Valorisation of Plastic Bottle Wastes as Pavement Blocks

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Abstract. In response to the growing accumulation of plastic waste, particularly polyethylene terephthalate (PET) from packaging, this study explores its potential use as a binder in the production of pavement blocks. The goal is to replace traditional cement with PET, reducing non-degradable plastic waste and its harmful environmental impact.

Four formulations were used. First, the percentage of PET was fixed at 30%, and the percentage of crushed sand was varied at 70%, 65%, 63%, and 60% depending on the addition of clay at 0%, 5%, 7%, and 10%, respectively. The prepared mixtures were then used to produce ecological pavement blocks using adapted molding and compaction techniques.

These pavement blocks were subjected to mechanical, physical tests to evaluate their performance, including tensile splitting strength, abrasion resistance, and water absorption. For each type of test, three samples were taken from each formulation in order to determine the formulation offering the best mechanical characteristics. The obtained results demonstrate that the pavement blocks made from plastic waste and aggregates show promising performance, comparable to traditional concrete pavement blocks in terms of tensile strength and wear resistance, while exhibiting low water absorption.

The formulation, which includes an additional 5% of clay, achieves a significant reduction, with a 93% decrease in water absorption compared to concrete pavement blocks. Microscopic analysis reveals that while clay is essential for filling the voids between aggregates, enhancing both cohesion and the structural integrity of the pavement blocks, an excessive amount (particularly above 5%) can negatively impact their overall performance. These findings underscore the importance of carefully optimizing the clay content in eco-friendly pavement formulations to ensure a sustainable and durable alternative to conventional concrete pavers.

Moreover, this novel solution offers a sustainable alternative to conventional paving materials, offering several environmental and economic benefits and reduces the environmental footprint associated with the production, transport, and disposal of plastic waste while valorizing renewable resources such as sand and clay, and producing construction materials with satisfactory mechanical properties..

Keywords: Plastic waste, Concrete, Pavement blocks, Mechanical properties.

1 Introduction

The rapid accumulation of plastic waste, particularly from polyethylene terephthalate (PET) used in packaging, presents significant environmental risks, such as soil and water pollution. Globally, the production and consumption of plastic materials have surged, especially in packaging applications, leading to an increase in plastic waste. Traditional disposal methods, such as landfilling and incineration, not only occupy valuable land space but also contribute to severe environmental issues, including the release of harmful chemicals and greenhouse gases. This situation has spurred extensive research into the recycling and reuse of plastic waste, with a growing emphasis on its integration into construction materials.

Early research focused on the partial replacement of cement with plastic waste in concrete mixes, revealing promising results in terms of mechanical properties and durability. These studies [1–3] demonstrated that plastic waste could enhance certain properties of concrete, such as workability and resistance to harsh environmental conditions, while also offering a sustainable disposal method for non-degradable plastics. Additionally, incorporating plastic waste into construction materials has been shown to reduce the overall weight of the final product, leading to potential cost savings in transportation and handling.

Luhybi and Qader [4] investigate the use of recycled plastic waste as a partial replacement for conventional aggregates in concrete. The study aims to evaluate how incorporating different proportions of recycled plastic with three different lengths: 22 mm, 45 mm, and a combination of both lengths 22 + 45 mm.. For each length of Fiber, it was added in three percentages to concrete 0.1, 0.3 and 0.5% of cement weight. They conclude that the addition of plastic waste generally leads to a decrease in compressive strength, particularly at higher replacement levels. However, the reduction in strength is accompanied by improved workability and a lower density of the concrete, which could be beneficial in certain construction applications where weight reduction is crucial.

