



Mechanical Performance of Recycled Plastic-Based Paving Blocks with Sand and Fly Ash Fillers

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Abstract. The use of recycled plastic waste as a binder for paving blocks has been reported in a number of previous studies. However, most of these studies focus on feasibility and do not clearly explain how different plastic types behave mechanically over time. In this study, the compressive strength performance of paving blocks made from polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) was experimentally compared using sand or fly ash as fillers. All mixtures were prepared with a fixed composition of 60% plastic and 40% aggregate. Compressive strength testing was carried out at 28 and 56 days using three specimens for each mix. The results show that the HDPE–sand mixture achieved the highest compressive strength at 28 days, reaching 15.7 MPa. Nevertheless, a noticeable reduction in strength was observed at 56 days, particularly in the HDPE-based mixtures. This reduction is mainly associated with polymer shrinkage and the development of interfacial stresses between the plastic binder and the aggregates. Overall, the results indicate that plastic-based paving blocks can meet the requirements of SNI 03–0691–1996 for light-duty applications, although their long-term mechanical stability remains a limitation that needs further attention.

Keywords: recycled polymer binder, cementless paving block, compressive strength degradation, sustainable construction materials, plastic-based paving block

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1. Introduction

Plastic materials are widely used in daily life and contribute significantly to solid waste generation[1,2]. Among the various plastic categories, thermoplastics such as polypropylene (PP)[3], polyethylene terephthalate (PET)[4], and high-density polyethylene (HDPE)[5], are of particular interest because they can be melted and reshaped repeatedly. This characteristic makes them potential candidates for use as alternative binders in cementless construction materials[6–8].

In recent years, several studies have explored the use of recycled thermoplastics as binders in paving blocks and related products[9–11]. Most of these studies report that plastic-based paving blocks are feasible and highlight potential benefits such as reduced density and material reuse. Other works have examined the role of mineral fillers, including sand and fly ash, in improving compressive strength[12–14]. However, these investigations are typically carried out in isolation, often focusing on a single plastic type or a specific filler system. As a result, the findings remain fragmented, and the combined influence of polymer type and filler material on mechanical performance is still not well understood.

From an engineering standpoint, the behavior of plastic-based paving blocks is closely related to polymer–aggregate bonding[15,16], thermal response[17,18], post-cooling shrinkage[19,20], and filler–polymer interaction[21,22]. Different thermoplastics exhibit distinct melting temperatures, stiffness, and cooling behaviors, which can significantly influence the development and stability of compressive strength over time[23]. Despite this, comparative studies that examine multiple thermoplastic binders under identical mix proportions and testing conditions are still limited. In particular, the issue of time-dependent strength degradation and its material-related causes is rarely discussed in existing research.

To address these limitations, this study advances current understanding by conducting a controlled experimental comparison of PP, PET, and HDPE used as cementless binders in paving blocks prepared with identical mix proportions and processing conditions. Rather than focusing solely on feasibility or sustainability aspects, the present work examines how the choice of polymer affects both compressive strength development and strength reduction over time, providing practical engineering insight into material behavior.

Furthermore, this study seeks to answer the following research questions: (1) how does the type of thermoplastic binder (PP, PET, and HDPE) affect the compressive strength of paving blocks when identical mix proportions are used; (2) how does compressive strength change between 28 and 56 days for different plastic–filler combinations; and (3) to what extent do the resulting paving blocks comply with the performance requirements specified in SNI 03–0691–1996[24] for light-duty applications? By integrating a comparative material evaluation with standard-based performance assessment, this study aims to clarify both the engineering feasibility and the limitations of plastic-based paving blocks, moving beyond general sustainability discussion toward a more practical assessment of material performance.

2. Methods

This study adopted an experimental approach to investigate the compressive strength of plastic-based paving blocks produced using different thermoplastic types and filler materials. Before specimen preparation, the literature study was conducted to identify appropriate mix proportions and processing parameters.

2.1. Materials

The thermoplastic waste used in this study were polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE), as illustrated in Figure 1. Two types of filler materials were

employed, namely natural sand and fly ash, as shown in Figure 2. Sand is widely used as a filler in paving block production because of its availability and favorable mechanical properties. In this study, fly ash was additionally employed as an alternative filler to examine its effect on the mechanical performance of plastic-based paving blocks. By using both sand and fly ash, this research enables a direct comparison between fillers with different mechanical and chemical characteristics, which forms one of the key contributions of the study.

