of the sand. A value of 2.10 indicates a reasonably well-graded sand, which facilitates efficient compaction and contributes to the uniform stress distribution in the manufactured paving stones.

Apparent Density (1.63 g/cm³)

The apparent density, representing the mass of sand particles, including the void spaces between them, is recorded at 1.63 g/cm³. This property influences the overall density and stability of the paving stone mixture. The value aligns with expectations for fine sands and highlights its suitability for producing lightweight but durable composite materials.

Density (2.60 g/cm³)

The specific gravity of the sand, measured at 2.60 g/cm³, closely approximates the density of quartz (2.65 g/cm³), suggesting that the sand is predominantly composed of siliceous materials. This indicates high-quality sand with sufficient strength and durability for engineering applications, including paving stone production.

Sand Equivalent (63%)

The sand equivalent test, which quantifies the relative proportion of fine, clay-like particles, yielded a result of 63%. This value is within acceptable ranges for structural applications but slightly lower than ideal for paving stones subjected to rigorous loading conditions. The presence of clay fines may potentially weaken the mix if not adequately addressed through proper mix design and binder integration.

3.1.2. Implications for Paving Stone Production

The analyzed sand properties demonstrate its suitability for paving stone production, particularly regarding its workability, compaction characteristics, and inherent durability.

The moderately fine particle size and uniform gradation facilitate efficient mixing and ensure even stress distribution within the paving stones. The high specific gravity also highlights the sand's structural stability, a critical attribute for engineering applications.

Nevertheless, the moderate sand equivalent value indicates that attention is required to mitigate the potential impact of clay fines during the production process. This study employs several strategies to address this challenge effectively, including thorough sand washing, precise control of the plastic-to-sand ratio, and incorporating reinforcing fibers.

These measures are complemented by rigorous quality control during the preparation and mixing stages to ensure that the mechanical and physical properties of the paving stones align with performance standards. Combining fine gradation, adequate specific gravity, and acceptable cleanliness establishes this sand as a viable and sustainable raw material for paving stone production.

However, further validation through experimental trials is essential to optimize the interaction between the sand and plastic binder, thereby enhancing the durability and mechanical strength of the final product.

3.1.3. Preparation and Processing of PET Fibers for Paving Stone Reinforcement

The study utilized fibers extracted from polyethylene terephthalate (PET) plastic bottles collected from landfills and post-consumer waste streams. Before incorporation into the paving stone manufacturing process, the bottles underwent meticulous cleaning and drying to remove impurities and ensure their suitability for further processing. Using a precision cutting device, the cleaned bottles were then mechanically shredded into fibers with uniform dimensions, specifically 6 cm in length and 5 mm in diameter. This uniformity in fiber dimensions was critical to maintaining consistency in the composite material and optimizing its mechanical performance.

Fig. 3 Fibers obtained from plastic bottles

3.2. Methods

This study employed an artisanal approach to manufacture paving stones using plastic waste as a binder. The process involved melting plastic bags and mixing them with sand to create paver samples, followed by molding and cooling. A series of paving stones measuring 20×10×8 cm was fabricated, with plastic content varying from 20% to 40% by weight of dry sand.

3.2.1. Paving Stone Manufacturing Process

The methodology for producing the paving stones can be summarized in the following steps:

- Material dosing: Accurate measurement of sand and plastic bag proportions.
- Melting: Heating plastic bags at a temperature exceeding 200°C until fully melted.
- Mixing: Gradually add sand to the melted plastic while ensuring uniform mixing.
- Molding and compaction: Pouring the mixture into molds, followed by compaction to eliminate voids.
- Demolding: Allowing the pavers to cool for four hours before removing them from the molds.

Figure 4 illustrates the steps involved in the manufacturing process. Compression and splitting tensile tests were conducted on these paving stone samples to identify the plastic-to-sand ratio yielding the most favorable mechanical properties. The optimal ratio was subsequently used for the next phase of the study.

3.2.2. Enhanced Paving Stones with Plastic Fibers

To further improve the mechanical properties of the paving stones, a second series of pavers was fabricated using the previously identified optimal plastic-to-sand ratio. This series incorporated polyethylene terephthalate (PET) fibers at proportions of 0.5%, 1%, 1.5%, and 2% by weight of sand. The enhanced manufacturing process included an additional step. After mixing the sand and melted plastic, the mixture was removed from the heat to lower its temperature. The plastic fibers were then carefully added to ensure even distribution before the mixture was placed into molds. Figures 5 and 6 illustrate the manufacturing process and fiber-enhanced paving stones. This methodology ensured consistency in sample dimensions and provided a systematic approach to evaluate the effects of PET fiber incorporation on the mechanical and physical properties of paving stones.