More recent advancements have expanded beyond partial cement replacement to the complete substitution of cement with plastic waste, particularly in the production of pavement blocks [5–7] Karisma et al. [8] investigate the potential of using plastic bottle waste as a primary material for producing paving blocks without the use of traditional cement. The study focuses on creating sustainable, aesthetically pleasing paving blocks by replacing cement with melted plastic waste. Physical and mechanical tests showed that the paving blocks performed adequately. A mixture with 20% PET and 80% sand resulted in a compressive strength of 19.65 MPa, classifying it as category C paving. Another mixture, with 20% PET and 80% stone ash, achieved a compressive strength of 24.20 MPa, placing it in category B. These results suggest that PET can provide sufficient strength for applications such as parks, pedestrian walkways, and parking lots. However, morphological and structural analysis reveals the presence of pores in the paving block that can affect the overall strength. These pores are caused by uneven melting of PET plastic during the manufacturing process. Tulashie et al. [9] have investigated various formulations and processing techniques to optimize the performance of plastic-based pavement blocks, focusing on factors such as compressive strength, tensile strength and water absorption in order to explore the potential of converting plastic waste into pavement blocks as a sustainable solution to the growing plastic waste problem in Ghana. They conclude that using plastic waste to produce pavement blocks is a viable and effective method for managing plastic waste in Ghana. It provides a practical solution to reduce plastic pollution while contributing to sustainable construction practices.

This study offers a novel solution to the pressing issue of plastic waste by investigating its use as a binder in eco-friendly pavement blocks, reducing reliance on traditional cement and minimizing the harmful environmental impacts of plastic disposal. The plastic bottle waste was cut in a small pieces and then melted at temperatures ranging from 180°C to 280°C in a controlled environment and combined with crushed sand (0-5mm), and clay in varying proportions to create paver block samples. The percentage of PET was fixed at 30%, and the percentage of crushed sand was varied at 70%, 65%, 63%, and 60% depending on the addition of clay at 0%, 5%, 7%, and 10%, respectively. The prepared mixtures were then used to produce ecological pavement blocks using adapted molding and compaction techniques. Cement-based paver blocks were also used for comparative purpose. The blocks underwent a series of tests, including splitting strength, abrasion resistance and water absorption tests. The findings indicate that paver blocks with plastic additives exhibit higher tensile strength, better water absorption, greater corrosion resistance, and reduced heat resistance compared to cement-based blocks. Additionally, plastic paver blocks demonstrated significantly lower water absorption. The use of plastic waste in paver block production presents an innovative solution for managing plastic waste, contributing to environmental cleanliness. Moreover, plastic paver blocks are found to be stronger, more durable, cost-effective, and more wear resistant than conventional cement paver blocks.

2 Preparation of the specimens

2.1 Materials

In this study, as shown in Fig. 1, the materials used for the paver blocks include (a) plastic waste, (b) crushed sand, and (c) clay. The plastic waste is PET, commonly found in bottles of water. The density of PET is 900 kg/m³ with a high melting temperature ranging from 180°C to 280°C and a tensile strength of 45 MPa. The crushed sand is sourced from Djebel Resas and has specific density of 2650 kg/m³. The sand's cleanliness is assessed with a sand equivalent value of 77.82, classifying it as clean sand suitable for construction purposes. The crushed sand has a particle size range of 0-5 mm with 13% of fillers. The clay has a density of 2500 kg/m³. The liquid limit (WL) of the clay is measured at 30.5, which defines the moisture content at which the clay transitions from a plastic to a liquid state. The plastic limit (Wp) is 21.73, representing the moisture content at which the clay begins to exhibit plastic behavior. The plasticity index (Ip), calculated as the difference between the liquid limit and the plastic limit, is 8.77. This value falls within the range of 5 to 15, categorizing the clay as a low-plasticity soil. This means the clay has moderate workability and is less likely to undergo significant deformation under stress. Finally, the consistency index (Ic) of the clay is 3, which is greater than 1, classifying the soil as solid.

