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Utilization of Plastic Waste in Road Paver Blocks as a Construction Material

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Abstract: India is confronted with the substantial issue of plastic debris due to the absence of an efficient waste management infrastructure. Recycled plastic has the potential to enhance various construction materials, such as roofing tiles, paving blocks, and insulation. The aforementioned materials possess notable attributes such as high strength, low weight, and exceptional resistance to extreme temperatures and humidity. The objective of this study is to ascertain feasible alternatives for manufacturing road paver blocks utilizing plastic waste (Polyethene terephthalate (PET)), and M-sand (stone dust). Three variations of a discarded plastic cube measuring 150 mm × 150 mm × 150 mm were prepared for the experiment. The experimental findings indicated that a ratio of 1:4 was determined to be the most effective in achieving the desired level of compressive strength. I-section road and brick paver blocks were produced as an alternative to the traditional concrete ones. Compressive strength tests were performed on I-sections and brick paver blocks, revealing that the 1:4 mix ratio exhibited the highest average compressive strength for both materials. The findings indicated that including plastic waste positively impacted the compressive strength of the I-sections and brick paver blocks. Additionally, the quality grading of these materials was evaluated using an ultrasonic pulse velocity test. The ultrasonic pulse velocity test results demonstrated a high-quality grading for the I-sections and brick paver blocks. Scanning electron microscopy (SEM) tests assessed the microstructural behavior and performance. The results of this study demonstrate that incorporating plastic waste in combination with M-sand can effectively improve the mechanical characteristics of composite materials, rendering them viable for use in construction-related purposes.

Keywords: plastic waste; PET; M-sand; road paver block; compressive strength

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1. Introduction

Plastic is a material that has become ubiquitous in today's society. Plastic's small size and light weight make it a suitable material for many modern reusable products. Plastic is widely used for containers, bottles, food storage, and packaging [1]. Plastic's inability to break down is a significant issue. The polymer chemicals used to make plastic are not biodegradable. Plastic is a restorative material that is flexible, robust, and rigid, it becomes waste after its use and pollutes the air and land. Recycling is processing the used material or waste into new products to prevent the demolition of potentially valuable materials [2]. The increased popularity of using eco-friendly, low-cost, and lightweight construction materials in the building industry has brought about the need to investigate how this can be achieved while benefiting the environment and maintaining the material requirements and their standards [3]. India currently generates approximately 1.45 Lakh metric tons of solid waste, 35% of which is dry waste. Plastic is the major component of this dry waste. India generates around 9.4 million tons per annum of plastic waste out of which only 5.6 million tons per annum is recycled. It is projected that the plastic waste generation will grow by more than three times of current levels by 2031 [4]. Polyethene terephthalate (PET) is a polymer deemed safe to be mechanically recycled and used in food contact applications [5]. Utilizing recycled PET in construction reduces the need for new polymeric materials, significantly impacting pollution (e.g., carbon dioxide emission and waste disposal problems) [6]. Using plastic waste in construction will significantly enhance the sustainability of the environment and serve as a reliable source of materials for construction purposes [7,8]. Researchers have studied how plastic waste may be combined with other raw materials to make plastic–sand bricks and other construction materials [9–13]. Pradeep et al. [14], in the context of densely populated urban slums, explores the use of plastic bottles as one of the urban wastes for building construction and how it can lead to sustainable development. They also emphasize the benefits of using plastic bottles in construction over conventional materials, including savings in both time and money, increasing load capacity and adaptability, reducing waste, and lowering energy consumption. The findings of this study determine plastic waste in the South Canara region and recommend the types of construction that should be used for slum housing, as well as analyze the feasibility of using PET bottles as a building material. Making this proposed method economically viable and providing affordable housing to India's urban poor may be the focus of future research. Muntean et al. [15] provides practical strategies for recycling PET plastic from beverage containers. Gaps executed with lost formworks made of PET can reduce the amount of concrete needed for certain reinforced concrete elements, such as monolithically cast reinforced definite plates. There are also suggestions for using plastic bottles as attachments in mattresses for thermal insulation in construction and other creative ways to put this waste to good use. Al-Sinan et al. [16] studied plastic–sand as a construction material. They revealed that low-density polyethylene (LDPE) and polyethylene terephthalate (PET) plastics can make bricks or pavement blocks. Agyeman et al. [17] analyzed the characteristics of concrete paving blocks and composite paving blocks having less plastic (LP) and high plastic (HP) content at 7, 14, and 21 days. The mix proportion of concrete paving blocks was 1:1:2 (cement: quarry dust: sand). For composite blocks, the mix proportion was 1:1:2 (LP) and 1:0.5:1 (HP). They found that at the end of 21 days HP and LP, paving blocks have a compressive strength of 8.53 N/mm^2 and 7.31 N/mm^2. The water absorption of HP blocks was 0.5% and 2.7% for LP blocks less than concrete paving blocks. Therefore, plastic paving blocks may be utilized in non-traffic areas such as walkways, footpaths, pedestrian plazas, and flooded regions.

