

ECO - FRIENDLY PAVEMENT BLOCKS USING PLASTIC - BASED AGGREGATE ALTERNATIVES

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Abstract

Permeable pavements are gaining popularity as an innovative solution to mitigate urban stormwater runoff and reduce the environmental impact of traditional impermeable pavements. This study examines the viability of producing permeable pavement blocks by partially substituting plastic aggregate with conventional coarse aggregate. The study employs a rigorous experimental methodology that encompasses material characterization, mechanical testing, permeability evaluations, and environmental impact assessments. Plastic aggregates are used to partially replace coarse aggregates at varying replacement levels of 0%, 5%, 10%, 15%, 20%, and 25% by weight, to evaluate their influence on the mechanical strength and durability of the permeable pavement blocks. Additionally, the hydraulic conductivity of the modified blocks is measured under controlled conditions to determine their effectiveness in managing stormwater runoff. Results demonstrate that the incorporation of plastic aggregates maintains structural integrity while significantly improving water permeability, offering potential benefits for stormwater management and urban flood mitigation, considering factors such as reduced carbon emissions and decreased landfill waste. This study further integrates a Technology Readiness Level (TRL) assessment, highlighting the current developmental stage of this technology and its potential for real-world implementation. The findings from this research contribute to the ongoing efforts to develop sustainable construction practices by reducing the dependence on traditional coarse aggregates and promoting the recycling of plastic waste. This paper provides valuable insights into the potential applications of plastic aggregate in permeable pavement construction and emphasizes the importance of environmentally responsible urban infrastructure development.

Keywords: Permeable Concrete; Flood Control; Waste Plastic Management; TRL; SDG

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Introduction

Urbanization continues to reshape our cities at an unprecedented pace, accompanied by a surge in infrastructure development. However, this growth presents a dual challenge: the escalating volume of stormwater runoff and the piling up of plastic waste, thereby highlighting the pressing need for sustainable construction practices (United Nations, 2018).

Concrete is the most widely used material globally, primarily driven by urbanization and the need for infrastructure development such as housing, buildings, and roads. Concrete is a mixture of cement, fine aggregate, coarse aggregate, water, and some additives. Worldwide, concrete consumption is estimated to be approximately 30 billion tons annually, and the number is expected to rise (Provis, 2018). The aggregates typically account for 65-80% of the total volume of concrete and have a significant impact on the fresh and hardened properties of the cementitious matrix (Saikia and De Brito, 2014). The worldwide aggregate production market forecasts a 59% increase in aggregate consumption by the end of 2025 (Ryu *et al.*, 2020). However, this extensive use of concrete places immense pressure on natural resources, due to which these are rapidly being exhausted, causing severe impacts on the environment, along with the escalating problem of construction and demolition waste. Moreover, the rapid expansion of urban areas often leads to the covering of vast land surfaces with impermeable concrete, inhibiting water from penetrating the soil. This, in turn, contributes to issues like flooding, increased runoff, and drainage problems, which are detrimental to the environment and human well-being (Dingman, 2002).

One more significant concern associated with urbanization and environmental degradation is

plastic pollution. Unfortunately, the estimated 8.3 billion tonnes of plastic, since the 1950s have been generated in India, yet only 9% of that amount has been recycled (Centre for Science and Environment, 2020). The general framework of the Indian plastic industry and plastic waste flow is shown in Figure 1 and Figure 2 (Kataki *et al.*, 2022). Figure 1 illustrates the structural flow of the Indian plastics industry, including key stakeholders such as producers, consumers, collectors, and recyclers, as outlined in the MoEFCC's 2020 EPR guidelines. This flowchart emphasizes the complexity of plastic waste management and highlights the multiple intervention points for improving recycling and circular economy strategies in India. Figure 2 presents the plastic waste flow in India as per the MoEFCC's 2020 EPR guidelines. It shows the transition of plastic from production and consumption to collection, segregation, and final treatment through recycling or disposal. The diagram highlights the gaps in waste segregation and the high volume of unmanaged plastic that escapes into the environment, thereby emphasizing the need for improved waste valorization strategies. Plastic production and consumption have skyrocketed over the last five decades, with global plastic production reaching a staggering 320 million tonnes per year. What makes this problem even more alarming is that plastic is an enduring material, persisting in the environment for centuries. For instance, a single plastic water bottle can remain on the planet for approximately 450 years (United Nations Environment Programme, 2018). As plastic have several disadvantages, but this waste can be utilized as a replacement of the materials in the concrete.

