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From Waste to Walkways: Recycled Plastic Pavement Blocks for a Circular Economy

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Abstract

The indiscriminate disposal of plastic waste poses significant environmental and economic threats, necessitating innovative recycling strategies that align with circular economy principles. The primary objective was to assess the impact of varying plastic-to-sand ratios on the compressive strength of these composite pavement blocks, optimising resource utilisation. These objectives were achieved through research investigating the feasibility of utilising four common post-consumer thermoplastics—HDPE, PP, PET, and PS, as binding agents in pavement block production. This directly addresses the circular economy imperative by transforming waste into a valuable construction resource, minimising landfill burden, and creating a closed-loop system. Compared with conventional concrete pavers, these plastic-sand blocks offer the potential for a reduced carbon footprint by valorising waste materials and potentially decreasing reliance on energy-intensive cement production. The methodology involved melting each plastic type individually and combining it with sand at five different ratios: 3:7, 4:6, 5:5, 6:4, and 7:3 (plastic:sand). The resulting mixtures were moulded into pavement blocks and subjected to compressive strength testing. One-way ANOVA revealed varying optimal plastic-to-sand ratios for HDPE, PP, PET, and PS pavement blocks, as determined by compressive strength analysis. For HDPE, while ratios of 30:70, 50:50, 60:40, and 70:30 showed comparable performance, and the 40:60 combination exhibited the highest compressive strength. In contrast, PP mixtures demonstrated optimal strength at a 60:40 ratio, with the 40:60, 50:50, and 70:30 ratios showing similar behaviour that could be substituted. PET mixtures achieved peak strength at a 30:70 ratio, and only the 40:60 and 70:30 ratio combinations could be substituted without impacting the compressive strength. Similarly, PS mixtures exhibited optimal performance at a 50:50 ratio, with some substitution potential observed at 30:70, 40:60, 60:40, and 70:30 ratios. These findings demonstrate that specific plastic types have unique optimal mixing ratios with sand to achieve maximal compressive strength, thereby transforming plastic waste into durable pavement blocks that support a circular economy.

Keywords

Plastic Waste Recycling, Pavement Blocks, Compressive Strength, Plastic-Sand Ratios, Circular Economy, Thermoplastics (HDPE, PP, PET, PS)

1. Introduction

Globally, plastic production has increased dramatically in recent decades, posing significant threats to the environment and human health through the indiscriminate disposal of plastic waste (Geyer et al., 2017; Umar et al., 2024; Nayanathara Thathsarani Pilapitiya & Ratnayake, 2024; Hossain et al., 2021). The widespread domestic, industrial, and agricultural use of plastics has substantially contributed to their accumulation in landfills and the environment (Ritchie & Roser, 2018), posing a threat to ecosystems, wildlife, and food security (Lakhiar et al., 2024). Poor plastic waste management causes considerable environmental damage. Plastic debris harms both terrestrial and aquatic ecosystems, disrupting food webs and affecting multiple trophic interactions (Barnes et al., 2009). Ocean pollution is acute, with millions of tons of plastic debris entering and accumulating on the sea floor and surface annually (Jambeck et al., 2018), harming marine life. Plastic fragmentation into microplastics (i.e., sizes ranging between <5 mm and <0.1 μm) further complicates the issue (Wright & Kelly, 2017). While biodegradable plastic types can gradually degrade in the short term, the long-term persistence of non-biodegradable plastics exacerbates their environmental impacts (Andrady, 2011). Effective and sustainable waste management strategies and approaches are critical (Anon, 2017), requiring urgent, innovative solutions and a circular economy.

The construction industry relies on conventional materials like cement and concrete, because their durability significantly contributes to environmental and climate-change issues through increased greenhouse gas emissions. Notably, cement production represents the third-highest (i.e., 8%) contributor to anthropogenic greenhouse gases, explicitly constituting 4.8% sulfur oxide, 7.8%, and 6.4% particulate matter of size 2.5 microns of the global emissions (Miller & Moore, 2020) and affecting natural resources (Habert et al., 2010). This necessitates a shift towards sustainable alternatives, such as using recycled plastics as binders in pavement production, to reduce the construction industry's environmental impact.

The unsustainable "take-make-dispose" linear economy, characterised by resource depletion and environmental damage (Anon, 2023), contrasts sharply with a circular economy. The linear model contributes to climate change, pollution, and resource depletion. A circular economy decouples economic growth from resource consumption, minimising waste and maximising resource utilisation through reuse, repair, remanufacturing, and recycling (Geissdoerfer et al., 2017; Bocken et al., 2016). Adopting a circular economy is crucial for sustainable resource management, as it reduces demand for new resources, conserves natural resources, and decreases pollution and landfill waste (Murray, 2005). It fosters innovation and new business opportunities, and enhances economic stability. Ultimately, a circular economy provides a path to sustainable development, creating a more resilient, efficient, and equitable economic system (Sauvé et al., 2016) that addresses resource scarcity, waste, and climate change.

The growing concern about plastic waste influxes in the environment, as well as the environmental and conventional construction material effects, has spurred interest in sustainable alternatives, particularly the incorporation of recycled plastics into construction materials. Recycled plastics offer dual advantageous properties as a source of building applications and concurrently help regulate plastic waste proliferation in the environment. They can function as versatile components in composite materials, partially substituting for aggregates in concrete (Saikia & de Brito, 2012a, 2012b), and can be used to manufacture durable, weather-resistant building products such as bricks and paving stones (Al-Manaseer & Dalal, 1997), as well as for insulation (Fauzi et al., 2021). Careful formulation and testing are critical to mitigate potential alterations in mechanical strength and durability (Akbarzadeh et al., 2020). The growing plastic waste stream is driving research into innovative solutions, including the use of plastics in construction. Incorporating plastics into pavement blocks, also known as eco-blocks, is a promising avenue that potentially reduces landfill waste and provides a resilient alternative to conventional concrete blocks (Giddey et al., 2021).