Based on the results of the research of Jawaid et al. [18], incorporating recycled plastic waste as a component in cementitious composites is the most beneficial option. Newer methods are more effective regarding the environment and sustainability. Still, they are not economical, as shown by the sought-after qualitative analysis of various plastic waste management techniques, focusing on the most significant features. Lamba et al. [19] conducted research aiming to compare and contrast international road construction technology against South African design standards and material specifications. The primary objective of this study was to determine if low-value waste plastics could be used effectively as a replacement for traditional materials in South African road construction. Koppula et al. [20] use high-density polyethylene (HDPE), quartz sand, and bitumen to make bricks, and found that this combination led to an improvement in the strength of the bricks while reducing their weight. So, recycling plastic waste into construction material will help in economic, environmentally friendly, and sustainable construction [21–23].

Hamzah et al. [24] examined the potential for using plastic trash to create novel, lightweight, affordable, and environmentally friendly bricks that could replace conventional fossilized clay-based bricks in the building industry. They discovered that the created bricks are lighter, less porous, and have greater compressive strength. These bricks' water retention is incredibly low, at less than 1%, compared to the water retention of conventional soil bricks, which is between 15% and 20%. Zulkernain et al. [25] optimized the mix design ratio of cement bricks containing plastic waste as aggregate replacement. To create plastic–cement brick mixtures, cement bricks with varying cement contents (150, 300, and 450 g) and plastic replacement percentages were mixed with four different types of plastic waste, including polyethylene terephthalate (PET), high-density polyethylene, low-density polyethylene, and polypropylene (0, 3, and 6 percent). It revealed that the optimum cement brick mixed design is C3-1% PET with a compressive strength of 27.50 MPa and water absorption of 1.16%. Paver blocks were made with plastic (PP and HDPE) to sand ratios of 30:70%, 40:60%, 50:50%, 60:40%, and 70:30% [26]. Paver blocks were inspected after 28 days. Paver block compressive strength, LA abrasion, and water absorption increased from 30% to 40% HDPE, then dropped to 70%. Paver block abrasion and water absorption decreased from 30% to 70% PP content. PP paver blocks' compressive strength decreased from 30% to 50%, then increased to 60% and 70% PP. The strongest paver blocks were PP60 and HDPE40. PP60 pavers absorb more water than HDPE40 pavers. PP60 had 0.53% water absorption and 11% abrasion; HDPE40 had 0.03% and 24.2%. PP60 had 20.09 MPa, 11% and 0.53%; and HDPE50 had 13.06 MPa, 12.1% and 0.03%.

The study demonstrated the durability of recycled plastic waste paving blocks in terms of compressive strength. The study examined the potential for recycling plastic trash in India [27]. India's road network consists of about 114,158 km of national highways, 761,217 km of state and district roads, and 4.2 million km of rural roads [28]. In recent research, the replacement and addition were carried out with the direct inclusion of polyethylene, polyethylene terephthalate (PET) bottles in shredded form, chemically treated polyethylene fiber, and PET in the form of small particles by replacing natural coarse aggregate and river sand. In this study, plastic waste is incorporated with M-sand (crushed stones) to produce paving blocks. The paving blocks will then be tested to study the sieve analysis, compressive strength, water absorption, and will be scanned with a scanning electron microscopy (SEM).