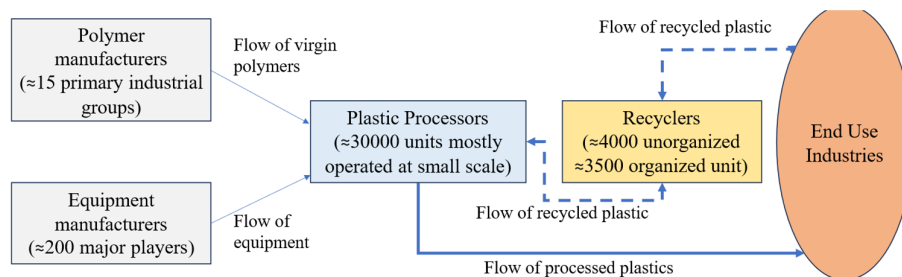


Figure 1. The Indian plastics industry's structure (adapted from the MoEFC's 2020 EPR guidelines)

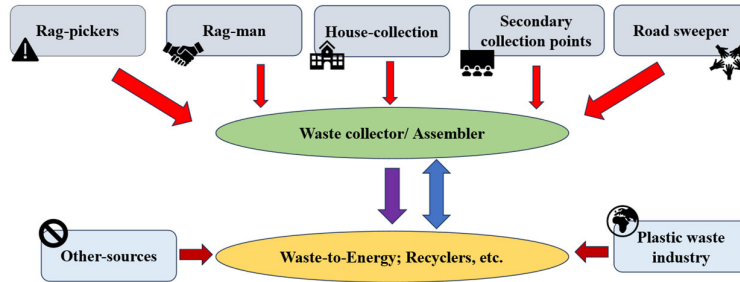


Figure 2. Diagram of India's Plastic Waste Flow (adapted from MoEFCC Guidelines on EPR, 2020)

To mitigate these challenges, permeable paver blocks offer a sustainable engineered alternative for constructing surfaces like parking lots, pedestrian flooring, and footpaths, especially in low to moderate traffic areas. These concrete blocks allow rainwater to seep into the ground, preventing runoff peaks and reducing the risk of floods. (Fassman and Blackburn, 2010). Plastic, which is a waste, can be utilized as a substitute material in construction materials. By substituting plastic trash for aggregates and asphalt in the construction of roads, in particular, it is possible to increase performance and strength while lowering costs by using fewer building materials. (Zainuri *et al.*, 2022). The waste plastic offers an advantage that it has a lower specific gravity than other materials; using it as an aggregate reduces the self-weight of the concrete, which further reduces the cost of transportation and fuel. Also, plastic is durable as it does not absorb water, which increases the lifespan of the paver block (Islam *et al.*, 2016). In addition to avoiding the environmental pollution caused by plastic, the concrete sector has accepted the previously mentioned solutions to partially replace some natural aggregates in the concrete with aggregates made from plastic waste in an effort to protect the environment. Promoting the adoption of permeable pavement and the utilization of plastic aggregates in construction projects holds significant potential for advancing the Sustainable Development Goals (SDGs) by 2030. Permeable pavement, designed to manage stormwater runoff and reduce flooding, aligns with SDG 11's aim to create sustainable and resilient cities. It underscores its effectiveness in enhancing urban infrastructure while minimizing environmental impact. On the other hand, incorporating plastic aggregates, derived from recycled plastics, supports SDG 12's goal of Responsible Consumption and Production by minimizing plastic waste and conserving resources. These eco-friendly solutions offer a practical pathway toward achieving the 2030 sustainability agenda, contributing to sustainable

development and responsible resource management. (Copello de Souza *et al.*, 2016; De Sousa, 2021) Many researchers have utilized plastic as a binding material (Lu *et al.*, 2019), as a fine fraction (Saha *et al.*, 2023), but no research to date is available on utilizing synthetic plastic aggregate as a replacement for coarse aggregate for making permeable paver blocks. Recent studies have demonstrated the potential of incorporating waste materials in construction to enhance sustainability. However, research specifically focusing on synthetic plastic aggregate as a replacement for coarse aggregate in permeable pavement blocks remains scarce. This study aims to address this gap by systematically evaluating the impact of plastic aggregates on mechanical performance and permeability.

To better understand the feasibility of permeable plastic aggregate blocks, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis comparing them with conventional pavers is presented in Table 1. The SWOT analysis has been developed by the authors based on their interpretation of experimental results and relevant sustainability factors in pavement block design.