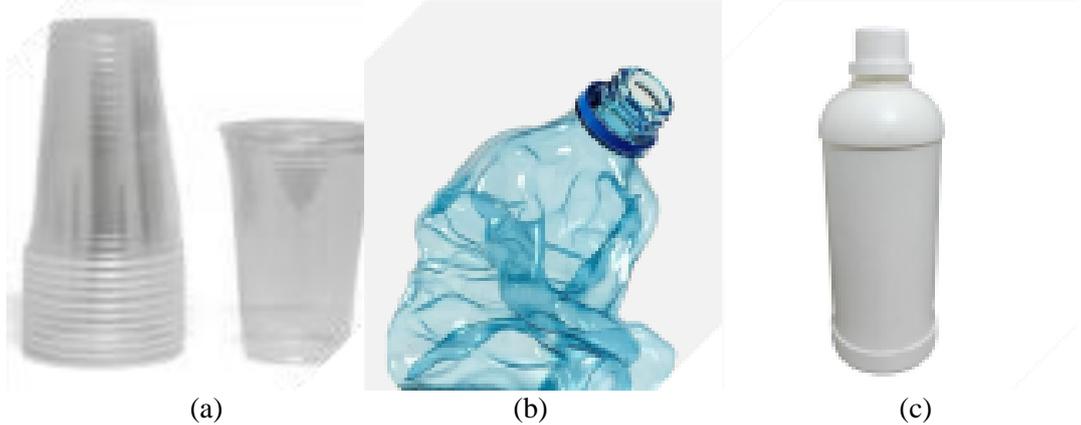


Figure 1. Types of plastic. (a) Polypropylene, (b) Polyethylene Terephthalate, (c) High-Density Polyethylene



Figure 2. Aggregate as filler paving. (a) fly ash, (b) sand

2.2. Specimen Preparation and Processing Parameters

Prior to mixing, the plastic waste was cleaned, dried, and weighed according to the specified mix proportions. The plastics were then melted in an electric furnace within their respective melting temperature ranges[25,26], as listed in Table 1. The furnace temperature was maintained at 200–280 °C for HDPE, 200–300 °C for PP, and 160–180 °C for PET, and heating was continued until complete melting was visually observed[27]. Once the target temperature was reached, the molten plastic was mechanically stirred for approximately 3–5 minutes to ensure uniformity. The filler material (sand or fly ash) was then added gradually while mixing was continued for an additional 5 minutes to obtain a homogeneous composite mixture and to minimize agglomeration[28].

Table 1. Melting Point of Plastics

Material	Temperature	
	°C	°F
HDPE	200-280	392-536
PP	200-300	392-572
PET	160-180	320-365

The molten mixture was subsequently poured into pre-lubricated steel molds measuring 20 × 10 ×

6 cm. Placement was carried out in layers, accompanied by light manual vibration and shaking of the mold to reduce entrapped air. After casting, the specimens were allowed to cool naturally under laboratory conditions (27 ± 2 °C) for 24 hours before demolding. To establish a suitable reference mixture, preliminary experiments were carried out using PP plastic as the base material combined with sand at different proportions, as summarized in Table 2. These mixtures included 100% PP as well as sand–PP combinations with sand contents ranging from 10% to 40% by weight.

Table 2. PP Plastic Paving against Sand

No	Mix Design
1	Sand + PC
2	100% PP
3	10% Sand: 90% PP
4	20% Sand: 80% PP
5	30% Sand: 70% PP
6	40% Sand: 60% PP

Based on preliminary compressive strength observations, the mixture containing 40% sand and 60% PP showed the most favorable performance among the tested PP–sand combinations. This composition was therefore selected as the reference mix for subsequent experiments involving different plastic types and filler materials. Accordingly, further mixtures were prepared using a fixed ratio of 40% filler (sand or fly ash) and 60% plastic, as presented in Table 3.

Table 3. Mix design of paving fly ash and sand for various types of plastic

No	Mix Design
1	fly ash 40%: PP 60%
2	fly ash 40 %: PET 60%
3	fly ash 40 %: HDPE 60%
4	Sand 40 %: PP 60%
5	Sand 40 %: PET 60%
6	Sand 40 %: HDPE 60%

2.3. Conditioning and Testing Procedure

Unlike cement-based materials, plastic-based paving blocks do not undergo hydration-based curing. Accordingly, all specimens were conditioned under ambient laboratory conditions without water curing. Compressive strength testing was conducted at specimen ages of 28 days and 56 days [29,30] representing short-term and medium-term mechanical performance. Compressive strength tests were performed using a standard compression testing machine. The compressive strength was calculated as the ratio of the maximum applied load to the cross-sectional area of the specimen.