2. Materials and Methods

2.1. Plastics

Polyethylene is the most common and cost-effective plastic used everywhere. PE can be processed efficiently and transformed into various shapes and forms [29]. PET is a transparent polymer with good mechanical properties and dimensional stability under variable load (Table 1). Moreover, PET has good gas barrier properties. The polyethylene used in this study was gathered from local sources such as dumpsters, landfills, factories, and restaurants. After cleaning of plastic waste, the collection of plastics is crushed into 2 mm to 3 mm sizes for the preparation of cubes, I-section road pavers, and road paving bricks, as shown in Figure 1. Zone-1 M-sand used in this study had fineness modules between 2.9 and 3.2. The fineness modulus of sand is an index number representing sand's average particle size [30]. The moisture content of M-sand was determined by the oven-dry method. The weight of the sample of M-sand was taken as 500 g by determining the moisture content. To find the suitable ratio of plastic and sand, The IS code standard size of a 150 × 150 × 150 mm cube mold was used to prepare the specimens, which were tested in a compressive testing machine (CTM) (Figure 2). In this study, the plastic: sand proportions (i.e., 1: 2, 1: 3, and 1: 4) were used to manufacture plastic–sand cubes to achieve a desirable strength. Table 2 shows the different mix ratios of plastic: sand proportions.

Table 1. Properties of polyethylene terephthalate (PET) [31].

Density	1350 kg/m^3
Ultimate Tensile Strength	150 MPa
Yield Strength	40 MPa
Young's Modulus of Elasticity	9 GPa
Brinell Hardness	20 BHN
Melting Point	267 °C

Figure 1. Crushed plastic waste of 4 mm to 5 mm in size.

Figure 2. Size of the cube = 150 × 150 × 150 mm.

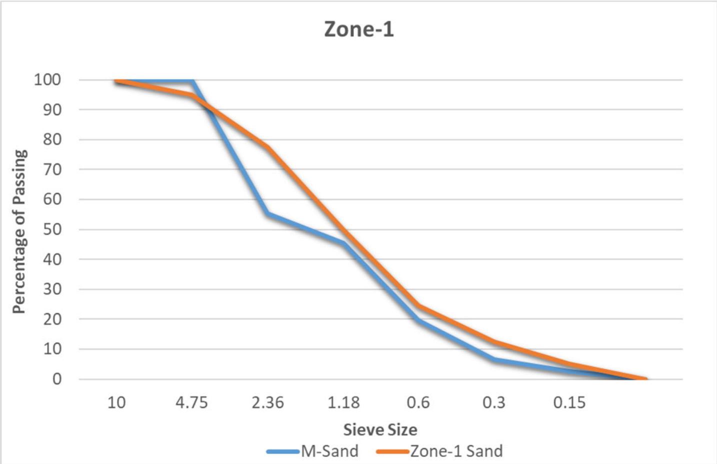
Table 2. The ratio of plastic waste and M-sand.

Ratio of Plastic Waste and M-Sand (Plastic Waste:M-Sand)	% of Crushed Plastics Waste	% of M-Sand
1:2	33.33	66.66
1:3	25	75
1:4	20	80

2.2. M-Sand

Manufactured sand, commonly called M-sand, is a viable substitute for river sand in various construction applications. The production process involves comminating solid rocks or granite stones into finely fragmented particles that exhibit uniformity in size and shape. M-sand is a synthetic substitute for river sand, produced by crushing solid rocks into smaller particles. The construction industry has preferred this material due to its superior quality, consistent properties, and environmentally friendly characteristics. M-sand's utilization in construction activities diminishes reliance on river sand. It advances sustainable practices, thereby fostering the conservation of natural resources and facilitating the holistic advancement of the construction industry.