Incorporating recycled plastics into construction, particularly pavement blocks, has attracted significant attention as a sustainable solution for waste management and infrastructure development (Da Silva et al., 2021; Alyousef et al., 2021). Research in this area encompasses a broad range of topics, including material properties, performance evaluation, environmental impact, and economic feasibility. Various techniques are employed, from partially replacing concrete aggregates with recycled plastic to fabricating blocks composed entirely of plastic, often with additives to enhance strength and UV resistance. The type of plastic utilised varies, with common choices including HDPE, LDPE, PET, and PP (Kalantar et al., 2019). A substantial body of research investigates optimal mix designs and plastic types, exploring the use of various recycled plastics such as HDPE, LDPE, PP, PET, and mixed plastic waste (MPW) in different proportions with traditional concrete components or as primary binding agents. Studies have demonstrated the feasibility of using recycled plastic as a partial substitute for aggregates (Kalantar et al., 2019), which may potentially enhance tensile strength and reduce water absorption. However, increased plastic content can reduce compressive strength while potentially enhancing ductility (Ghazavi & Roustaei, 2010). Further research explores the use of plastic fibres or particles as admixtures to enhance mechanical performance (Saikia et al., 2017). Other studies focus on developing pavement blocks entirely from plastic waste, examining the effects of various plastic types and additives on mechanical properties and UV resistance (Ramakrishna & Sundararajan, 2017). Additives such as stabilisers and fillers are often incorporated to enhance performance. The type of plastic and its content significantly impact the final block properties, including compressive strength. Studies typically explore a range of plastic content from 5% to 50% to identify optimal ratios for specific applications (Almeshal et al., 2020; Mohammed et al., 2020; Zulkernain et al., 2021).

The escalating generation of plastic waste represents a significant global challenge (Geyer et al., 2017). The widespread use of plastics, driven by their versatility and cost-effectiveness, results in substantial accumulation in landfills and the environment (Ritchie & Roser, 2018), posing threats to ecosystems, wildlife, and human health (Senthil Rathi et al., 2023; Akande & Beal, 2023). Inadequate plastic waste management leads to considerable environmental damage, as plastic debris disrupts both terrestrial and aquatic ecosystems and food webs (Barnes et al., 2009). Marine environments are particularly impacted, with millions of tons of plastic entering the oceans annually (Jambeck et al., 2018), which contribute to pollution and harm marine biota. Moreover, the fragmentation of plastic into microplastics introduces further complexities, with the potential to enter the food chain and pose health risks (Wright & Kelly, 2017). The long-term persistence of non-biodegradable plastics exacerbates these environmental issues (Andrady, 2011). These concerns underscore the urgent need to transition away from the linear "take-make-dispose" model towards circular, sustainable waste management strategies (Anon, 2017). This unsustainable linear economy, characterised by resource depletion and environmental damage (Anon, 2013), contrasts sharply with a circular economy. While the linear model assumes infinite resources and contributes to climate change, pollution, and resource depletion, a circular economy seeks to decouple economic growth from resource consumption. This is achieved by minimising waste and maximising resource utilisation through reuse, repair, remanufacturing, and recycling (Geissdoerfer et al., 2017; Bocken et al., 2016), with key principles including designing out waste, keeping products in use, and regenerating natural systems (Anon, 2023).

The construction industry's heavy use of cement and concrete contributes to environmental problems through carbon emissions and resource depletion (Gursel et al., 2014; Olivier et al., 2017; Andrew, 2018). Shifting to sustainable alternatives, such as recycled plastics as pavement binders, is crucial for reducing the industry's environmental impact. The rising concern over plastic waste and the environmental impact of traditional construction materials has driven interest in sustainable solutions, with the use of recycled plastics in construction as a particularly promising approach. Recycled plastics offer desirable properties for building applications while addressing the issue of plastic waste. They can serve as versatile components in composite materials, partially replacing aggregates in concrete (Saikia & de Brito, 2012a, 2012b). They can be used to manufacture durable, weather-resistant building products, such as bricks and paving stones (Al-Manaseer & Dalal, 1997), as well as for insulation (Fauzi et al., 2021). However, careful formulation and testing are necessary to address changes in mechanical strength, durability, and insulation properties (Akbarzadeh et al., 2020).

The increasing use of recycled plastics in pavement blocks is promising; however, several research gaps hinder its broader adoption. This study addresses some of these limitations by systematically analysing specific recycled plastics and optimising mix ratios for compressive strength. Firstly, a Comparative Analysis of Multiple Plastic Types is lacking. Existing studies often focus on one or two plastic types in sand composites, limiting our understanding of how different plastics (PP, PET, PS, and HDPE) individually affect compressive strength (Al-Manaseer & Dalal, 2017; Tulashie et al., 2020; Acuña-Pizano et al., 2022). This study directly compares the compressive strength of these four plastics using systematic variations in mix ratios. Secondly, there is a need to optimise mix ratios. Many studies lack a systematic, statistically rigorous optimisation of mix ratios across multiple plastic types to maximise compressive strength and often do not explore ratios where the plastic content exceeds that of sand (Kalantar et al., 2019; Saikia et al., 2017). Our research uses ANOVA to determine significant differences between mixes and to compare the compressive strength performance across the different mix formulations to identify optimal mix proportions, testing a range of sand-to-plastic ratios (3:7, 4:6, 5:5, 6:4, 7:3) specifically for each plastic type, enabling the identification of optimal ratios for compressive strength and plastic content.

2. Materials and Methods

2.1. Materials

This study examined the use of recycled plastics and sand in the production of pavement blocks. The following sections detail the materials used, their sources, and their characteristics.