Table 2. Quantities of raw materials

Plastic/sand mixture percentage	Specimen number	Sand quantity (Kg)	Sachet quantity (Kg)
20/80	6	16	4
25/75	6	21.00	7
30/70	6	21.00	9
35/65	6	18.57	10
40/60	6	16.50	11

The methodology for producing paving stones can be outlined as follows:

a) Dosing of materials b) Melting bags at over 200 degrees c) Adding sand and mixing

d) Molding and compaction e) Unmolding after 4 hours

Fig. 4 Pavers making process

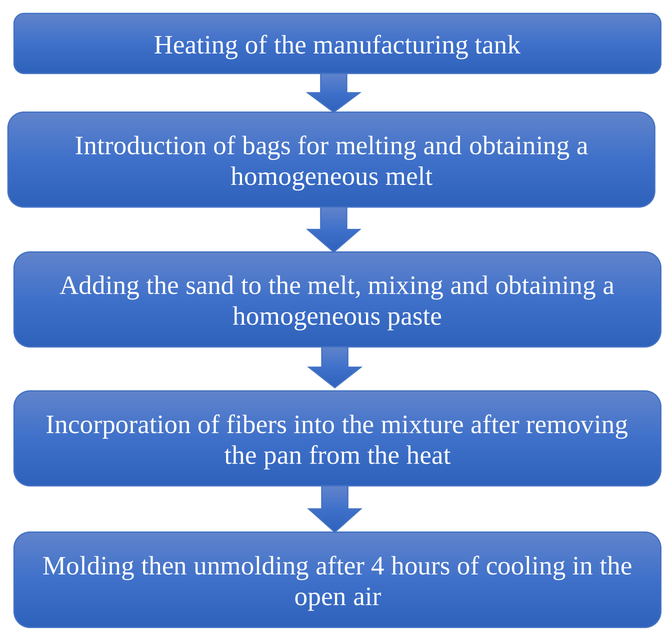

Fig. 5 Pavers manufacturing processes enhanced with plastic fibers

Fig. 6 Fiber-enhanced pavers

4. Results and Discussion

4.1. Effect of Plastic Content on the Compressive Strength of Fiber-Free Paving Stones

4.1.1. Analysis of Compressive Strength Variations in Fiber-Free Paving Stones with Different Plastic Content

Figure 7 and Table 3 present the results of the compressive strength tests conducted on paving stones without PET fiber reinforcement. The data indicates a distinct trend: the compressive strength increases from 3.74 MPa to a maximum value of 4.85 MPa as the plastic-to-sand ratio rises from 20% to 25%. However, further increasing the plastic content beyond 25% results in a gradual compressive strength, dropping to 3.52 MPa at a 40% plastic content.

4.1.2. Influence of Plastic-to-Sand Ratio on the Mechanical Performance of Fiber-Free Paving Stones

This behavior can be attributed to the balance between the binding capabilities of the molten plastic and the inherent structural contribution of the sand particles:

Optimal Plastic-to-Sand Ratio (25%)

At 25% plastic content, the molten plastic effectively coats the sand particles, creating a well-bonded matrix that distributes compressive stresses uniformly. This optimal ratio enhances the interaction between sand grains and the plastic binder, resulting in the highest observed compressive strength of 4.85 MPa.

Decrease in strength Beyond 25% Plastic Content

Exceeding the 25% threshold leads to an excessive presence of plastic in the matrix. As plastic is less mechanically resistant compared to sand, this higher binder content reduces the overall structural integrity of the paving stones. The diminished intergranular friction and over-saturation of plastic weaken the ability of the composite to resist compressive forces, resulting in the observed decline in strength.

Material Performance and Standards

While the maximum compressive strength of 4.85 MPa surpasses typical values for paving stones produced from plastic waste, it remains below the benchmark compressive strength of conventional concrete paving stones, which ranges between 20 MPa and 25 MPa. This discrepancy underscores the need for further optimization of the mixture, potentially by adding PET fibers or other reinforcing additives, to meet industrial standards such as NF EN 1338.