The technique of sieve analysis is frequently used to evaluate the particle size distribution of granular materials, such as M-sand. The process entails subjecting a representative sample of M-sand to a sequence of sieves with decreasing aperture sizes while quantifying the quantity of material on each sieve. The sieves are organized in descending order based on the size of their openings. Following the shaking process to segregate the particles, the material on each sieve is measured in terms of weight. Determining the cumulative weight retained and cumulative percentage passing involves the summation of weights and the subsequent calculation of the proportion of material that passes through each sieve. The aforementioned data are subsequently utilized to construct a particle size distribution curve. This curve offers significant insights into the gradation and quality of the M-sand, as depicted in Figure 3. These findings prove beneficial in diverse construction-related endeavors.



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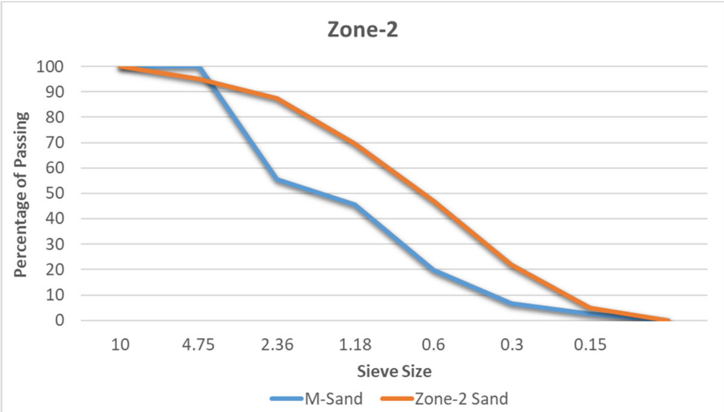

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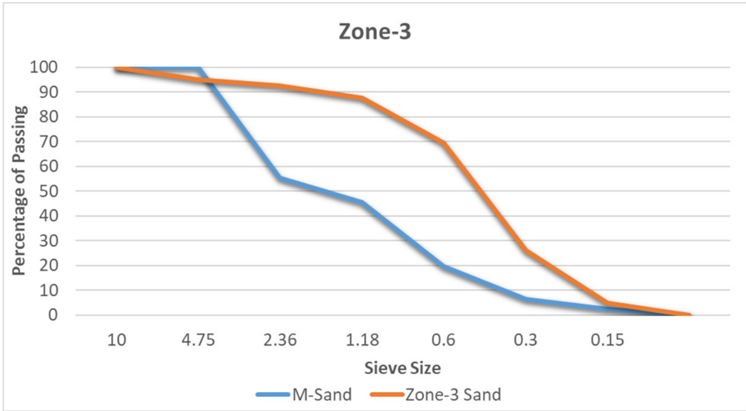
Figure 3. *Cont.*



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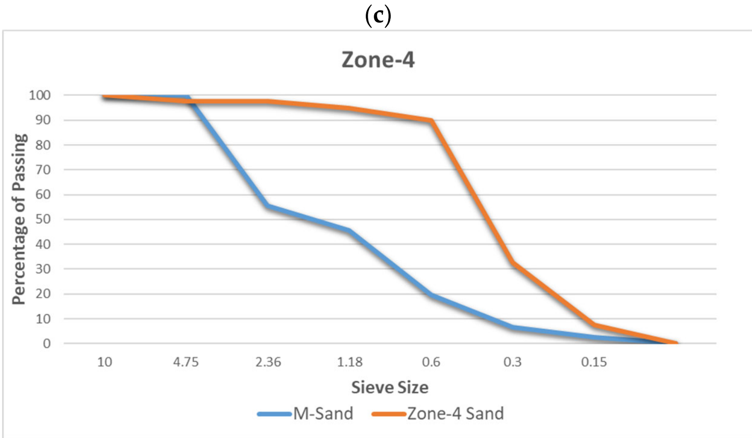


(**d**)

Figure 3. Comparative particle size distribution curve: (**a**) Zone-1 and M-Sand, (**b**) Zone-2 and M-Sand, (**c**) Zone-3 and M-Sand, (**d**) Zone-4 and M-Sand.