2.1.1. Recycled Plastics

Four types of recycled plastics were used in this study: HDPE, PP, PET, and PS. All recycled plastics were sourced locally from restaurants, water sachet-producing companies, and social events. The plastics were collected, cleaned, and shredded into flakes using a shredder. The HDPE was primarily sourced from water sachets. The HDPE was chosen for its high tensile strength and chemical resistance (Giddey et al., 2021). The recycled PP was obtained from containers, buckets, and other rigid packaging materials. PP was chosen for its high strength, flexibility, and fatigue resistance at lower temperatures (Nanda et al., 2023). The recycled PET was derived from plastic bottles and containers. The PET was selected for its high strength and stiffness. Polystyrene (PS) was selected due to its significant presence in the waste stream, primarily as food containers and packaging, and the associated recycling challenges. Its rigidity and moldability make it potentially suitable as a binding agent in pavement blocks, addressing a research gap and unlocking a recycling pathway for a commonly landfilled material. All plastics were cleaned with water and dried before shredding, ensuring that no contamination was present in the final blocks.

2.1.2. Sand

The sand used in this study was locally sourced from Abosso in the Tarkwa Nsuaem Municipal Assembly. The sand was medium-coarse, composed predominantly of quartz. The sand was sieved to remove debris and oversized particles, and the particle size distribution was determined through sieve analysis. No additional materials, such as binding agents or additives, were used to prepare the pavement blocks. The study focused on using recycled plastics and sand without adding other components to isolate the effects of the plastic type and mix ratios.

2.2. Methods

2.2.1. Analysis of Particle - Size Distribution (Gradation) and Fineness Modulus (BS 812: Part 103)

The particle size distribution (gradation) of the sand was determined according to established BS standard test methods. A representative 500 g sample of dry fine aggregate was oven-dried at 105˚C to constant mass before undergoing sieve analysis. The dried sample was then mechanically sieved through a series of sieves with aperture sizes of 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm and 0.15 mm. Following sieving, the mass of sand retained on each sieve was measured and expressed as a percentage of the total initial sample mass using Equation 1. The resulting data were used to generate a grading curve, characterise the fineness of the aggregate, and determine the per cent passing and per cent retained for each sieve, calculated using Equations 1 and 2, respectively.

Calculations:

$$\%\text{Retained on any sieve} = Ms/Md \times 100\% \qquad (1)$$

where Ms = Mass retained on the sieve;

Md = Total Mass of sample used.

$$\%\text{Passing through any sieve} = 100 - \left[\text{Cumulative \% Retained on any sieve}\right] \qquad (2)$$

2.2.2. Sand-Plastic Composite Mixture Preparation

The sand-plastic composite mixture was formulated using defined ratios of sand and recycled plastics.

Plastic Melting: For each mixing ratio, the shredded plastic was added to a temperature-controlled, palm-kernel-heated mixing container. The plastic was heated to a molten state, ensuring that all flakes were completely melted. The specific temperature for each plastic was as follows, based on the findings of previous studies: HDPE at 180˚C (Giddey et al., 2021), PP at 170˚C (Nanda et al., 2023), PET at 260˚C (Awale et al., 2020), and PS at 160˚C (Singh et al., 2020).

Sand Addition: The measured amount of sand was gradually added to the mixing container once the plastic was fully molten. The mixture was continuously stirred using a metal steel stirrer for 10 minutes to achieve a homogeneous mix.

This ensured that the sand particles were well distributed throughout the molten plastic.

Specific Sample Preparation: The above steps were followed for each mixing ratio used in this study, and all new sample mixtures were made in a clean container to prevent cross-contamination between tests using different plastics.

2.2.3. Mix Ratios and Sample Numbers

The following sand-to-plastic ratios were used to prepare the pavement blocks. For each ratio, twelve samples were prepared. The mix ratios were calculated by volume. The specific mix ratios tested are shown in **Table 1**.

Table 1. Composition ratio of pavement blocks by mass.

Mix Ratio	Plastic	Sand	Number of Samples
Mix 1	3	7	12
Mix 2	4	6	12
Mix 3	5	5	12
Mix 4	6	4	12
Mix 5	7	3	12

All samples tested were prepared using only one type of plastic at a time for each mix ratio. When the testing was to start on Mix 1 using a particular plastic, example PP, all the previous mixture was removed from the container, and the new plastic-and-sand ratio was prepared separately to ensure no cross-contamination.

2.2.4. Pavement Block Formation

The molten sand-plastic mixture was immediately poured into steel moulds. The moulds were designed to create blocks that are 50 × 50 × 50 mm^3. These dimensions were selected to be consistent with standard dimensions for pavement block testing, offering a reasonable size that is both small enough to work with in the lab and large enough to provide useful testing results. The interior of the mould was coated with a thin layer of oil to facilitate easy demoulding. The molten mix was poured carefully to minimise air pockets and to ensure uniform distribution within the mould. Once poured, the moulds were left to cool and cure at ambient temperature in the open air and were demoulded. The blocks were cured and were inspected for any defects before testing. All pavement blocks produced in this study were of a standard square shape.

2.3. Experimental Procedure

This section outlines the experimental procedures for evaluating the compressive strength of sand-plastic composite pavement blocks, including the testing equipment, loading rate, curing conditions, and sample selection processes.

2.3.1. Unconfined Compressive Strength (UCS)

This test was conducted to determine the compressive strength of the pavement block, also known as the pavement block's crushing strength. The most popular method for assessing concrete's hardened quality and capacity to withstand loads is its compressive strength (Tuffour, 2016). ASTM D29.38 was the standard reference used in the compressive strength determination. The surface of the specimen was smoothed to ensure it was flat and aligned with the compression machine, thereby ensuring uniform load transfer. A cube of pavement block, 50 × 50 × 50 mm^3, was used, where the length and the diameter were determined. The specimen was then placed between the upper and lower plates of the calibrated compression machine. By turning on the machine and adjusting the stress rate knob, loads were continually delivered to the specimen at consistent stress rates until failure occurred within 1 - 2 minutes of loading. Next, the specimen's maximum load at failure was noted. Afterwards, the UCS for the specimen was estimated using equation 3.

$$\text{UCS} = \left(\text{Failure Load } (P)\right) \Big/ \left(\text{Area of Specimen } (A)\right) \tag{3}$$

$$\text{Area of specimen} = \left(\pi d^2\right) \Big/ 4 \tag{4}$$

All compressive strength tests were conducted using a uniaxial compressive machine tester (C089-19N concrete compression machine, 3000 kN automatic, Servo-plus Evolution) as shown in 4 (A-G).