Scientific Implications

These findings emphasize the critical role of the plastic-to-sand ratio in determining the mechanical performance of paving stones. Maintaining an optimal balance ensures sufficient bonding without compromising the contributions of the sand particles. This insight serves as a basis for developing improved materials with enhanced mechanical properties through systematic adjustments in binder content and matrix composition.

In conclusion, the observed compressive strength trends underline the importance of maintaining an optimal plastic-to-sand ratio for maximizing mechanical performance. The results suggest that 25% plastic content is ideal for the tested materials, offering the best compromise between strength and material utilization. Further research should explore strategies such as incorporating PET fibers, improved compaction methods, and using hybrid binders to address the limitations observed at higher plastic contents.

Table 3. Compressive strength at varying plastic-to-sand ratios

Plastic/Sand Dosage (%)	Compressive Strength (MPa)
20/80	3.74
25/75	4.85
30/70	3.83
35/65	3.58
40/60	3.52

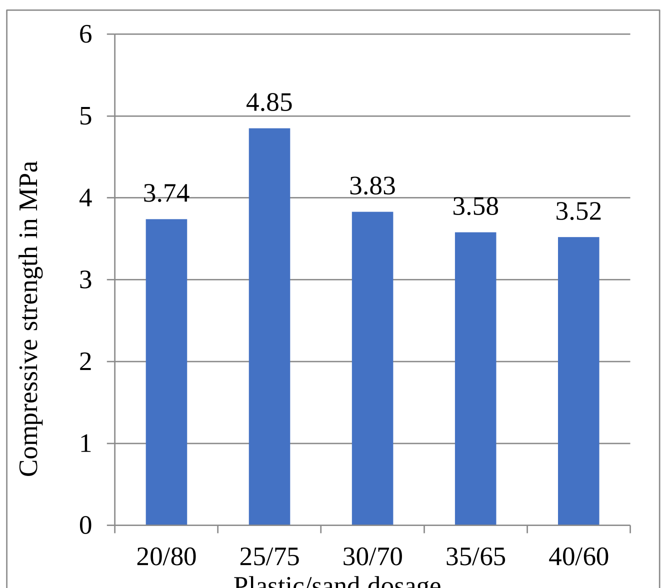

Fig. 7 Evolution of the compressive strength of pavers as a function of the plastic content

4.2. Impact of Plastic Content on the Tensile Strength of Fiber-Free Paving Stones

4.2.1. Tensile Strength Trends in Fiber-Free Paving Stones Across Plastic Content Ratios

The splitting tensile test results, as shown in Figure 8 and Table 4, reveal a trend consistent with the compressive strength findings. Tensile strength increases with the plastic-to-sand ratio, peaking at 1.38 MPa at 25% plastic content. Beyond this optimal threshold, tensile strength diminishes steadily, reaching a minimum value of 0.73 MPa at a 40% plastic content.

4.2.2. Influence of Plastic Content on Tensile Performance and its engineering implications

Optimal Plastic Content (25%)

At 25% plastic content, the molten plastic forms a cohesive matrix that binds sand grains effectively. This results in an optimal stress transfer mechanism, where tensile stresses are evenly distributed across the paver structure. The observed peak tensile strength of 1.38 MPa demonstrates the efficiency of this composition in resisting splitting forces.

Decrease Beyond 25% Plastic Content

As plastic content exceeds 25%, the excessive binder saturates the sand matrix, weakening intergranular bonding and stress transfer capabilities. Plastic, being less resistant to tensile forces than sand, reduces the overall tensile strength of the paving stones. This is evident from the observed decrease in tensile strength to 0.73 MPa at 40% plastic content.

Comparison with Standards and Applications

While the maximum tensile strength of 1.38 MPa is an improvement over other plastic waste-based materials, it remains below the NF EN 1338 standard requirement of 3.6 MPa for paving stones used in road construction.

This underscores the need for further enhancements, such as fiber reinforcement or alternative additives, to achieve the necessary mechanical properties for practical applications.

Scientific Implications

The results emphasize the critical influence of plastic content on the tensile performance of paving stones. Achieving a balance where the binder enhances cohesion without compromising the structural contribution of sand particles is essential. These findings provide a foundation for optimizing material proportions to maximize both compressive and tensile strengths. In conclusion, the tensile strength trends reinforce the importance of maintaining an optimal plastic-to-sand ratio for improved mechanical performance. At 25% plastic content, the paving stones achieve their highest tensile strength, offering a promising direction for future material optimization. However, additional strategies, such as incorporating PET fibers, are recommended to bridge the gap between current performance and standard requirements for tensile strength.