In the current article, research has been done to use synthetic plastic aggregates that are manufactured from HDPE. The novelty is to assess the feasibility of plastic aggregate in permeable paver blocks as a partial replacement of coarse aggregate under normal STP conditions. The paver blocks for M-35 grade concrete were prepared, and compressive strength was determined using UTM. In this research article, various experiments were performed to determine the compressive strength, the permeability, and also the workability of the permeable paver concrete block specimens that contain the proposed plastic aggregates. Regression analysis was also used to determine the relationship between the compressive strength of the paver block and the percentage of replacement of coarse aggregate. Also, despite prior research on plastic aggregate-based permeable pavements, their

practical implementation is constrained by unpredictability in performance, durability, and scalability. The Technology Readiness Level (TRL) methodology was implemented to comprehensively assess the developmental state of this technology. So, unlike earlier studies using shredded PET or mixed plastic waste, our work employs synthetic HDPE aggregates with controlled size and mechanical properties, coupled with a TRL-based implementation pathway.

This evaluation establishes the research within a wider implementation framework, connecting laboratory investigations to actual field or industry-level applications (Olechowski *et al.*, 2015; Zorrilla *et al.*, 2024). These initiatives align with multiple SDGs related to water management, infrastructure development, responsible consumption and production, and climate action, thereby promoting a more sustainable and inclusive future.

Materials

Cement and Water

In order to serve as a binding agent for the study's data, Ordinary Portland Cement (OPC), which was created by the ACC Cement Company Limited, was purchased from a regional manufacturer. Cement is a binder, or material that binds other materials together during construction by setting, hardening, and adhering to them. This study uses ordinary Portland cement of grade 53 that complies with IS: 456-2000 and IS: 12269-1987. Table 2 lists the physical and chemical characteristics of cement used as a binding agent. experiments on the properties of cement were estimated by following IS:4031. The concrete mixture was chosen to be made with potable tap water that is safe for drinking.

Table 1. SWOT Analysis of Normal vs. Permeable Plastic Aggregate Paver Blocks

Factor	Normal Paver Blocks	Permeable Plastic Aggregate Blocks
Strengths	✓ High compressive strength	✓ Sustainable – utilizes plastic waste
	✓ Proven durability	✓ Reduces urban flooding with better water permeability
	✓ Well-established in construction	✓ Lighter weight, easier handling
		✓ Potential cost reduction with waste materials
Weaknesses	✗ Non-permeable – causes waterlogging	✗ Potential reduction in compressive strength
	✗ Uses natural resources (sand, gravel)	✗ Long-term durability uncertain
	✗ Higher density, heavier blocks	✗ Need for standardization & regulatory approvals
Opportunities	✓ Established market demand	✓ Promotes circular economy & sustainability
	✓ Compatible with existing infrastructure	✓ Potential for green certifications & incentives
		✓ Growing interest in eco-friendly construction
Threats	✗ Contributes to urban flooding & heat island effect	✗ Regulatory restrictions on plastic use
	✗ Rising cost of raw materials (natural aggregates)	✗ Public perception & acceptance
		✗ Performance concerns under heavy loads

Table 2. Physical and chemical properties of Ordinary Portland Cement

S.No.	Test	Result Obtained	Limit
1	Specific Gravity	3.12	
2	Initial setting time	65 minutes	Min 30
3	Final setting time	180 minutes	Max 600
4	7-day compressive strength-M20	18.5 ± 3 N/mm ²	Min 17.5 N/mm ²
5	28-day compressive strength-M20	22.5 ± 2 N/mm ²	Min 20 N/mm ²
6	Consistency	32%	
7	Soundness-Le-Chatelier method	0.10%	Max 10

Table 3. Properties of Fine and Coarse Aggregates

S.No.	Properties	Coarse aggregate	Fine aggregate
1	Specific Gravity	2.75	2.65
2	Bulk Density (kg/m ³)	1680	1600
3	Water Absorption (%)	0.7	1.1
4	Finess modulus	2.54	2.73