Compressive Strength Testing: The compression testing of each sample was performed at 7, 14, and 28 days of curing. At each time, a separate batch of samples was used to avoid compromising the material properties by retesting.

Curing Conditions and Block Ages: The pavement blocks were cured by open-air drying in the laboratory under ambient temperature and humidity conditions. The blocks were placed on a flat surface and allowed to dry for 28 days. The compressive strength of the blocks was tested at three different curing ages: 7, 14, and 28 days. These timeframes were selected to evaluate the development of compressive strength over time and are in line with previous research on cement-based materials (Neville, 2011). Before testing, each selected sample was visually inspected for any apparent defects, such as cracks or uneven surfaces. Blocks with severe defects were excluded from testing and replaced with randomly selected blocks from the same batch to avoid inconsistent or inaccurate results. This visual inspection process was critical to improving the quality of the experimental data. The blocks were all tested in the same orientation to avoid any directional issues with the compression test results.

2.3.2. Statistical Analysis

This section outlines the statistical methods used to analyse the compressive strength data collected in this study. One-way analysis of variance (ANOVA) was the primary statistical tool used to compare the mean compressive strengths across different sand-plastic mix ratios, with post-hoc tests for multiple comparisons.

One-way ANOVA was utilised to determine if there were any statistically significant differences in the mean compressive strength between the different sand-plastic mix ratios. One-way ANOVA is a parametric test used to compare the means of two or more independent groups when the independent variable is categorical (in this case, mix ratio) and the dependent variable is continuous (compressive strength) (Montgomery, 2017). The assumptions of one-way ANOVA were assessed using diagnostic plots and Levene's test, as recommended in the literature (Zhou et al., 2023). A one-way ANOVA was performed on the compressive strength data obtained for each mix ratio at the three curing ages (7, 14, and 28 days). This allowed for comparing the performance of different mixes while controlling for variations within each period. The F-statistic from the ANOVA test was used to determine if a statistically significant difference exists across the mix ratios.

If the one-way ANOVA revealed a statistically significant difference in compressive strength among the mix ratios ($p < 0.05$), post hoc tests were used to perform multiple comparisons and determine which specific mix ratios were significantly different from one another (Field, 2018). Specifically, the *Tukey's Honestly Significant Difference (HSD) test* was employed. Tukey's HSD test is a commonly used method for pairwise comparison of means when ANOVA reveals a significant overall effect. It controls the family-wise error rate, thus reducing the risk of falsely identifying differences between groups (Tukey, 1949).

The significance level (alpha) used for all statistical tests in this study was set at *$p< 0.05$*. This means that a probability of less than 5% ($p < 0.05$) that the observed results could have occurred by chance was considered statistically significant enough to reject the null hypothesis. This level is commonly used in scientific research to identify statistical significance (Fisher, 1925). Using one-way ANOVA (SPSS), followed by Tukey's HSD post-hoc tests, allows for systematically determining the effect of sand-plastic mix ratios on compressive strength while controlling for the potential for Type I error and ensuring robust conclusions.

3. Results and Discussion

3.1. Molten HDPE-Sand-Bonded Pavement Blocks

Results of the compressive strength development of HDPE-sand pavement blocks at different HDPE percentages indicate that compressive strength increased with curing age, reaching a maximum at 28 days (**Figure 1**), which is consistent with previous findings (see Abas & Pandey 2015; Jaivignesh & Sofi 2017; Alani et al., 2019; Gashahun, 2020). Several physical mechanisms contribute to this behaviour, even though HDPE is a thermoplastic and does not undergo the same type of chemical curing as cement-based concrete. The increased compressive strength of HDPE-sand blocks over time is primarily driven by consolidation and improved mechanical interlocking between the HDPE and sand during cooling and solidification (Campbell, 2010). Secondary crystallisation within the HDPE matrix also contributes, leading to improved intermolecular chain packing and increased van der Waals forces (Mallick, 2007; Ward & Sweeney, 2004). Finally, stress relaxation within the HDPE matrix helps to minimise internal stresses, further enhancing strength and creep resistance over time (Ward & Sweeney, 2004). The 30% HDPE mixture showed a modest increase in strength, rising from 11.83 N/mm^2 at 7 days to 12.51 N/mm^2 at 28 days. Similarly, all other HDPE mixtures (40%, 50%, 60%, and 70%) also exhibited an increasing trend in compressive strength with curing time, although all percentage increases were below 15%.

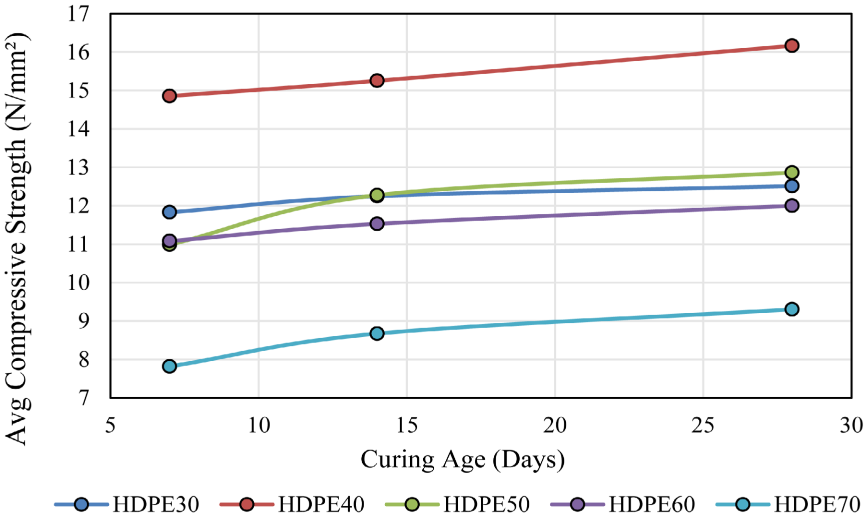

Figure 1. Variation of compressive strength with curing age using molten HDPE-sand-bonded pavement blocks.