Table 4. Tensile strength at varying plastic-to-sand ratios

Plastic/Sand Dosage (%)	Tensile Strength (MPa)
20/80	0.95
25/75	1.38
30/70	0.96
35/65	0.9577
40/60	0.73

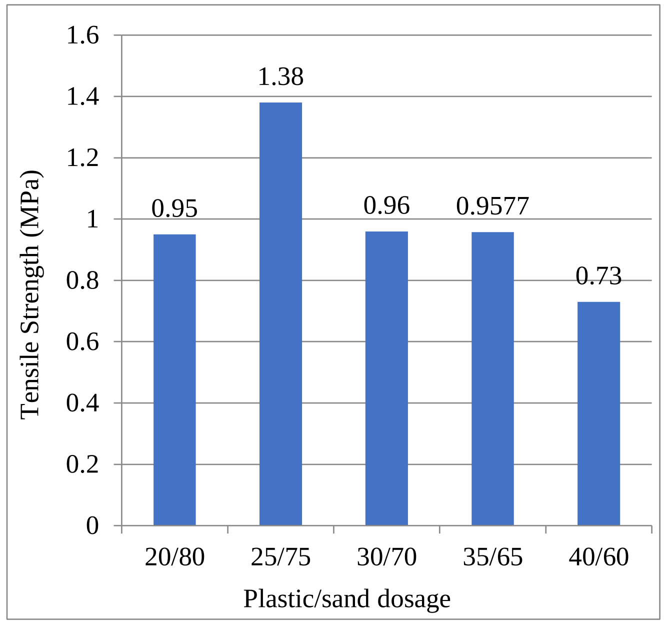

Fig. 8 Evolution of the tensile strength of pavers as a function of the plastic content

4.3. Impact of Fiber Addition Rate on Paver Compressive Strength

4.3.1. Effect of Plastic Fiber Incorporation on the Compressive Strength of Paving Stones

The results of the compressive strength tests, illustrated in Figure 9 and Table 5, demonstrate a significant influence of plastic fiber incorporation on the mechanical performance of the paving stones. The compressive strength increased substantially from 4.85 MPa (without fibers) to a peak value of 10.68 MPa at 1.5% fiber content, representing an enhancement of over 120%. However, a further increase in fiber content to 2% led to a notable reduction in compressive strength, falling to 6.29 MPa.

4.3.2. Optimization of Fiber Content for Enhanced Compressive Strength in Paving Stones

Impact of Fiber Addition on Compressive Strength

Incorporating PET fibers enhances the structural integrity of the paving stones by providing additional reinforcement within the composite matrix. The optimal fiber content of 1.5% ensures effective bonding between the fibers, sand particles, and the molten plastic binder, resulting in a well-integrated matrix capable of withstanding compressive forces. This reinforcement mechanism leads to the observed peak compressive strength of 10.68 MPa.

Strength Reduction Beyond Optimal Fiber Content

When the fiber content exceeds 1.5%, the excessive presence of fibers disrupts the homogeneity of the matrix. This results in poor adhesion between the fibers and the plastic binder, weakening the composite structure. Consequently, the compressive strength declines to 6.29 MPa at 2% fiber content. This reduction highlights the importance of maintaining an optimal balance between fiber reinforcement and matrix cohesion.

Comparison with Conventional Materials

Although the peak compressive strength of 10.68 MPa represents a significant improvement over fiber-free paving stones, it remains below the compressive strength of conventional concrete, which typically ranges between 20 MPa and 25 MPa. This discrepancy underscores the potential for further optimization through advanced manufacturing techniques, improved fiber dispersion, or hybrid reinforcements to achieve comparable performance.

Scientific Implications

The findings illustrate the critical role of fiber content in enhancing the compressive strength of plastic waste-based paving stones. The improvement observed at 1.5% fiber content demonstrates the effectiveness of fiber reinforcement in addressing the inherent weaknesses of plastic binders. These results serve as a foundation for exploring more sophisticated fiber reinforcement strategies to meet industrial performance standards. In conclusion, adding PET fibers significantly improves the compressive strength of paving stones, with an optimal inclusion rate of 1.5%, achieving a strength enhancement of over 120%. However, excessive fiber content adversely affects the matrix, reducing performance. Future research should focus on refining fiber dispersion techniques and exploring the synergistic effects of hybrid reinforcements to bridge the performance gap with conventional concrete paving stones.