2.4. Experimental Design and Result Evaluation

The experimental design was structured to evaluate the effects of different thermoplastic types (PP, PET, and HDPE) and filler materials (sand and fly ash) on the compressive strength of plastic-based paving blocks. A two-stage approach was adopted. In the first stage, PP-based paving blocks with varying sand contents were prepared to identify a suitable reference mixture. In the second stage, this reference composition was applied to different plastic types and filler materials to allow consistent comparison among all mixture variations.

For each mixture variation, three specimens were prepared and tested in compression. The compressive strength values reported in this study represent the average of three measurements. The use of three specimens per test condition follows common experimental practice in compressive strength testing, as reflected in standards such as ASTM C39/C39M, where multiple specimens are tested, and mean values are reported to represent the material's performance[31].

The evaluation of results in this study focused on comparative trends rather than inferential statistical analysis. Differences in compressive strength were assessed by comparing mean values across plastic types, filler materials, and testing ages (28 and 56 days). This descriptive evaluation approach was considered appropriate for identifying material-dependent behavior and performance tendencies in plastic-based paving blocks.

3. Results and Discussion

This section discusses the compressive strength behavior of plastic-based paving blocks by relating the experimental results to the characteristics of the thermoplastic binders, filler materials, and thermal effects associated with the processing and conditioning stages.

3.1. Effect of Sand Content in PP-Based Paving Blocks

Figure 3 presents the compressive strength results of paving blocks produced using polypropylene (PP) with varying sand contents. The specimen composed of 100% PP exhibited the lowest compressive strength, reaching 5.7 MPa at 7 days and 5.8 MPa at 28 days. This behavior can be attributed to the absence of rigid filler particles, causing the material to be governed primarily by the mechanical response of the polymer matrix. Under compressive loading, PP without filler tends to deform plastically, resulting in limited load-bearing capacity.

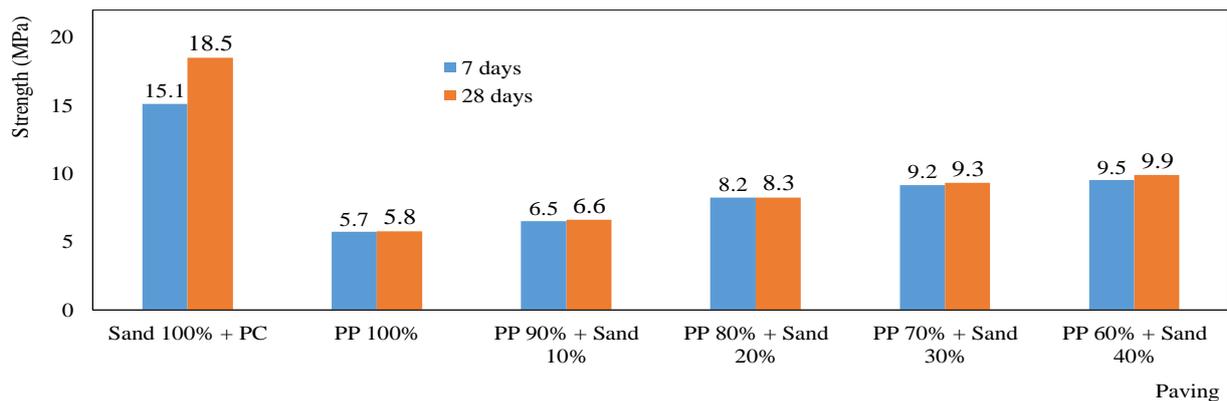


Figure 3. Compressive strength of PP plastic paving with sand

The incorporation of sand significantly improved the compressive strength of PP-based paving blocks. The highest strength among the PP–sand mixtures was achieved at a composition of 60% PP and 40% sand, with compressive strengths of 9.5 MPa at 7 days and 9.9 MPa at 28 days. This improvement is associated with the role of sand as a rigid filler that enhances packing density and provides effective load transfer pathways within the composite. The presence of sand particles restricts polymer deformation and distributes applied stress more evenly throughout the specimen, which is consistent with strengthening mechanisms reported in polymer–aggregate composite systems. Based on these results, the 60% PP–40% sand mixture was selected as the reference composition for subsequent experiments involving different plastic types and alternative filler materials.