2.3. Determining the Optimum Percent of the Plastic Mix in M-Sand Plastic Cube

The casting of a cube using a mixture of M-sand and plastic waste at different ratios (33.33:66.66, 25:75, and 20:80) is employed in this method. The procedure begins with preparing the cube mold and calculating the required quantities of M-sand after the sieve analysis. The mix ratios of M-sand and plastic waste are mentioned in Table 2. The plastic waste is shredded into small pieces measuring 2 mm to 3 mm. Subsequently, the sand is heated in a furnace until it reaches a temperature of 270 °C. Once the M-sand is adequately heated, it is combined with the shredded plastic particles. The contact between the heated M-sand and plastic waste causes the plastic to transform into a semi-liquid state. After 1–3 min, the mixture is poured into the cube mold, and proper tamping is performed to eliminate undesired air voids. After 2–3 h of cooling, the cube is carefully removed from the mold.

The final step involves testing the cube's compressive strength using appropriate methods. The compressive strength testing of the plastic–sand cubes revealed that the optimal ratio of plastic to sand for achieving the highest compressive strength was 1:4. This means that the cubes prepared with one part plastic waste and four parts M-sand exhibited the highest average compressive strength compared to other ratios tested (1:2 and 1:3). This result indicates that increasing the proportion of plastic waste in the composite material positively influenced its compressive strength as shown in Table 3. The addition of plastic waste to the sand matrix creates a more interconnected structure, enhancing the load-bearing capacity of the cubes. The plastic particles act as fillers, effectively occupying the void spaces between the sand particles, thereby reducing porosity and increasing the overall density of the composite material. This densification and improved interlocking mechanism contribute to the increased compressive strength observed in the plastic-sand cubes.

Table 3. Result of compressive strength of plastic waste cube.

Mix Ratio	Weight of Plastic Waste Cube (kg)	The Density of Plastic Waste Cube (kg/m^3)	Failure Load (kN)	Compressive Strength (N/mm^2)	Avg. Compressive Strength (N/mm^2)
1:2 50% PW + 50% MS	3.105	920	800	36	36.15
	3.150	933	825	37	
	3.210	951	815	36	
1:3 25% PW + 75% MS	3.430	1016	850	38	36.89
	3.400	1007	825	37	
	3.105	920	815	36	
1:4 20% PW + 80% MS	3.105	920	845	38	38
	3.105	920	855	38	
	3.105	920	865	38	

2.4. Method of Casting I-Section Road Paver Blocks and Road Paver Bricks Blocks

The process for generating the optimal strength in waste plastic cubes involves the addition of a plastic mix ratio, which is subsequently applied to creating I-section road paver blocks and brick road paver blocks. The determination of the mix ratio hinges on the composition that yields the maximum strength in the waste plastic cube, as evidenced in Table 3. This data reveals a mix ratio of 1:4, consisting of 80% M-sand, to deliver the highest compressive strength, amounting to 38 N/mm^2.

In the production procedure of both I-section road paver blocks and brick road paver blocks, a crucial step involves the integration of crushed plastic waste with heated sand. Specifically, M-sand is subjected to a temperature of 270 °C within a furnace. Before this mixing phase, the plastic waste is reduced to minute fragments, with dimensions spanning 2 mm to 3 mm, to prime it for the mixing process.