The optimal compressive strength observed with the 40% HDPE mix indicates a balance between having sufficient HDPE to fully encapsulate the sand particles and maintaining a structure that allows for effective load transfer between the HDPE matrix and the sand reinforcement (Campbell, 2010). Higher HDPE percentages may lead to a softer, more deformable matrix, while lower percentages may not provide sufficient binding and stress distribution capacity; hence, 40% gives optimal performance. According to Mageswari & Arunachalam (2019), the optimal blend ratio for compressive strength over time is 40% HDPE.

3.2. Impact of Percentage Replacement of HDPE

After 28 days of curing, HDPE-sand pavement blocks exhibited a compressive strength range of 9.30 to 16.16 N/mm^2 (**Figure 1**), suggesting their potential for various load-bearing applications. Increasing the HDPE content from 30% to 40% led to a significant increase in compressive strength (25.45%), likely due to improved binding within the material. However, further increases in HDPE to 50%, 60%, and 70% resulted in compressive strength reductions of 22.74%, 6.92%, and 25.35%, respectively, indicating a potential saturation point beyond the optimal 40% HDPE. This strength reduction is consistent with previous studies, which have demonstrated optimal compressive strength in HDPE-sand composites within a 40% - 50% HDPE content range (Tawfiq & Hassan, 2019; Ahmad & Thaheem, 2020; Memon & Siddiqui, 2020). These results suggest that while higher HDPE content can improve bonding mechanisms up to a certain point, an excessive amount can limit the bonding space for sand particles, thereby weakening the structure. Further analysis is needed to confirm this mechanism and define the saturation point for HDPE-sand mixtures.

3.3. Molten PP-Sand-Bonded Pavement Blocks

The results of the compressive strength development of PP-sand pavement blocks show increases in strength with increasing curing age for most mixtures (**Figure 2**). The 30% PP mixture slightly decreased by 2.1% at 14 days, followed by a 10.22% increase at 28 days. The 40% PP mixture increased by 3.14% and 4.26% at 14 and 28 days, respectively, while the 50% PP mix increased by 3.12%, and coefficients are mitigated by stress relaxation, improving long-term strength and creep resistance (Ward & Sweeney, 2004), 10.06% at 14 and 28 days. The varied strength behaviour across PP percentages likely reflects the complex interplay of these mechanisms, underscoring the importance of achieving an optimal PP-sand ratio for efficient stress transfer and particle packing (Campbell, 2010), 10.06% at 14 and 28 days. The 60% PP mixture showed no change at 7 and 14 days but increased by 11.07% at 28 days. The 70% PP mixture increased by 6.6% and 6.84% at 14 and 28 days, respectively. Overall, these results demonstrate a general trend of increasing compressive strength with curing age, per the findings of Jagadish et al. (2016). While the magnitude of increase varied between the PP percentages, a general trend of strengthening over time exists. The increasing compressive strength of PP-sand blocks over time is attributed to a combination of mechanisms. As molten PP cools and solidifies, it shrinks and consolidates around the sand, enhancing mechanical interlocking and improving resistance to compression (Campbell, 2010). While PP solidifies quickly, its polymer chains continue to organise through secondary crystallisation, increasing intermolecular forces and strength, influenced by the PP grade and cooling conditions (Mallick, 2007; Ward & Sweeney, 2004). Furthermore, thermal stresses arising from differing thermal expansion.

3.4. Impact of Percentage Replacement of PP

PP-sand pavement blocks exhibited compressive strengths ranging from 14.60 to 23.83 N/mm^2 (**Figure 2**). Increasing the PP content from 30% to 60% resulted in increases in compressive strength of 22.06%, 16.98%, and 9.82%, respectively. However, further increasing the PP content to 70% led to a decrease in compressive strength of 21.9%. The 16.98% increase in compressive strength when raising PP content from 40% to 50% is comparable to the enhancement reported by Zhang et al. (2020), where a maximum increase of 19.5% was observed at 50% PP waste. The 9.82% increase observed when raising PP from 50% to 60% also aligns with the improvement reported by Akindahunsi et al. (2020), who also followed a 13.2% increase with 60% PP.

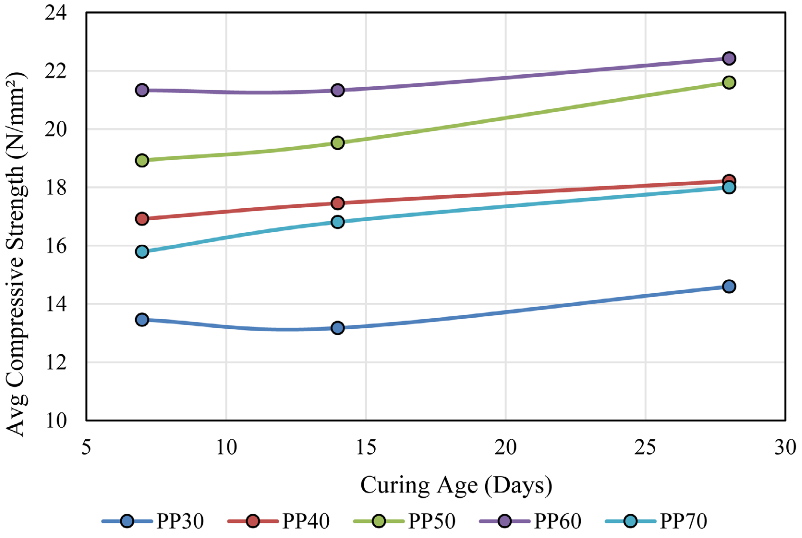

Figure 2. Variation of compressive strength with curing age using molten PP-sand-bonded pavement blocks.