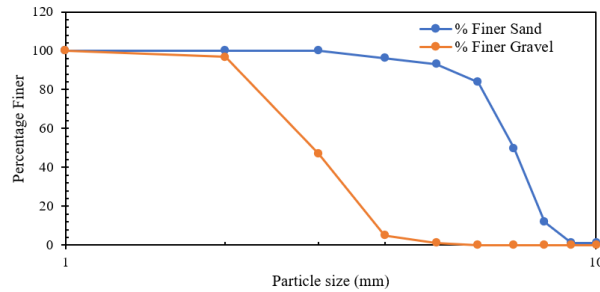


Figure 3. Granulometry of the fine aggregate and coarse aggregates

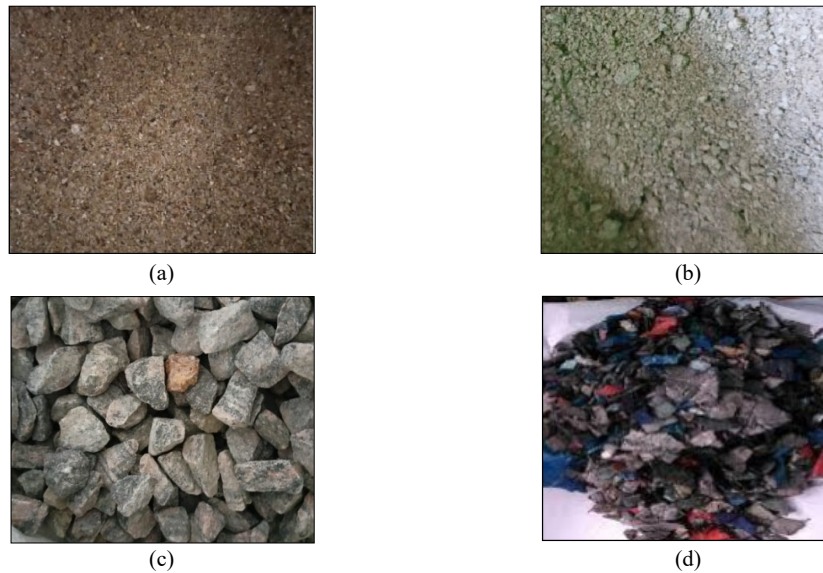


Figure 4. Raw material for permeable pavement block with plastic aggregate: (a) Fine aggregate (FA)-sand; (b) Cement; (c) Coarse aggregate (CA)-gravel; (d) Synthetic Plastic aggregate

Natural Aggregates

Fine aggregates, i.e., sand passing through a 4.75 mm IS sieve, are a granular material composed of finely divided rock and mineral particles. Sand used in the study was obtained from a local vendor with having fineness modulus of 2.72. The results indicate that the sand conforms to zone II of IS: 383-1970. The properties of sand were determined by conducting tests as per IS:2386, listed in Table 3.

The coarse aggregate, having a maximum size of 20 mm, prepared by crushing rocks, was used in this study. The coarse aggregates obtained from local sources conforming to IS2386:1963 (parts I, II, and III) were used as coarse aggregate in this study. Specific gravity of coarse aggregate is found to as 2.7. The properties were determined by conducting tests as per IS: 383-1970, listed in Table 3. Particle size distribution is shown in Figure 3 for fine and coarse aggregates.

Plastic aggregates

Plastic aggregates prepared from plastic waste represent the discarded waste from plastic containers. The plastic aggregates used were pre-sized to a nominal 10 mm and obtained from a commercial manufacturer. They were visually screened and sieved to ensure uniformity in shape, size, and density across all mixes. There is no problem using plastic aggregate in concrete; in particular, plastic coarse aggregate with a 10 mm size is employed. No chemical or mechanical surface treatments were applied to the plastic aggregates. The aggregates were used in their raw form to assess baseline performance. However, surface modification methods could enhance bonding and which can be explored further in future studies. General characteristics of plastic aggregates are tabulated in the Table. 4. The major component of these plastics is High-Density

Polyethylene (HDPE). HDPE-based synthetic aggregates were selected over mixed plastic waste due to their superior shape stability, reproducibility, and consistent mechanical behavior, making them more suitable for controlled lab testing.

day, 14th day, and finally on the 28th day. A permeability test was conducted by the falling head method on the 28th day. Three specimens were prepared for each sample. So, in total, 54 cubes were cast.

Table 4. General Properties of Plastic Aggregates

S.No.	Particulars	Value
1	Melting Point	170°C
2	Specific gravity	1.02
3	Water adsorption (%)	0.12%
4	Nominal size(mm)	10
5	Young's Modulus (MPa)	2000

Methods

Preparation of Design Mix

The mix design of permeable paver block was prepared for M-35 grade, as per IS: 10262-2009 and IS: 15658-2006. The design mixture was prepared such as to get the desired strength as well as permeability. M-35 grade concrete was selected based on its balanced mechanical strength and permeability properties, making it suitable for medium-traffic pavement applications as per IS: 15658-2006. Table 5. represent the ratio of cement, fine aggregate, coarse aggregate, and water used in the preparation of concrete.