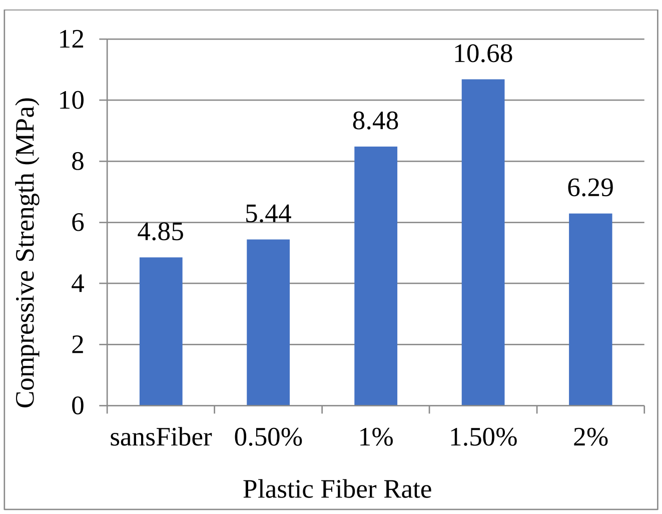

Fig. 9 Compressive strength of pavers as a function of the rate of fiber addition

Table 5. Compressive strength of paving stones at different fiber content levels

Fiber Content (%)	Compressive Strength (MPa)
0 (No Fiber)	4.85
0.5%	5.44
1%	8.48
1.5%	10.68
2%	6.29

4.4. Effect of Fiber Addition Rate on Paver Tensile Strength

4.4.1. Effect of Plastic Fiber Incorporation on the Tensile Strength of Paving Stones

The results of the tensile strength tests, presented in Figure 10, demonstrate the positive influence of plastic fiber incorporation on the mechanical properties of paving stones. Tensile strength increases significantly from 1.38 MPa (without fibers) to a peak value of 2.48 MPa at 1.5% fiber content, representing an improvement of over 79%. However, further increasing the fiber content to 2% results in a reduction in tensile strength to 1.31 MPa.

4.4.2. Optimizing Fiber Content for Improved Tensile Strength in Paving Stone

Effect of Fiber Addition on Tensile Strength

The incorporation of PET fibers enhances the tensile strength of the paving stones by mitigating the rapid propagation of cracks under tensile forces. The fibers' geometry and reinforcing mechanism effectively distribute tensile stresses, leading to a substantial increase in tensile strength at the optimal fiber content of 1.5%, where the peak value of 2.48 MPa is observed.

Strength Reduction Beyond Optimal Fiber Content

At fiber contents exceeding 1.5%, the excessive addition of fibers disrupts the uniformity of the matrix, reducing the effectiveness of the bonding between the fibers and the molten plastic binder. This leads to a decline in tensile strength to 1.31 MPa at 2% fiber content, highlighting the importance of maintaining an optimal balance between fiber content and matrix cohesion.

Comparison with NF EN 1338 Standard

Despite the notable improvement in tensile strength, the maximum value of 2.48 MPa achieved with fiber reinforcement remains below the NF EN 1338 standard requirement of 3.6 MPa for paving stones used in road construction. This suggests the need for further enhancements, such as improving fiber dispersion, optimizing fiber geometry, or incorporating additional reinforcement strategies to meet industrial standards.

Scientific Implications

The findings underscore the critical role of PET fibers in enhancing the tensile performance of plastic waste-based paving stones. Achieving the optimal fiber content of 1.5%

significantly improves tensile strength while maintaining matrix integrity. These results serve as a foundation for exploring more advanced reinforcement strategies to bridge the gap between current performance and industry standards. In conclusion, incorporating PET fibers significantly enhances the tensile strength of paving stones, with an optimal fiber content of 1.5% resulting in a 79% improvement over fiber-free samples. However, exceeding this threshold reduces matrix uniformity, leading to diminished performance. Further research should focus on optimizing fiber content, geometry, and dispersion to achieve tensile strengths that meet or exceed industry standards.