Fig. 1. Materials used for casting the pavement blocks: (a) Plastic waste; (b) crushed sand; (c) Clay

2.2 Mixture proportion details

The standard pavement block shape with a thickness of 6 cm is selected as shown in Fig. 2. This choice of dimensions allows for a direct comparison in terms of mechanical properties, durability, and performance between the eco-friendly blocks and conventional concrete blocks. By using the same shape and thickness, we can accurately assess how well the plastic blocks perform, providing a reliable benchmark for evaluating their potential as a sustainable alternative.

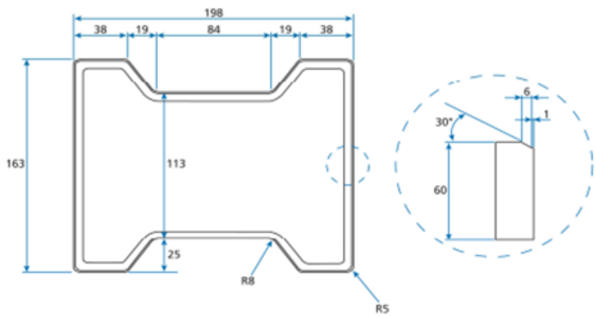

Fig. 2. Dimensions of the pavement blocks

In order to determine the exact quantities of sand, clay, and PET required, a mass-based formulation was developed to determine the quantities of sand, clay, and PET required for each block, with 3.5 kg used as the reference weight for one block. Table 1 provides a detailed breakdown of the mixture proportions used in the four different formulations. The study examines different clay content 0%, 5%, 7%, and 10% to determine the optimal formulation. The proportions of these materials were carefully varied to produce different formulations of the paver blocks. In all formulations, the PET content was fixed at 30%, while the percentage of crushed sand was adjusted based on the amount of clay added.

Table 1. Mixture proportions for casting the pavement blocks

Formulations	Constituents	Percentage (%)	Weights (g)
1st Formulation	Sand	70 %	2450
	PET	30 %	1050
	Clay	0 %	0
2nd Formulation	Sand	65 %	2275
	PET	30 %	1050
	Clay	5 %	175
3rd Formulation	Sand	63 %	2205
	PET	30 %	1050
	Clay	7 %	245
4th Formulation	Sand	60 %	2100
	PET	30 %	1050
	Clay	10 %	350

2.3 Casting process

The process begins with extracting the clay, which is then dried in an oven for 24 hours to remove any moisture. After drying, the clay is compacted into a fine powder and sieved using a 1 mm mesh to ensure uniformity. Then, the sand and clay are preheated in an oven to prevent thermal shock when mixed with the melted PET. Concurrently, the plastic waste is ground into smaller pieces to facilitate the melting process. The PET is then heated to a high temperature until it reaches a liquid state.

Once the PET is fully melted, the clay is gradually added. The mixture is stirred continuously to ensure proper incorporation. Following this, the preheated sand is introduced into the mixture, and continuous mixing is maintained until a homogeneous blend is achieved. The homogeneous mixture was then poured into pre-prepared moulds designed for pavement blocks. The filled moulds were subjected to compaction to remove air voids. After moulding and compaction, the blocks were allowed to cool and solidify at room temperature. After the mixture sets, the moulds are carefully removed, resulting in well-shaped, eco-friendly pavement blocks as shown in Fig. 3.