Table 5. Mix proportions for Block

W/C ratio	Cement	Fine aggregates	Coarse aggregate
172.35	383	546	1188
0.45	1	1.425	3.1

A permeable paver block for testing is prepared by using the design mix proportions. The first sample was a control mix, which means without plastic aggregate, and then the plastic aggregates were added by replacing coarse aggregate in 5%, 10%, 15%, 20%, 25% respectively, by weight.

The dimensions of the cube used for casting paver blocks were 100mm × 100mm × 100mm. Figure 5 shows specimen casting. The 100 mm cube specimen size was selected to align with standard laboratory practices and IS:516 protocols. This dimension allows ease of casting, handling, and testing. However, we acknowledge that larger field-scale specimens may provide more realistic performance insights. Then the cubes were cast, cured in water, and then tested as per IS 456-2000. Compressive strength test was performed on the 7th



Figure 5. Permeable paver block Specimens

Evaluation of Mix Properties

The concrete permeable paver blocks were prepared, cured, and tested for fresh properties of concrete as well as for hard properties of the concrete.

Properties of Fresh Concrete

The workability or consistency of a freshly mixed concrete mixture is determined by the slump. The slump of a concrete and cement mortar mix incorporating plastic aggregate was thoroughly investigated because it is a crucial characteristic. The vertical distance between the top surface of the fallen concrete and the original cone mold was used to calculate the value of concrete slump. This test was conducted in accordance with (IS-1199:1959). Figure 6 shows a slump test conducted in the laboratory.



Figure 6. Slump Test for fresh concrete

Fresh Density was another quality of fresh concrete that was estimated. By filling a container with concrete mix, compacting it, and then weighing the container, a fresh sample of concrete was collected before it was cast into the molds to determine its fresh density.

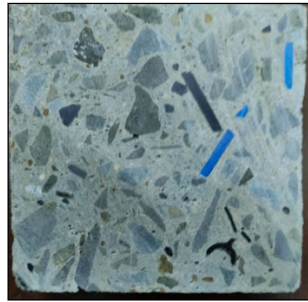


Figure 7. Paver block with 5% plastic aggregates

Properties of Hardened Concrete

Figure 7 shows the hardened permeable paver block specimen containing 5% plastic aggregates. The compressive strength tests were performed for the hardened concrete, as shown in Figure 8 (a). The test was conducted as per IS: 516-1959 for each sample. The Compression Testing Machine (CTM) is shown in Figure 8(a). A specimen is loaded in one axis during this test, and the load is increased over a predetermined amount of time until the specimen fails. The compressive strength is calculated using the ultimate load at failure.

Permeability

Permeability of the pervious paver block is also an important parameter, which is determined by the Falling Head apparatus. The apparatus is shown in Figure 8(b). The hydraulic conductivity of materials or other porous structures is measured by their permeability. It shows how quickly a specific amount of water will go through a porous structure at a specific hydraulic gradient. Permeability tests were performed only on the 28th day to simulate long-term drainage performance. However, this approach does not account for time-dependent clogging effects, which should be addressed in future studies.

Results and Discussion

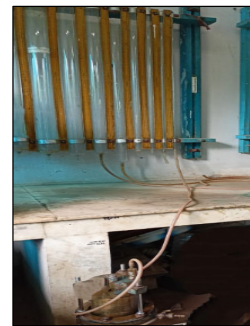
Compressive Strength

Compressive strength tests were performed using the cube specimen of the sample to assess the

compressive load-carrying capacity of permeable paver blocks made up of concrete. The results of the 7, 14, and 28-day compressive strength tests performed on samples of permeable paver blocks in which coarse aggregate was replaced by plastic aggregates in amounts of 0%, 5%, 10%, 15%, 20%, and 25% by weight are shown in Figure 9 and the amount of the mixture is listed in Table 6. Permeable paver blocks' compressive strength has been seen to decline as the proportion of plastic materials increases. For replacements of 5%, 10%, 15%, 20% and 25% plastic aggregates in the samples, the compressive strength was reported to have decreased by approximately 5%, 8.75%, 17.5%, 40% and 47.5%, respectively.