3.2. Influence of Plastic Type and Filler Material on Compressive Strength

The compressive strength results for various combinations of plastic types and filler materials are shown in Figure 4. Among all mixtures, the HDPE–sand combination exhibited the highest compressive strength, reaching 15.7 MPa at 28 days. This superior early-age performance can be explained by the relatively high stiffness and strong interparticle adhesion of HDPE when melted and compacted with rigid fillers. However, despite its high early-age strength, HDPE-based paving blocks experienced a pronounced reduction in compressive strength at 56 days. For the HDPE–sand mixture, the strength decreased from 15.7 MPa to 11.2 MPa, while the HDPE–fly ash mixture showed a more severe reduction from 14.0 MPa to 7.5 MPa. This time-dependent strength degradation is closely related to the thermal

and viscoelastic behavior of HDPE.[32] As a semi-crystalline polymer, HDPE undergoes post-solidification shrinkage and molecular rearrangement during cooling and subsequent conditioning. Over time, this shrinkage can induce internal stresses and micro-scale debonding at the plastic–filler interface, leading to reduced load-bearing capacity under compression.

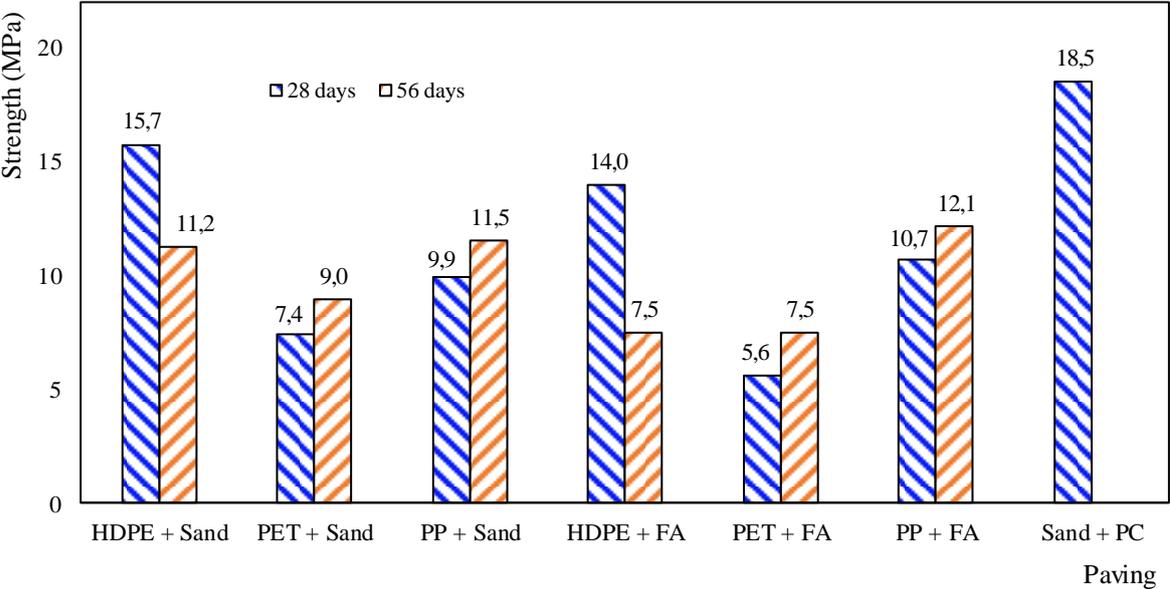


Figure 4. Compressive strength of various plastic paving against sand and fly ash

In contrast, PP-based mixtures exhibited more stable compressive strength behavior over time, although their strength levels were lower than those of HDPE at early ages. This indicates that while HDPE provides higher initial strength, its long-term performance may be compromised by shrinkage-related effects, whereas PP offers more consistent mechanical stability.

3.3. Effect of Filler Characteristics: Sand versus Fly Ash

The influence of filler characteristics on compressive strength is closely related to differences in particle size distribution, morphology, and bulk density of the aggregates used, as illustrated in Figures 6 and 7. Sand exhibits a well-graded particle distribution with relatively larger and more varied grain sizes, whereas fly ash consists of finer and more uniformly sized particles.