Table 6. Tensile strength of paving stones at varying fiber content levels

Fiber Content (%)	Tensile Strength (MPa)
0 (No Fiber)	1.38
0.5%	1.65
1%	2.1
1.5%	2.48
2%	1.31

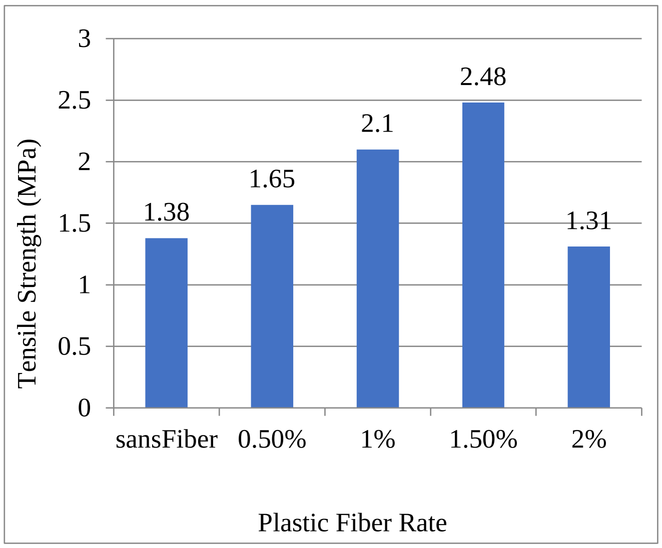

Fig. 10 Tensile strength of pavers as a function of the rate of fiber addition

Fig. 11 Appearance of improved pavers after tensile failure

4.5. Impact of Fiber Content on the Water Absorption Rate of Paving Stones

4.5.1. Reduction in Water Absorption of Paving Stones with Increasing Fiber Content

Figure 12 and Table 7 depict the variation in water absorption rates of paving stones in relation to fiber content. The results indicate a clear trend: water absorption decreases significantly from 1.27% (fiber-free pavers) to 0.24% at a fiber content of 2%. This trend highlights the effectiveness of plastic fibers in improving the pavers' resistance to water infiltration.

4.5.2. Enhancing Water Resistance of Paving Stones: Fiber Content Effects and Performance Implications

Reduction in Water Absorption with Increasing Fiber Content

Incorporating PET fibers reduces water absorption by enhancing the structural density and minimizing voids within the paving stones. As fiber content increases, the fibers act as reinforcements that fill micro-pores, restricting pathways for water infiltration. This improvement is particularly evident at higher fiber content levels, with the lowest absorption rate of 0.24% achieved at 2% fiber content.

Comparison with NF EN 1338 Standard

The water absorption rates for all tested samples, including fiber-free pavers, remain well below the maximum permissible limit of 6% stipulated by the NF EN 1338 standard for paving stones. This demonstrates the suitability of the tested materials for applications where water resistance is a critical requirement.

Implications for Durability and Performance

Lower water absorption enhances paving stones' durability and long-term performance by reducing susceptibility to water-induced degradation, such as freeze-thaw cycles and chemical erosion. The significant reduction observed in this study underscores the potential of PET fibers as a viable reinforcement strategy for improving the physical properties of paving stones.

Scientific Implications

The results reinforce the critical role of fiber incorporation in improving the water resistance of plastic waste-based paving stones. These findings provide valuable insights for developing sustainable construction materials that meet mechanical and physical performance standards.

In conclusion, incorporating PET fibers significantly enhances the water resistance of paving stones, reducing water absorption rates to as low as 0.24% at 2% fiber content. This demonstrates the effectiveness of fiber reinforcement in achieving compliance with NF EN 1338 standards and improving the durability of paving stones. Future research should focus on optimizing fiber dispersion and exploring hybrid reinforcement strategies to further enhance these properties.