(a)



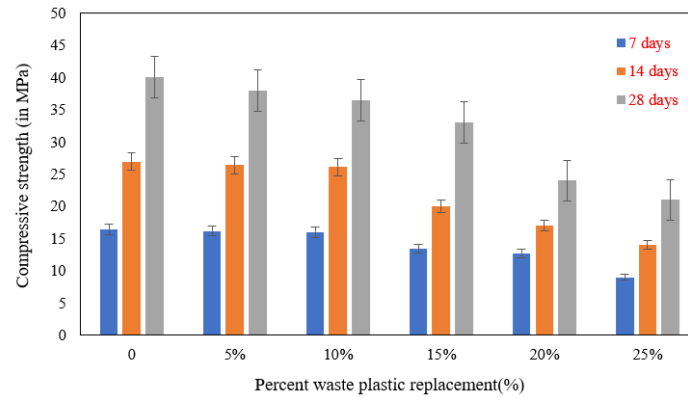
(b)

Figure 8. Experimental setup (a) Compression strength - UTM; and (b) Falling head Permeability apparatus

The upper limit of 25% plastic aggregate replacement was selected based on a combination of prior literature and preliminary trials. Beyond this level, compressive strength was observed to fall significantly below the minimum requirement of 35 MPa for M35 grade paver blocks, making them unsuitable for structural applications. Therefore, 25% was considered the maximum practical replacement threshold in this study.

Table 6. Design mix for permeable paver block of M35 grade

Percentage vol replace by plastic	Quantity of cement (kg/m ³)	Quantity of water (kg/m ³)	Quantity of coarse aggregate (kg/m ³)	Quantity of fine aggregate (kg/m ³)	Quantity of plastic aggregate (kg/m ³)
0	383	172.35	1188	546	0
5	383	172.35	1128.6	546	59.4
10	383	172.35	1069.2	546	118.8
15	383	172.35	1009.8	546	178.2
20	383	172.35	950.4	546	237.6
25	383	172.35	891	546	297

**Figure 9. Compressive strength**

The smooth surface texture of the plastic, which results in poor interface bonding between the Plastic aggregate and cement paste, is likely the cause for the decrease in compressive strength (Gu and Ozbakkaloglu, 2016). According to research from ITZ (Hannawi *et al.*, 2010) Utilizing data from a scanning electron microscope (SEM), a weak link between the cement matrix and plastic aggregates was found in the interfacial transition zone (ITZ). Additionally, as shown in the SEM testing (Pezzi *et al.*, 2006). The hydrophobic characteristic of plastic aggregates results in the formation of a thin water film around aggregates, which gradually weakens paver blocks. Our study's findings also indicated that the main factor contributing to the decline in strength is a weak bond between plastic aggregates and cement paste. Additionally, because plastic aggregates are hydrophobic, there is often an excess of water in the mixture. This could eventually weaken the concrete used to make paver blocks. Visible surface cracks and slight edge segregation were observed in paver blocks with more than 20% plastic aggregate, which may be attributed to weak interfacial bonding and higher porosity.

The results of the compressive strength study provide validity to earlier research on using plastic

trash as a partial replacement for natural aggregates. The replacement of coarse aggregate with plastic aggregate by up to 10% is judged fair when taking into consideration the minimum compression capacity for regularly used permeable paver blocks in medium traffic regions (i.e., 35 MPa).

Regression Analysis

The correlation between compressive strength and the use of plastic aggregate in place of coarse aggregate is a crucial component of our research. According to earlier research, changing the aggregate composition in concrete mixtures has a considerable impact on the concrete's compressive strength. It is crucial to evaluate how the replacement affects the compressive strength of the concrete specimens as we investigate the addition of plastic aggregate to the concrete mix, and also form an empirical equation. Due to the lower mechanical properties of plastics compared to traditional coarse aggregates, studies by (Alqahtani *et al.*, 2017; Ali *et al.*, 2023; Ramakrishnan and Jegan, 2023) have shown that increasing the proportion of plastic aggregate in the mix tends to decrease the compressive strength.

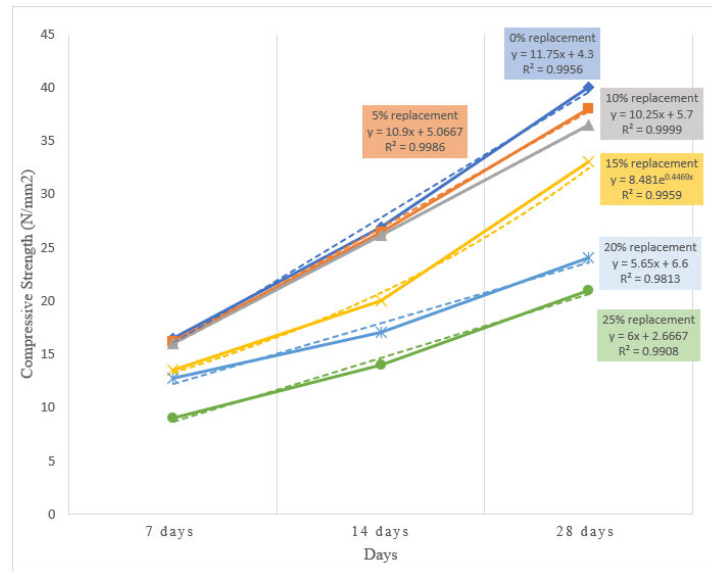


Figure 10. Compressive strength

The correlation between compressive strength and the replacement of coarse aggregate with plastic aggregate is a key focus of this research, which needs to be supported by empirical evidence.