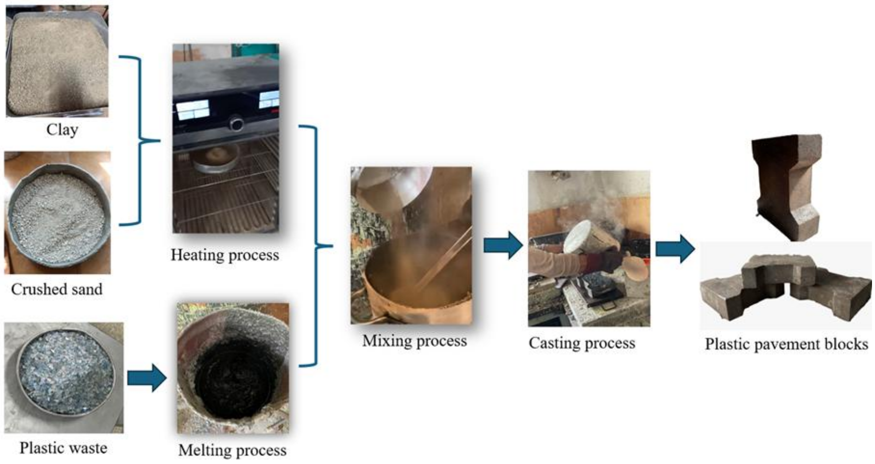

Fig. 3. Casting process of plastic pavement blocks

3 Standardized laboratory tests

3.1 Water absorption test

The water absorption test is a standardized laboratory method used to evaluate the porosity and water-retentive capacity of a concrete pavement block [10]. This test involves immersing pavement blocks in water for three days, allowing the material to absorb water. The sample's mass is measured before and after immersion to determine the amount of water absorbed.

The dried weight of the plastic block was recorded as (W1). The blocks were submerged in a water tank for 72 hours after which each was reweighed and recorded as (W2). As expressed in (1), the water absorption of the specimen was calculated as percent increase in mass resulting from water immersion.

$$A(\%) = \frac{W_2 - W_1}{W_1} \; x \; 100 \tag{1}$$

The results showed in Fig. 4 demonstrate that all four formulations of eco-friendly pavement blocks successfully meet the standard water absorption requirements, with rates not exceeding 5.4% as per NF P 98-303 [10]. Specifically, the absorption rates for the first, second, third, and fourth formulations are 0.39%, 0.19%, 0.43%, and 1%, respectively. These results indicate a substantial reduction in water absorption compared to conventional concrete blocks.

The first formulation, which contains a mix of sand and PET, shows a 86% reduction in water absorption. These two materials are insensitive to water. This explains that the plastic as a water-impermeable material, acts as a binding agent in eco-friendly pavement blocks. The second formulation, which includes an additional 5% of clay, achieves an even greater reduction, with a 93% decrease in water absorption. By filling the porous spaces within the structure, the clay reduces the percentage of voids, which in turn lowers the amount of water absorbed compared to traditional concrete pavement blocks. However, when the clay content is increased to 10% in the fourth formulation, a significant rise in water absorption is observed. This indicates that while a moderate amount of clay can improve the block's moisture resistance, excessive clay content may lead to increased porosity, resulting in higher water absorption. The water absorption results demonstrate a clear trend: as the clay proportion in the pavement formulations increases, the water absorption rate also increases. This suggests that clay plays a critical role in determining the porosity of eco-friendly pavement blocks. Clay particles naturally tend to adsorb water on their surfaces and swell, which impacts the material's overall porosity.

Adding 5% clay to the mixture enhances the pavement block's ability to control water absorption by reducing porosity, which can be advantageous in certain environmental conditions where regulated water absorption is beneficial. These findings highlight the importance of carefully optimizing the clay content in the formulation to strike a balance between the mechanical properties and porosity of eco-friendly pavement blocks. Additionally, understanding the material's resistance to water penetration is crucial, as it can significantly influence its durability and vulnerability to damage from freeze-thaw cycles.