Table 7. Water absorption rates of paving stones at different fiber content levels

Fiber Content (%)	Water Absorption (%)
0 (No Fiber)	1.27
0.5%	0.94
1%	0.52
1.5%	0.38
2%	0.24

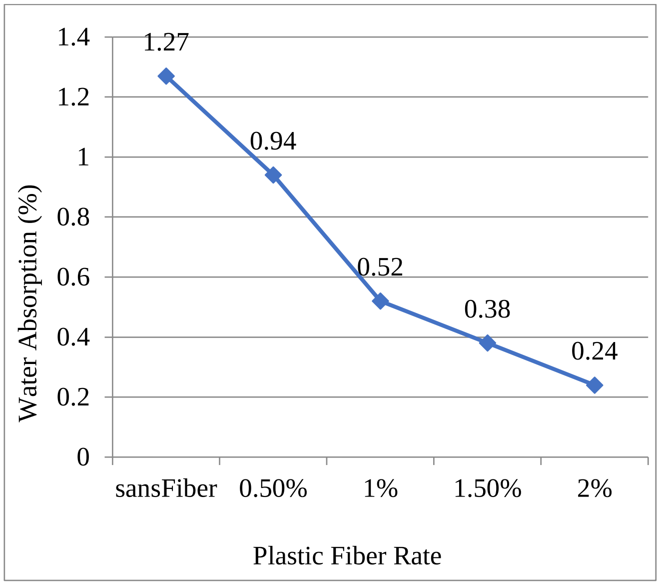

Fig. 12 Evolution of water absorption as a function of fiber content

Fig. 13 Pavers after immersion for 3 days

5. Conclusion

This study has highlighted the potential of plastic waste as a resource for producing paving stones, contributing to sustainable waste management and the development of alternative construction materials. Key findings emphasize the critical role of optimizing material proportions and incorporating reinforcements to enhance paving stones' mechanical and physical properties.

5.1. Optimization of Plastic Content

The research identified an optimal plastic content of 25% through artisanal production methods, which maximizes compressive strength at 4.85 MPa and tensile strength at 1.38 MPa. This ratio ensures effective binding of sand particles by the molten plastic, resulting in a well-structured composite material.

5.1.1. Effect of Fiber Incorporation

Including polyethylene terephthalate (PET) fibers further enhanced the compressive and tensile strengths of the paving stones, achieving increases of 120% and 79%, respectively, at an optimal fiber content of 1.5%.

These fibers effectively reinforce the matrix by limiting crack propagation and improving stress distribution. Despite these significant improvements, the mechanical performance remains below the NF EN 1338 standard for compressive strength (20–25 MPa) and tensile strength (3.6 MPa), underscoring the need for further optimization.

5.1.2. Improvement in Water Absorption Rates

The physical properties of the paving stones exhibited notable enhancements, particularly in water resistance. The water absorption rate decreased from 1.27% (fiber-free pavers) to 0.24% at 2% fiber content, well within the NF EN 1338 standard of ≤6%. This improvement demonstrates the effectiveness of PET fibers in reducing porosity and increasing material durability.

5.1.3. Overall Implications

The mechanical and physical performance of the paving stones is intricately tied to the careful selection of raw material proportions and the manufacturing process. The geometric and mechanical properties of PET fibers, combined with optimal plastic content, have proven to be effective in enhancing the overall performance of the paving stones. However, further advancements in manufacturing techniques, such as improved compaction and fiber dispersion, are required to meet industrial standards.

5.2. Future Perspectives

Moving forward, additional research and development are essential to bridge the performance gap between these paving stones and conventional materials. Efforts should focus on:

- Incorporating hybrid reinforcements to further enhance mechanical properties.
- Exploring advanced production techniques, including thermo-mechanical processing and automated compaction.
- Evaluating the long-term durability of the paving stones under varying environmental conditions.
- Assessing environmental and economic benefits, ensuring scalability and sustainability.

5.3. Summary of Key Findings

- The optimal plastic content for paving stones is determined to be 25%, providing the best balance of strength and material utilization.
- Including 1.5% PET fibers enhances compressive and tensile strengths by 120% and 79%, respectively, but falls short of NF EN 1338 mechanical requirements.
- The water absorption rate improves significantly, reaching 0.24%, well below NF EN 1338 standards.

In conclusion, this study underscores the viability of using plastic waste, reinforced with PET fibers, in paving stone production as a sustainable and innovative solution for civil engineering applications. While current results are promising, further optimization and technological advancements are required to achieve compliance with industry standards and ensure broader application in infrastructure development.

Prospects for Improvement

This study has revealed that, even with artisanal techniques, the incorporation of plastic bottle fibers can substantially enhance paving stones manufactured from plastic waste. This implies that:

- Adoption of modernized technology may yield outcomes aligning with industry standards.
- Further investigations should explore the impact of additional manufacturing parameters (such as molding compression, waste melting temperature, etc.) on the properties of the resulting pavers.