In our study, we build upon this prior research, employing regression analysis to provide quantitative insights. Our preliminary findings confirm the negative correlation between plastic aggregate content and compressive strength. However, it is important to note that our analysis also reveals nonlinearity in this relationship. At lower replacement levels, the impact on compressive strength is relatively modest, but as plastic aggregate content exceeds a certain threshold, the decline becomes more pronounced. Figure 10 represents the relations as well as the empirical relation between the compressive strength and the replacement of coarse aggregate with fine aggregate with increasing time interval. A non-linear regression model was employed to predict compressive strength based on plastic replacement percentage. The R^2 value of >0.98 suggests a strong correlation, indicating predictive reliability for future studies.

As shown in Figure 10, regression equations were developed to capture the strength variation across all levels of plastic aggregate replacement. Additionally, a second-order polynomial regression model was fitted to the complete dataset to establish a generalized trend. The derived empirical equation is:

$$y = -0.025x^2 - 0.35x + 40, \text{ with } R^2 = 0.98,$$

which reflects a strong nonlinear correlation between compressive strength and replacement percentage.

While the regression analysis yielded a high R^2 value (0.98), it must be noted that this was based on averaged values from only three replicates per mix. A small sample size can artificially inflate R^2 , especially in polynomial fitting. Future studies with larger sample sets and statistical tests (e.g., ANOVA or t-tests) are recommended to validate and strengthen the observed trends.

Permeability of Mix

The permeability values for permeable paver block made using recycled plastic aggregate as a coarse aggregate in 0%, 5%, 10%, 15%, 20% and 25% were illustrated in Figure 11. Every phase of replacement showed an upward trend in permeability. The value scaled from 2.19 mm/s to 10.68 mm/s with a 79% increase from the control mix when reaching its highest for 25% replacement. However, raising the replacement rate above 15% resulted in a compromise with the compressive strength of the concrete-based permeable paver block, which should be 35 MPa. This might be due to the interfacial gap voids caused by the microcracks that result from an inefficient bond between the cement matrix and the plastic aggregate. According to (Najim and Hall, 2013) The bond on the interfacial transition zone is greatly influenced by the non-absorbent properties of the plastic surface and the variations in elastic moduli between cement paste and plastic aggregates. This

might be explained by the aggregate's form and smooth surface, which makes a continuous channel between pores and raises porosity. Additionally, more pores are created by the insufficient compaction brought on by the low density of plastic (Khalil and Obeidy, 2018). Overall, the study depicts that using recycled plastic aggregate as coarse aggregates increased the permeability of concrete mixes.

Technology Readiness Level (TRL) Assessment

A Technology Readiness Level (TRL) evaluation was done to evaluate the maturity of permeable pavement blocks that incorporate plastic aggregates, as shown in Table 7. TRL is an internationally acknowledged system that

categorizes the stages of technology development from TRL 1 (fundamental research) to TRL 9 (commercial implementation) (Mankins, 2004). This study positions the technology at TRL 4 (Validation in a Lab Environment), as laboratory testing has confirmed its structural feasibility, permeability, and durability, but further field trials and regulatory compliance assessments are required for real-world adoption (Rybicka *et al.*, 2016; Kolade *et al.*, 2022).

To progress from TRL-4 to TRL-5, pilot-scale field testing under real environmental conditions is necessary. Collaborations with municipal agencies and material testing facilities are also needed to validate field performance.