Figure 6. Well-graded sand aggregate



Figure 7. Fly ash grains are uniformly graded

According to SNI 1971:2011[33], natural sand typically has a bulk density ranging from 1,400 to 1,550 kg/m³ under normal conditions, with a moisture content not exceeding 5%. This higher density and broader gradation allow sand particles to pack more efficiently within the plastic matrix, promoting mechanical interlocking and the formation of continuous load-transfer paths. As a result, sand-filled composites tend to exhibit higher packing density and improved stress distribution, which contributes to enhanced compressive strength. In contrast, fly ash particles are significantly finer, with particle sizes

generally ranging from below 1 μm to approximately 100 μm , and in some cases extending up to 300 μm , as reported in SNI 9092:2022 [34] and related study [35]. The majority of fly ash particles are smaller than 20 μm , with only 10%–30% exceeding 50 μm . Due to this fine and uniform particle size, fly ash has a much lower bulk density than sand, typically ranging from 540 to 860 kg/m^3 in a loose state and 1,120 to 1,500 kg/m^3 when compacted [36].

While the fine particle size of fly ash can increase surface area contact, it also increases susceptibility to particle agglomeration and air entrapment during mixing. The lower bulk density and narrow gradation of fly ash limit effective packing within the molten plastic matrix, leading to a higher likelihood of internal void formation. These voids act as stress concentrators under compressive loading, thereby reducing load-bearing capacity. Consequently, fly ash-based mixtures generally exhibited lower compressive strength compared to sand-based mixtures across all plastic types evaluated in this study.

3.4. Surface Characteristics and Their Relation to Mechanical Performance

Surface observations of the paving blocks, shown in Figure 5, provide further insight into the mechanical behavior of the different mixtures. PP-based paving blocks displayed surface characteristics similar to conventional paving materials, with relatively few visible voids. This observation aligns with their moderate and stable compressive strength performance.

PET-based paving blocks exhibited a high number of voids and a brittle texture. This behavior suggests inadequate dispersion and weak interfacial bonding between PET and the filler materials. PET has a higher melting viscosity and limited wetting ability, which can hinder effective filler encapsulation and lead to void formation. These defects significantly reduce compressive strength by facilitating crack initiation and propagation under load.



Figure 5. Characteristics of plastic paving surfaces

HDPE-based paving blocks appeared dense and visually uniform, corresponding to their high early-age compressive strength. However, despite the dense surface appearance, long-term shrinkage of HDPE likely caused internal structural changes that were not visible on the surface but contributed to the observed reduction in compressive strength at later ages.

3.6. Summary of Observed Material Behavior

Overall, the compressive strength behavior of plastic-based paving blocks is governed by a combination of polymer-specific properties, filler characteristics, and thermal effects associated with processing and conditioning. HDPE provides superior early-age strength due to its stiffness and strong interfacial bonding with fillers [37,38]; however, its susceptibility to shrinkage and thermal relaxation results in reduced long-term performance. PP exhibits lower strength but greater stability over time, while PET

demonstrates limited suitability due to poor dispersion and high void content. These findings highlight the importance of considering polymer thermal behavior and composite mechanics when designing plastic-based paving blocks. Optimizing filler type and polymer selection is essential to achieving a balance between early-age strength and long-term mechanical stability.

4. Conclusion

This study investigated the compressive strength performance of plastic-based paving blocks produced using polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) in combination with sand and fly ash fillers. The results indicate that HDPE combined with sand provides the most favorable early-age mechanical performance, demonstrating its potential for use in paving applications where initial strength is required. Nevertheless, the findings also reveal important performance limitations. HDPE-based mixtures exhibited a noticeable reduction in compressive strength at later ages, which is attributed to shrinkage and time-dependent behavior inherent to HDPE. In comparison, PP-based paving blocks showed more stable strength development over time, although their overall strength remained moderate. PET-based mixtures displayed the weakest performance, largely due to poor dispersion and the formation of internal voids, which restricted effective load transfer.

From an engineering perspective, the results suggest that plastic-based paving blocks are suitable mainly for lower-grade paving applications, in accordance with SNI 03-0691-1996, but are not yet appropriate for high-load or long-term structural use without further material optimization. The superior performance of sand relative to fly ash highlights the importance of filler gradation and packing density in controlling the mechanical behavior of plastic–aggregate composites.

Limitations of this study include the limited number of specimens tested for each mixture and the focus on compressive strength as the primary performance indicator. Future research should involve larger sample sizes, evaluation of long-term durability and environmental exposure effects, and material modifications, such as improved mixing techniques, surface treatments, or coupling agents, to enhance interfacial bonding and mitigate shrinkage-related strength degradation. Overall, while the reuse of plastic waste in paving blocks offers environmental benefits, practical implementation must be guided primarily by mechanical performance and durability considerations. Addressing the identified limitations is essential for expanding the engineering applicability of plastic-based paving materials.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the grammar and clarity of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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