Funding Statement

ENSTP/UNSTIM Competitive Funds, 2023 edition of the National University of Science, Technology, Engineering, and Mathematics (UNSTIM).

Conflicts of Interest

The authors solemnly declare that no conflicts of interest are associated with the publication of this article. Our professional judgment regarding the validity of the research presented remains uninfluenced by any financial interests or other external pressures. This study was conducted impartially, without any involvement or influence from stakeholders, institutions, or funding sources in the design, execution, or dissemination of the research findings. The results and conclusions presented are derived solely from an objective evaluation of the research data.

Acknowledgments

The authors gratefully acknowledge the financial support received for this work from the ENSTP/UNSTIM Competitive Funds, 2023 edition of the National University of Science, Technology, Engineering, and Mathematics (UNSTIM).

References

[1] Global Plastic Waste Set to Almost Triple by 2060, Says OECD, OECD, 2022. [Online]. Available: https://www.oecd.org/en/about/news/press-releases/2022/06/global-plastic-waste-set-to-almost-triple-by-2060.html#:~:text=Globally%2C%20plastic%20leakage%20to%20the,to%201%2C014%20Mt%20in%202060.

[2] The Academy of Sciences, Plastics in the Environment, 2021. [Online]. Available: https://www.academie-sciences.fr/pdf/rapport/20210316_plastiques_environnement.pdf

[3] NF EN 1338:2004, Concrete Paving Blocks - Requirements and Test Methods, 2013. [Online]. Available: https://www.intertekinform.com/en-gb/standards/nf-en-1338-2004-77523_saig_afnor_afnor_163726/?srsltid=AfmBOopfDxTCUEHbcgj0q2cEBh917mzm-lhpCetV2H3CkuzJPHEplXLk

[4] Brahiman Traore, "*Development and Characterization of a Composite Structure (Sand and Recycled Plastic Waste): Improvement of Resistance by Clay Charges*," Doctoral Thesis, Republic of Ivory Coast, pp. 1-213, 2019. [Google Scholar] [Publisher Link]

[5] Cyrille Prosper Ndepete et al., "Recovery of Plastic Waste into Construction Materials," *European Scientific Journal*, vol. 18, no. 21, 317-329, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Dairou Saifoullah et al., "Valorization of Plastic Wastes in the Production of Building Materials: Paving Cases in the Garoua City (North Cameroon)," *American Journal of Innovative Research and Applied Sciences*, vol. 10, no. 6, pp. 215-221, 2020. [Google Scholar] [Publisher Link]

[7] Praise Onimisi Dawodu, Apata Akindele, and Udeme Imoh, "Recycling of Waste Plastic for the Production of Road Interlocking Paving Stone in Nigeria," *Journal of Engineering Research and Reports*, vol. 23, no. 12, pp. 296-301, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Pooja Bhatia, Nupoor Dewangan, and Abhyuday Titiksh, "Paver Blocks Made of Recycled Plastic-Bonded Sand," *Journal of Environmental Engineering and its Scope*, vol. 2, no. 2, 2019. [Google Scholar] [Publisher Link]

[9] C.T.G. Awodiji, S. Sule, and C.V. Oguguo, "Comparative Study on the Strength Properties of Paving Blocks Produced from Municipal Plastic Waste," *Nigerian Journal of Technology*, vol. 40, no. 5, pp. 762-770, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[10] Sachin Gahane et al., "Plastic Waste Utilization in Paver Block," *International Research Journal of Modernization in Engineering Technology and Science*, vol. 4, no. 4, pp. 851-857, 2022. [Publisher Link]

[11] Sarmed Fadhil, and Mohanad Yaseen, "The Production of Economical Precast Concrete Panels Reinforced by Waste Plastic Fibers," *American Journal of Civil Engineering and Architecture*, vol. 3, no. 3, pp. 80-85, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[12] Abdelhamed Ganaw et al., "Influence of Plastic Bottles Fibre on Self Compacting Concrete," *AIJR Books: Proceedings of First Conference for Engineering Sciences and Technology*, vol. 2, pp. 637-642, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[13] Younis M. Alshkane, "Reinforcement of Sandy Soil Using Plastic Fibres Made from Waste Plastic Bottles," *Iraqi Journal of Civil Engineering*, vol. 11, no. 2, pp. 45-54, 2017. [Google Scholar] [Publisher Link]