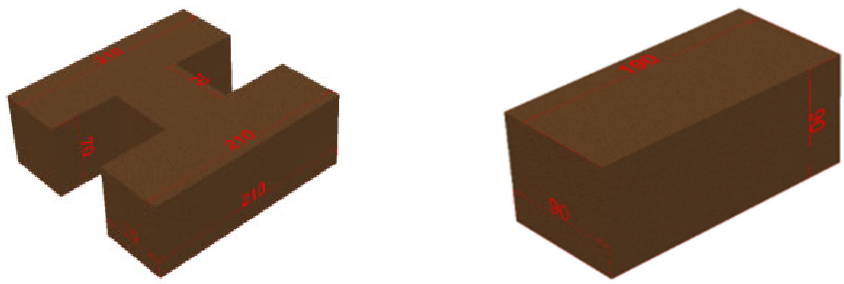
Upon the M-sand reaching the aforementioned temperature, it is amalgamated with finely shredded plastic particles. The elevated temperature of the M-sand induces a semi-liquid state in the plastic. Preparations for mold filling include applying oil to the mold walls, a step designed to expedite the subsequent removal of the pavers.

After 1 to 3 min, the mixture is dispensed into the mold designated for road paver blocks. This action is accompanied by vigilant tamping to preclude the formation of undesirable air pockets. Adopting a tampering rod ensures the mold is filled adequately and under optimal pressure.

The paver block is meticulously liberated from the mold after 2 to 3 h of cooling. Figure 4 showcases the completed road paver blocks, with two distinct types of paver blocks produced for this investigation. Comprehensive details relating to the dimensions of these road paver blocks are furnished in Figure 5.

(**a**) (**b**)

Figure 4. Waste plastic road paver blocks. (**a**) I-Shape Road Paver Block. (**b**) Waste plastic brick.



(**a**) (**b**)

Figure 5. The dimension details of the components (mm). (**a**) I section road paver block (**b**) Bricks Paver Block.

3. Results and Discussions

A compressive strength test on waste plastic, I-section road paver block, and plastic bricks pavers was carried out to determine the load-carrying capacity under compression with the help of a compression testing machine. The test was performed on the compressive testing machine (CTM). The procedure followed IS 3495: 1992 (Part I) Indian standard code.

$$\text{Compressive strength} = \frac{\text{Failure Load (P)}}{\text{Cross sec tion area of Cube (A)}}$$

It is observed that the compressive strength of the I-section road paver blocks and brick pavers increases as the proportion of M-sand in the mix ratio increases. Table 4 shows that the mix ratio of 1:4 with 80% M-sand has the highest compressive strength of 22.47 N/mm^2, followed by the mix ratio 1:3 with 75% M-sand and compressive strength of 21.61 N/mm^2. The lowest compressive strength is observed in the mix ratio 1:2 with 66% M-sand and a compressive strength of 21.44 N/mm^2. The mix ratio of 1:4 with 80% M-sand has the highest compressive strength of 25.27 N/mm^2, followed by the mix ratio 1:3 with 75% M-sand and compressive strength of 24.37 N/mm^2. The lowest compressive strength is observed in the mix ratio 1:2 with 66% M-sand and a compressive strength of 24.19 N/mm^2 (Table 5). Overall, the results suggest that a higher percentage of M-sand in the mix ratio can result in better compressive strength in plastic waste and M-sand mixtures. The mix ratio of 1:4 with 80% M-sand is the most effective in enhancing the compressive strength in all three cases. To determine the quality of a concrete structure, an evaluation technique known as ultrasonic pulse velocity (UPV) is frequently applied [32]. This study uses the UPV test to examine the homogeneity and quality of the waste plastic cubes. The test measures the time taken for a pulse to travel through the material, and the resulting pulse speed is an indicator of the quality of the material. A higher pulse speed indicates better quality. Table 6 presents the results of the ultrasonic pulse velocity test conducted on the plastic waste specimens. The results show that all specimens have excellent quality grading, with their pulse speeds above 4.5 m/µs. The plastic cube specimens have an average pulse speed of 4.70 m/µs, while the I-section and plastic brick specimens have an average pulse speed of 4.45 m/µs and 4.70 m/µs, respectively.

In addition, a comparison of the densities of waste plastic and concrete cubes is carried out as part of this investigation. As the density of concrete decreases, the compressive strength of the concrete also decreases. Concrete with a higher density generally results in higher compressive strength and a lower overall volume of voids [33].