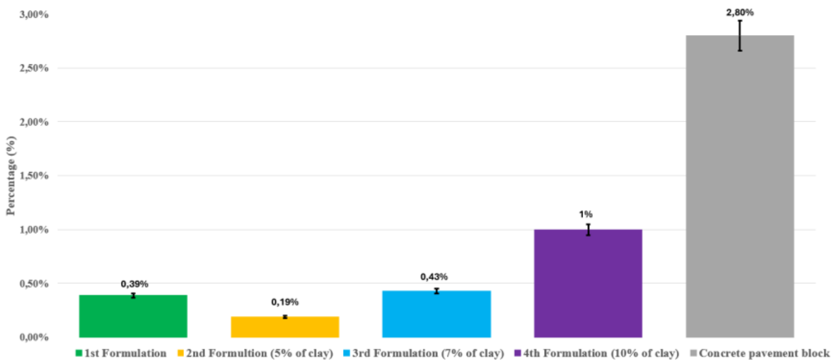

Fig. 4. Water absorption test

3.2 Splitting tensile test

The splitting tensile strength test, also known as the flexural splitting strength test, measures the indirect tensile strength of pavement blocks. The tensile strength is calculated using the formula below (2), according to reference [10]:

$$T = 0.637x\ \frac{P}{S} \tag{2}$$

Where:

T is the tensile strength in Megapascals (MPa),

P is the load at failure in Newtons (N),

S is the cross-sectional area of the test specimen, measured along its longitudinal axis and perpendicular to the viewed face, in square Millimetres (mm²), with S= 11880 mm^2.

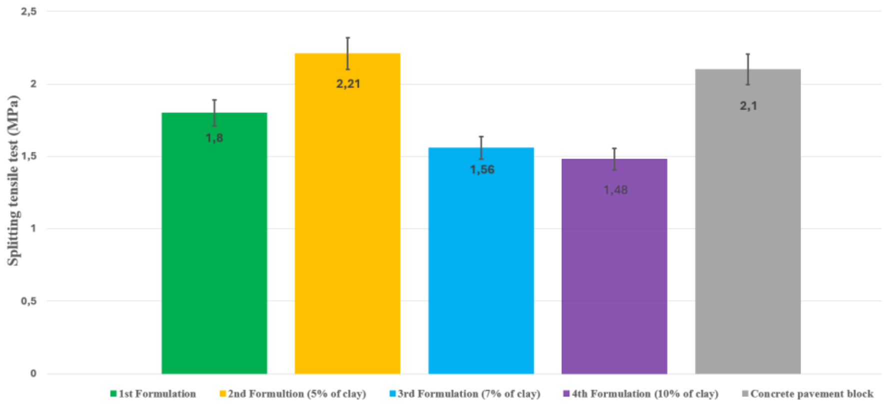

Fig. 5. Splitting tensile strength

According to Fig. 5, the tensile strength for the first, second, third, and fourth formulations are 1.8 MPa, 2.21 MPa, 1.56 MPa and 1.48 MPa, respectively. the results of the splitting tensile test on the eco-friendly pavement block samples and the concrete pavement samples are comparable. However, these values do not meet the requirements of the NF P 98-303 standard, which mandates a tensile strength higher or egal to 4 MPa [10]. Concrete pavement blocks are primarily composed of cement, aggregates, and water. Cement, a hydraulic binder, forms very strong bonds between the aggregates, providing the concrete block a high tensile strength up to 2.1 MPa.

The first formulation, which contains a mix of sand and PET, shows a 15% reduction in the tensile strength compared to the concrete pavement block. This explains that the plastic even when recycled, do not form bonds as strong as cement, leading to a reduction in the tensile strength of the material. The second formulation, which includes an additional 5% of clay, achieves an increase of 5% in the tensile strength. However, increasing the clay content to 7% and 10% in the third and fourth formulations leads to a significant decrease in tensile strength by 25% and 29%, respectively. These results indicate that while adding 5% clay can enhance the block's resistance, an excessive clay content may significantly reduce the tensile strength of the eco-friendly pavement blocks.