3.5. Molten PET-Sand-Bonded Pavement Blocks

The results of the compressive strength development of PET-sand pavement blocks with varying curing ages show no clear trend in strength changes from 7 to 28 days (**Figure 3**). The 30% PET mixture experienced a 3.77% decrease at 14 days but showed an increase of 5.6% at 28 days. The 40% PET mixture increased by 6.33% at 14 days and 5.86% at 28 days, while the 50% PET mixture showed 17.88% at 14 days and 2.02% at 28 days. The 60% PET mix displayed a 5.63% increase at 14 days and a 27.88% increase at 28 days, and the 70% PET mixture increased by 10.22% and 10.08% at 14 and 28 days, respectively. While these findings generally indicate an increase in compressive strength with curing age, which aligns with the observations of Jain et al. (2019), the overall compressive strength decreased when the PET content increased from 30% to 70%. The 30% PET mix exhibited the highest compressive strength, consistent with Ababio Ohemeng et al. (2014), who also observed a decrease in compressive strength with increasing PET content. This decline can be attributed to a weakened bond between the PET and sand particles, leading to pore deformation and cavity formation, as confirmed in previous studies (Ababio Ohemeng et al., 2014; Jain et al., 2019). The compressive strength of PET-sand blocks is governed by competing mechanisms. Consolidation and mechanical interlocking drive initial strength gains, relying on effective PET wetting and adhesion to sand (Campbell, 2010). While PET exhibits limited secondary crystallisation and stress relaxation helps mitigate thermal stresses, their contributions are less significant than mechanical interlocking (Mallick, 2007; Ward & Sweeney, 2004). However, increasing the PET content beyond an optimal point weakens the interfacial bond and promotes pore formation (Ababio Ohemeng et al., 2014; Jain et al., 2019), ultimately outweighing the benefits of consolidation and leading to a decrease in overall strength. Achieving optimal strength requires balancing PET content to maximise interfacial adhesion and minimise porosity (Campbell, 2010).

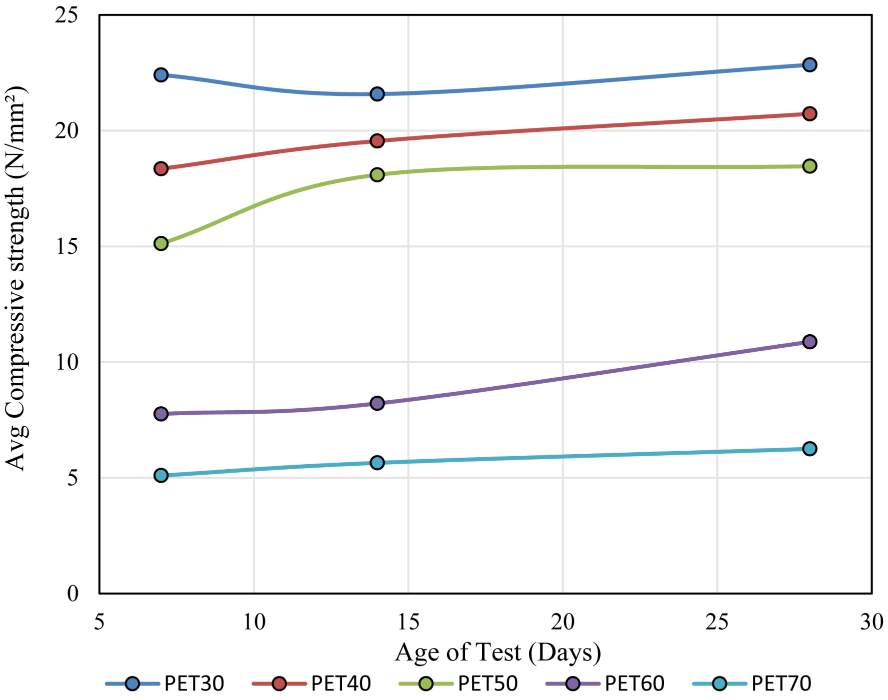

Figure 3. Variation of compressive strength with curing age using molten PET-sand-bonded pavement blocks.

3.6. Impact of the Percentage Replacement of PET

Figure 3 shows that the compressive strength of PET-sand pavement blocks decreased from 22.84 N/mm^2 for PET30 to 6.25 N/mm^2 for PET70, indicating an inverse relationship between PET content and compressive strength. This trend aligns with the findings of Mohajerani et al. (2014), who also observed a reduction in compressive strength with increasing PET waste content, with a maximum reduction of 16.7% at 50% PET content. While the present study shows a more substantial reduction with 50% PET (a strength of 18.46 N/mm^2), the variation in reduction magnitude can be attributed to differences in pavement block preparation methods (manual versus mechanical mixing).

3.7. Molten PS-Sand-Bonded Pavement Blocks

Figure 4 illustrates the development of compressive strength in PS-sand pavement blocks with varying curing ages. The 30% PS mixture exhibited an initial compressive strength of 56.28 N/mm^2 at 7 days, increasing by 0.88% at 14 days and 2.72% at 28 days. Similarly, the compressive strength increased for PS40, PS50, PS60, and PS70 blocks by 1.92%, 2.75%, 4.74%, and 14.11%, respectively, at 14 days compared with 7 days. At 28 days, the strength increased by 2.33%, 4.43%, 11.46%, and 5.9%, respectively. These results demonstrate an overall trend of increasing compressive strength with curing age for PS-sand pavement blocks, consistent with previous work by Singh et al. (2018). The increasing compressive strength of PS-sand blocks is primarily driven by consolidation, which enhances mechanical interlocking between the PS matrix and sand particles (Campbell, 2010). While PS is amorphous, some structural adjustments below its glass transition temperature might contribute to stability (Ward & Sweeney, 2004). Furthermore, stress relaxation mitigates thermal stresses, improving strength and creep resistance (Ward & Sweeney, 2004). Strength variations at different PS percentages underscore the importance of an optimal PS-sand ratio for effective particle packing and stress distribution (Campbell, 2010).