The deliberations on the findings of this research underscore the potential advantages of incorporating plastic waste into the fabrication of paving blocks for various applications. The research predominantly centered around I-section road paver blocks and brick paving blocks, both of which exhibited superior strength compared to other paving block categories.

Table 4. Result of compressive strength testing of I-sections.

Mix Ratio (Plastic Waste: M-Sand)	Weight of I-Section (kg)	Density of I-Section (kg/m^3)	Failure Load (kN)	Compressive Strength (N/mm^2)	Avg. Compressive Strength (N/mm^2)
1:2 33% PW + 66% MS	2.400	1000	635	19	21.44
	2.339	974	625	18	
	2.336	973	615	18	
1:3 25% PW + 75% MS	2.450	1020	650	19	21.61
	2.404	1001	625	18	
	2.431	1012	615	18	
1:4 20% PW + 80% MS	2.460	1025	645	19	22.47
	2.442	1017	655	19	
	2.450	1020	665	19	

Table 5. Result of compressive strength testing of plastic bricks.

Mix Ratio (Plastic Waste: M-Sand)	Weight of Brick (kg)	Density of Brick (kg/m^3)	Failure Load (kN)	Compressive Strength (N/mm^2)	Avg. Compressive Strength (N/mm^2)
1:2 33% PW + 66% MS	1.676	1089	680	40	39.33
	1.683	1093	670	39	
	1.680	1092	660	39	
1:3 25% PW + 75% MS	1.794	1166	695	41	39.67
	1.748	1135	670	39	
	1.775	1153	660	39	
1:4 20% PW + 80% MS	1.804	1172	690	40	41
	1.786	1160	700	41	
	1.794	1166	710	42	

Table 6. Result of ultrasonic pulse velocity test.

Section	Specimen	Weight (kg)	Density (kg/m^3)	Transit Time (μs)	Pulse Speed	Quality Grading
I-Section	A	4.463	520	33.8	4.44	Excellent
	B	4.477	522	34.2	4.39	
	C	4.491	524	33.2	4.52	
	Average	4.477	522	33.7	4.45	
Plastic Bricks	A	4.307	628	32.5	4.62	Excellent
	B	4.321	630	30.2	4.97	
	C	4.335	632	33.2	4.52	
	Average	4.321	630	32.0	4.70	

The compressive strength manifested by the waste plastic cube was remarkable, a testament to the efficiency of the plastic-to-sand ratio in producing robust and long-lasting paver blocks. Specifically, the ratio of 1:4, optimized for this process, engendered a higher compressive strength in the I-section road paver blocks than other ratios examined. This enhanced strength implies that the mixture of plastic waste and sand could be deemed suitable for road construction and other load-bearing applications.

The increased compressive strength discerned in the paver blocks can be credited to the superior particle packing and interlocking, which are consequences of including plastic waste particles. The plastic particles occupy the sand matrix's voids, facilitating a more condensed structure capable of resisting applied loads more effectively. This structural reinforcement renders the paver blocks more resistant to the rigors of vehicular traffic and external forces, enhancing their durability. The ultrasonic pulse velocity (UPV) test results further supported the high quality of the composite materials. The UPV test is a non-destructive method used to assess the integrity and homogeneity of materials.

The excellent quality grading obtained for the plastic–sand cubes and I-section road paver blocks indicated that the addition of plastic waste did not compromise the overall structural integrity of the materials.

The SEM analysis offered valuable microstructural insights into the composition of both the plastic–sand cubes and I-section road paver blocks. The SEM images clearly demonstrated a consistent dispersion of plastic waste particles within the sand matrix, signifying an extensive and well-executed mixing procedure. This homogeneous distribution plays a pivotal role in bolstering the mechanical properties of the composite materials.

Moreover, the SEM investigation definitively validated the successful integration of plastic particles within the composite materials. This affirmation was underpinned by the conspicuous evidence of robust interfacial bonding between the plastic and sand particles, as visually depicted in Figure 6. This robust bonding significantly amplifies the overall strength and durability of the composite materials, thereby ensuring their sustained and enduring performance.