Fig. 6 illustrates the load evolution over time during the splitting tensile tests. The concrete pavement block, characterized by its rigid and dense composition, withstands an applied load of 39.16 kN before experiencing a sudden and brittle failure. This behavior is attributed to the crystalline and rigid nature of the cement and aggregates used in the block's construction. In contrast, the plastic pavement blocks, which utilize recycled plastic waste (PET) as a binder in combination with crushed sand aggregates, exhibit a more flexible and elastic structural behavior. This flexibility enables the blocks to deform gradually under load, continuously absorbing the applied energy and delaying the point of rupture, as showed in Fig. 6. The first and second formulations of the plastic blocks record maximum loads of 33.56 kN and 41.21 kN, respectively. This demonstrates the potential of the eco-friendly blocks to achieve comparable or even superior performance in certain conditions while offering a more sustainable alternative to traditional concrete blocks.

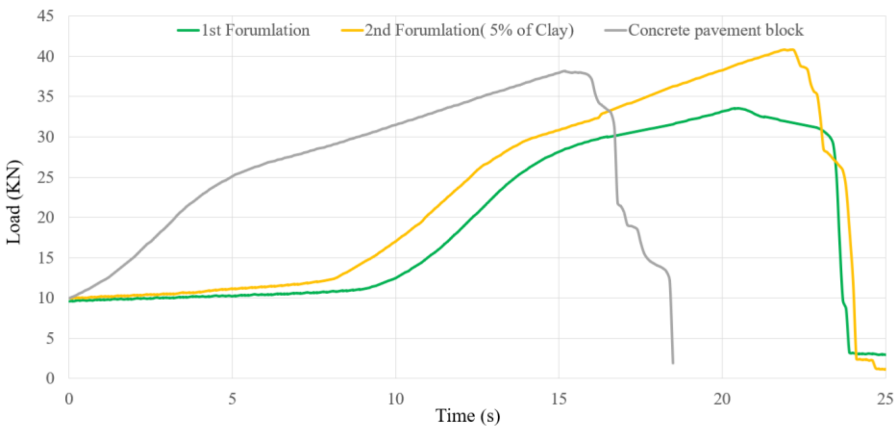

Fig. 6. Load time histories of the splitting tensile tests

3.3 Abrasion test

The abrasion test, conducted according to the NF EN 1338:2003 standard [11], evaluates the wear resistance of pavement blocks by exposing their surface to abrasion using white fused alumina sand. This method provides a reliable assessment of the durability of the blocks under abrasive conditions. The test involves creating an imprint on the block's surface using a rotating drum, with the width of the imprint measured to a precision of 0.5 mm. The procedure is repeated three times for each specimen to ensure accuracy, and the maximum value recorded is used for analysis (see Fig. 7).

Fig. 7. Abrasion test procedure

The test results, shown in Table 2, indicate that all formulations meet the standard abrasion resistance requirements, with average abrasion lengths of 25 mm or less [11]. The first and second formulations, as well as the concrete blocks, exhibited the highest resistance, with an average abrasion length of 24.33 mm. In contrast, formulations three and four, which contain higher clay content, showed slightly lower resistance, with an average imprint length of 25 mm.

Increasing the clay content in formulations three and four may introduce weak points within the PET matrix, making these blocks more prone to degradation under wear and friction and can lead to cracking and breaking more easily under abrasive forces compared to concrete pavement blocks. These findings suggest that while clay can contribute to the overall structural integrity of the pavement blocks, an excessive amount may compromise their resistance to abrasion. This highlights the importance of optimizing the clay content in eco-friendly pavement formulations (not exceed 5%) to ensure a balance between durability and resistance to wear.

Table 2. The abrasion test results

Formulations	Samples	Length of prints (mm)	Average length (mm)
1st Formulation (30% PET+70% sand)	1	24	24.33
	2	25	
	3	24	
2nd Formulation (30% PET+65% sand + 5% clay)	1	24	24.33
	2	25	
	3	24	
3rd Formulation (30% PET+63% sand + 7% clay)	1	24	25
	2	25	
	3	26	
4th Formulation (30% PET+60% sand + 10% clay)	1	26	25
	2	24	
	3	25	
Concrete pavement blocks	1	25	24.33
	2	24	
	3	24	

3.4 Microscopic Analysis

To confirm these findings, a microscopic analysis was conducted with a 20x magnification after the splitting tensile test. This examination aimed to observe the bond interactions between aggregates and the binder for different formulations and to understand how they affect the material's properties as shown in Fig. 8.