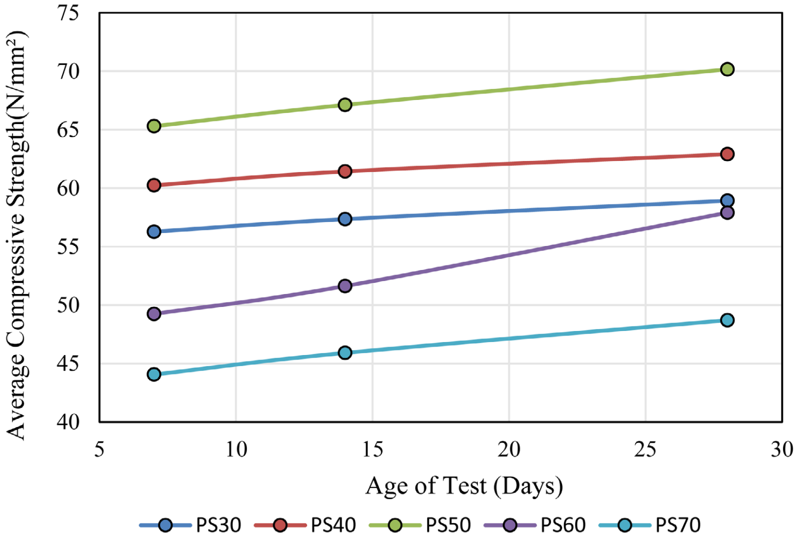

Figure 4. Variation of compressive strength with curing age using molten PS-Sand-bonded pavement blocks.

3.8. Impact of Percentage Replacement of PS

At 28 days, PS-sand pavement blocks exhibited compressive strengths of 58.93 N/mm^2, 62.90 N/mm^2, 70.16 N/mm^2, 54.19 N/mm^2, and 48.71 N/mm^2 for 30%, 40%, 50%, 60%, and 70% PS content, respectively (**Figure 4**). Increasing the PS content from 30% to 40% and 50% resulted in compressive strength increases of 6.5% and 10.91%, respectively. However, subsequent increases to 60% and 70% PS content resulted in decreases of 19.3% and 17.26% in compressive strength. The 6.52% increase from 30% to 40% PS is consistent with the 9.7% increase reported by Sun et al. (2021) at 30% PS content, and the 10.91% increase from 40% to 50% PS aligns with the 11.6% increase reported by Liu et al. (2019). The decrease in compressive strength beyond 50% PS content is likely due to sand agglomeration (Gao et al., 2019), which reduces the sand surface area and mix workability. This agglomeration also creates air-filled gaps, which limit the filling of cement paste and reduce density and compressive strength. Furthermore, as highlighted by Aliyu et al. (2020), the mechanical and durability properties of pavement blocks are also affected by the preparation method and conditions.

3.9. Statistical Analysis of Compressive Strength in Plastic-Sand Mixtures

A one-way ANOVA was performed using SPSS to assess the effect of varying plastic-to-sand ratios on the compressive strength of blocks made with different types of plastic. Prior to ANOVA, the data were confirmed to meet the assumptions of normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. Results from the ANOVA (**Table 2**) revealed a significant effect of plastic-sand ratio on compressive strength for all plastic types ($p < 0.05$). This indicates that the mean compressive strengths differed significantly across the tested ratios. Post-hoc Tukey's HSD tests were conducted to identify which specific ratios exhibited statistically significant differences. Since each plastic type involved five ratios, resulting in 10 unique pairwise combinations, 10 post-hoc tests were performed for each type of plastic to assess the specific pairwise differences. These analyses identified specific plastic-sand ratios that had significantly different compressive strengths.

Table 2. One-way ANOVA output for compressive strength of pavement blocks.

Type of Plastic Used	Mean	F	Significance
HDPE	18.928	(4, 10) = 20.599	p = 0.000
PP	28.003	(4, 10) = 30.527	p = 0.000
PET	129.053	(4, 10) = 119.037	p = 0.000
PS	235.082	(4, 10) = 27.538	p = 0.000

Post hoc Tukey's HSD tests (**Table 3**) for HDPE-sand mixtures revealed that six out of ten pairwise comparisons showed no statistically significant difference in mean compressive strength. Specifically, the combinations HDPE30-HDPE50, HDPE30-HDPE60, HDPE50-HDPE60, and HDPE60-HDPE70 exhibited similar compressive strengths. These findings suggest that, for waste management purposes, substituting HDPE30 with HDPE60 or HDPE50 with HDPE60, and HDPE60 with HDPE70 is feasible without significantly affecting compressive strength. However, the HDPE40 combination demonstrated the highest compressive strength, showing statistically significant differences when compared to other ratios, thus indicating its optimal use for applications requiring the highest strength. This finding is consistent with the study by Nagrale et al. (2019), which also concluded that 40% HDPE content resulted in optimal compressive strength.

Post-hoc analysis of PP-sand mixtures (**Table 4**) revealed that six of the ten pairwise comparisons showed statistically significant differences in mean compressive strength. Notably, the combinations PP40-PP50, PP40-PP70, and PP50-PP60 exhibited no significant differences, suggesting that PP40 can substitute for PP50 and PP70 and PP60 can substitute for PP50, for waste management purposes. However, PP60 displayed the highest compressive strength, demonstrating significant differences compared to other combinations. These results suggest that a 60% PP content is optimal for compressive strength in PP-sand pavement blocks. These findings align with those of Dissanayake et al. (2017), who observed a positive correlation between PP content and compressive strength up to 60%, beyond which the strength decreased, also suggesting a 60% PP content as the ideal for pavement block manufacturing.