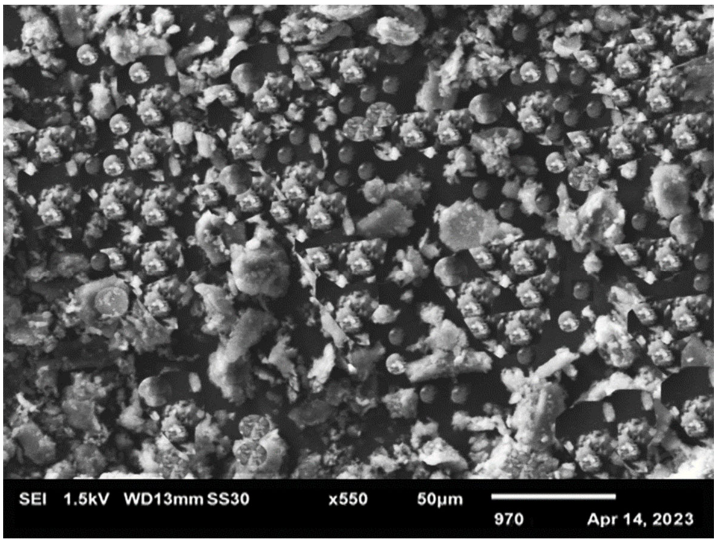


Figure 6. Scanning electron microscopy (SEM) tests image showing the bonds between the waste plastic and M-Sand.

The outputs of the study show that the plastic blocks can be stylized as building blocks or paver blocks. They will helpful to reduce plastic waste by converting it into different types of building blocks or into other building components. In comparison to conventional concrete blocks, the use of plastic–sand blocks for pavement construction has a number of benefits, including increased durability, economic efficiency, and reduced weight, which makes shipping and installation easier. However, there are concerns about the potential release of microplastics into the environment. To mitigate this issue, measures such as using high-quality, UV-resistant plastics and applying surface sealants can be considered.

4. Conclusions

The experimental results acquired from the compressive strength tests of the mixtures incorporating plastic waste and M-sand point to the fact that the 1:4 ratio, with an M-sand composition of 80%, produced the maximum compressive strength for both the I-section road paver blocks and the brick paver blocks. This specific ratio culminated in average compressive strengths of 22.47 N/mm^2 for the I-section and 25.27 N/mm^2 for the plastic bricks. In addition, the ultrasonic pulse velocity tests rendered exceptional quality grading for both the I-section and plastic bricks, with average pulse speeds of 4.45 m/μs and 4.70 m/μs, respectively.

These findings suggest that the compressive strength of the waste plastic cube is contingent on the ratio of plastic waste to M-sand, as well as the thoroughness of the mixing process. The 1:4 ratio demonstrated superior compressive strength, while reducing plastic waste resulted in diminished strength.

The study indicates that recycling plastic waste, specifically Polyethylene Terephthalate (PET), into road pavers, possesses considerable potential as a sustainable construction material in India. Exploiting plastic waste in the form of road pavers brings several benefits, including waste diminution, resource preservation, and environmental advantages.

The casting process combines plastic waste with heated sand to yield road pavers characterized by enhanced strength and durability. The inclusion of plastic waste not only addresses the pressing issue of plastic pollution and contributes to the circular economy, promoting the recycling and reuse of materials. Furthermore, the road pavers display satisfactory mechanical properties, indicating their appropriateness for load-bearing applications in road construction and other public spaces.

By embracing such innovative strategies, India can alleviate plastic waste, while simultaneously developing eco-friendly and sustainable infrastructure. This research underscores the potential of plastic waste recycling as a viable solution to environmental concerns, advocating for a greener future in the construction industry.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Polyethene terephthalate (PET); scanning electron microscopy (SEM); high-density polyethylene (HDPE); low-density polyethylene (LDPE); compressive testing machine (CTM); ultrasonic pulse velocity (UPV); less plastic (LP); high plastic (HP).

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