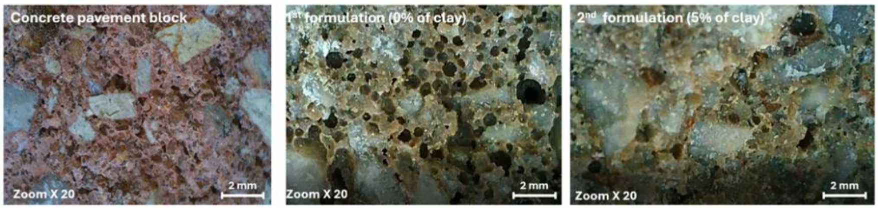

Fig. 8. Microscopic pictures of pavement blocks

The microscopic observations revealed that the conventional concrete block exhibited numerous pores around the aggregates, which is typical for concrete structures. Similarly, the first formulation (without clay, with 70% crashed sand and 30% PET) also showed many pores around the aggregates. However, with the addition of 5% clay in the second formulation, a significant reduction in the number of pores was observed. The clay appears to play a crucial role in filling the voids between the aggregates, thereby improving the material's cohesion. This reduction in porosity explains the lower water absorption and increased tensile strength observed in this formulation.

4 Results and discussions

This research focused on developing eco-friendly pavement blocks by incorporating plastic waste (PET) as a binder, along with varying proportions of sand and clay. The study examined the impact of different formulations on mechanical properties, including water absorption, tensile strength, and abrasion resistance, to evaluate their potential as a sustainable alternative to conventional concrete pavers.

Water Absorption:

The water absorption tests highlighted the importance of optimizing clay content. While all formulations met the standard requirement of 5.4% maximum absorption, a clear trend was observed: as clay content increased, water absorption also increased. The second formulation, containing 5% clay, reduced water absorption by 93% compared to concrete, demonstrating its effectiveness in lowering porosity. However, with 10% clay, water absorption increased, indicating that excessive clay negatively affects porosity management.

Tensile Strength:

The tensile strength tests showed that PET as a binder contributed to the structural integrity of the blocks, but the strength was lower than that of traditional concrete. The first formulation (70% sand, 30% PET) exhibited a 15% reduction in tensile strength compared to concrete, due to weaker bonds formed by recycled plastics. However, adding 5% clay increased the tensile strength by 5%, enhancing the block's resistance to tensile forces. Increasing clay content to 10% led to a significant decrease in tensile strength, highlighting the importance of optimizing clay content.

Abrasion Resistance:

The abrasion resistance tests confirmed that all formulations met the standard requirement of an abrasion length below 25 mm. The first and second formulations, along with concrete blocks, exhibited the highest abrasion resistance. The third and fourth formulations, with higher clay content, showed slightly lower resistance, likely due to the brittle nature of clay, which introduced weak points in the PET matrix.

Microscopic Analysis:

Microscopic observations, conducted after the splitting tensile test, revealed a reduction in pores around aggregates with the addition of 5% clay in the second formulation. This improvement in cohesion explains the increased tensile strength and reduced water absorption in this formulation. Conversely, formulations without clay or with excessive clay content exhibited more pores, which impacted the material's mechanical properties.

These results confirm that incorporating 5% clay into the eco-friendly pavement block formulation enhances density and internal cohesion, leading to improved mechanical performance and reduced porosity. However, excessive clay, particularly above 5%, compromises performance. The optimal clay content of 5% was found to balance durability, tensile strength, water absorption, and abrasion resistance effectively. These findings emphasize the need to carefully optimize the clay content in eco-friendly pavement formulations to provide a sustainable and durable alternative to conventional concrete pavers.

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