Table 3. Post hoc test of pavement blocks made with HDPE and sand (significant at $p < 0.05$).

Sample ID (i)	Sample ID (j)	Mean Difference (i-j)	Significance
HDPE30	HDPE40	−3.361	0.011
	HDPE50	−0.313	0.994
	HDPE60	1.468	0.387
	HDPE70	3.465	0.009
HDPE40	HDPE50	3.048	0.020
	HDPE60	4.829	0.001
	HDPE70	6.826	0.000
HDPE50	HDPE60	1.780	0.230
	HDPE70	3.778	0.005
HDPE60	HDPE70	1.997	0.154

Table 4. Post hoc test of pavement blocks made with PP and sand (significant at $p < 0.05$).

Sample ID (i)	Sample ID (j)	Mean Difference (i-j)	Significance
PP30	PP40	−3.787	0.005
	PP50	−6.273	0.000
	PP60	−7.952	0.000
	PP70	−3.125	0.017
PP40	PP50	−2.486	0.059
	PP60	−4.165	0.002
	PP70	0.663	0.909
PP50	PP60	−1.679	0.274
	PP70	3.149	0.016
PP60	PP70	4.827	0.001

Post-hoc analysis of PET-sand mixtures (Table 5) revealed statistically significant differences in mean compressive strength for nine of ten pairwise comparisons. The only pair that did not show a significant difference was PET40-PET70. This suggests that PET70 could be used as a substitute for PET40 in pavement block production for waste management purposes. However, the PET30 combination exhibited the highest compressive strength, making it the optimal mix.

This finding aligns with previous studies, which have suggested a 20% - 30% PET content combined with 70% - 80% sand for achieving pavement blocks with good compressive strength and durability (Oyedepo & Akinmusuru, 2016; Hamed et al., 2011).

Table 5. Post hoc test of pavement blocks made with PET and sand (significant at $p < 0.05$).

Sample ID (i)	Sample ID (j)	Mean Difference (i-j)	Significance
PP30	PET40	5.334	0.001
	PET50	7.629	0.000
	PET60	13.327	0.000
	PET70	16.61	0.000
PP40	PET50	2.296	0.124
	PET60	7.993	0.000
	PET70	11.276	0.000
PP50	PET60	5.698	0.000
	PET70	8.981	0.000
PP60	PET70	3.283	0.021

Post-hoc analysis of PS-sand mixtures (**Table 6**) indicated that six of ten pairwise comparisons showed statistically significant differences in mean compressive strength. The combinations PS30-PS40, PS30-PS60, PS40-PS50, and PS60-PS70 showed no significant differences, indicating that these combinations could be interchanged without a significant impact on compressive strength. However, the results show that the optimal PS-sand pavement block for compressive strength is achieved with PS50. This finding is supported by prior research, which has shown good compressive strength and durability with mixtures containing 50% - 60% PS and 40% - 50% sand, with Wu et al. (2019) specifically identifying 50% PS as optimal.

3.10. Exploring the Circular Economy Potential of Plastic-Sand Composites

The utilisation of (HPDE, PP, PET, and PS)-sand composites for pavement block production aligns with the principles of a circular economy by transforming plastic waste into a valuable construction resource. Each block of 50 × 50 × 50 mm^3 incorporates 0.070 kg of recycled plastic, diverting it from landfill disposal and reducing the demand for virgin plastic production. Compared to conventional concrete pavers, which rely on energy-intensive cement production, these composites offer the potential for a reduced carbon footprint. While the durability of (HPDE, PP, PET and PS)-sand blocks is a key consideration, our research aims to optimise the plastic-sand ratio to achieve acceptable compressive strength and longevity.

Table 6. Post hoc test of pavement blocks made with PS and sand (significant at $p < 0.05$).

Sample ID (i)	Sample ID (j)	Mean Difference (i-j)	Significance
PP30	PS40	−4.006	0.486
	PS50	−11.675	0.004
	PS60	5.831	0.18
	PS70	11.291	0.006
PP40	PS50	−7.669	0.056
	PS60	9.837	0.014
	PS70	15.298	0.001
PP50	PS60	17.506	0.000
	PS70	22.967	0.000
PP60	PS70	5.460	0.225

4. Conclusions and Future Prospects

4.1. Conclusions

This research investigated the feasibility of cement-free pavement blocks made from various ratios of recycled HDPE, PP, PET, and PS plastics mixed with sand. Compressive strength was evaluated for blocks containing 3:7, 4:6, 5:5, 6:4, and 7:3 plastic-to-sand ratios, with the 5:5 ratio providing the highest compressive strength, allowing for some substitutions to be made for waste management purposes. This validates the potential of using these recycled plastic-sand mixtures to produce durable pavement blocks, aligning with the principles of a circular economy approach. One-way ANOVA and post-hoc analysis revealed optimal ratios for each plastic-sand pavement block at 28 days were observed for HDPE (40:60, 16.16 N/mm^2), PP (60:40, 22.43 N/mm^2), PET (30:70, 22.84 N/mm^2), and PS (50:50, 70.16 N/mm^2), which provided the highest compressive strength, with some substitutions possible for waste management purposes. This validates the potential of using these recycled plastic-sand mixtures to produce durable pavement blocks, aligning with the principles of a circular economy approach.

4.2. Future Prospects

While this research provides valuable insights into the development of compressive strength in plastic-sand pavement blocks, it is essential to acknowledge certain limitations. Its exclusive focus on compressive strength limits the findings of this study. While this is a key performance indicator, further research is needed to evaluate other crucial properties for pavement applications, such as water absorption, abrasion resistance, durability under thermal cycling, and UV degradation. These properties are critical for assessing the long-term viability and performance of plastic-sand composites as a sustainable pavement material.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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