Table 7. TRL Table: Comparative Analysis for Plastic Aggregate Paver Blocks

TRL Level	Definition	Current Status & Future Steps for This Study
TRL-1	Basic research – theoretical concepts are explored	Plastic waste as an alternative aggregate for concrete has been proposed in the literature.
TRL-2	Technology concept formulated – initial experimentation begins	Preliminary research supports plastic waste's viability in construction materials.
TRL-3	Experimental proof of concept – early testing in lab conditions	Small-scale samples were fabricated and evaluated for compressive strength, permeability, and durability.
TRL-4 (Current Level)	Validation in a lab environment – controlled experimental results confirm feasibility	This study achieved TRL 4 by conducting laboratory testing of plastic aggregate-based permeable pavers. Structural and permeability tests confirm potential viability.
TRL-5	Validation in the relevant environment – pilot testing begins under real conditions	<i>Next step:</i> Large-scale field trials under actual weather and traffic conditions.
TRL-6	Demonstration in operational environment – performance evaluation in infrastructure projects	<i>Required:</i> Real-world performance monitoring for 12–24 months.
TRL-7	System prototype demonstrated – regulatory approval sought	<i>Needed:</i> Government approvals, compliance with IS/ASTM standards, and cost analysis.
TRL-8	Full system qualification – tested in large-scale construction	<i>Future goal:</i> Incorporation into commercial infrastructure projects.
TRL 9	Full commercial deployment – widespread industry adoption	<i>Final goal:</i> Market acceptance and integration into urban infrastructure.

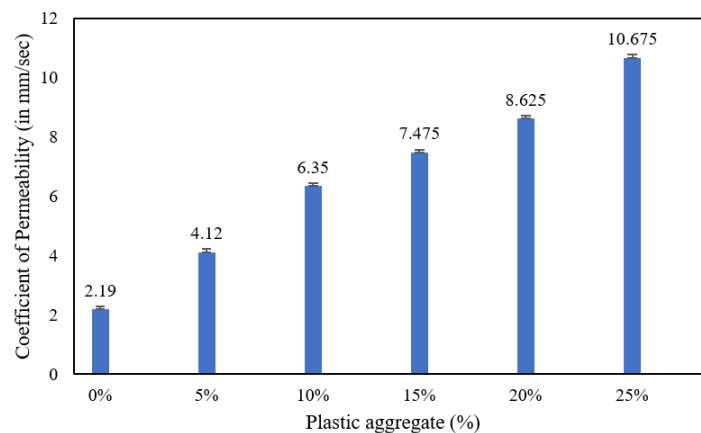


Figure 11. Permeability values for permeable paver block made using recycled plastic aggregate as a coarse aggregate in 0%, 5%, 10%, 15%, 20% and 25% replacements

Future Research Directions

While this study establishes the feasibility of using plastic aggregates in permeable pavement blocks, several key areas require further exploration for large-scale implementation.

- **Long-Term Durability & Weather Resistance:** Future research should analyze the freeze-thaw durability, abrasion resistance, and long-term strength retention of plastic aggregate-based permeable blocks under real-world traffic loads and varying climatic conditions.

- **Large-Scale Field Testing & Pilot Projects:** While lab-scale testing provides promising results, pilot-scale field implementation is necessary to validate the findings under actual road conditions. Future studies can explore real-world drainage efficiency, load-bearing capacity, and maintenance requirements.

- **Environmental & Groundwater Impact Assessment:** Further research should assess the potential leaching of microplastics and chemical compounds from plastic aggregates and their impact on groundwater quality. A detailed toxicity and sustainability study will strengthen its environmental feasibility.

- **Optimized Mix Design & Reinforcement Solution:** The compressive strength and permeability results were not subjected to statistical analysis due to limited sample size. Future studies should incorporate ANOVA or t-tests to validate the significance of observed differences. And also, to counteract the observed compressive strength reduction at higher plastic aggregate replacement levels, fiber reinforcements (e.g., steel fibers, basalt fibers) or surface-treated plastic aggregates could be explored as potential strength-enhancing modifications.

- **Cost-Benefit Analysis & Techno-Economic Feasibility:** A detailed cost analysis comparing traditional concrete blocks and plastic aggregate-based permeable blocks will provide better insight into their economic viability for commercial applications.

- **Standardization & Policy Integration:** For large-scale adoption, future research should develop guidelines aligning with Indian Standards/ASTM standards and work towards policy recommendations for promoting sustainable pavement solutions.

Conclusions

In conclusion, our research provided insight into the results of using plastic aggregate in place of coarse

aggregate for constructing permeable paver blocks. The findings of the study clearly indicate that the compressive strength of the paver blocks significantly decreases from 40N/mm² to 21N/mm² when the percentage of plastic aggregate increases from 0% to 25%. This reduction is mostly caused by the plastic aggregate's lower impact resistance and abrasion properties when compared to natural coarse aggregate. Additionally, the increased permeability of these blocks allows for enhanced water drainage, addressing surface water runoff concerns. Notably, the compressive strength maintains a good 36.5N/mm² value at a 10% replacement rate of coarse aggregate with plastic aggregate, exceeding the acceptable strength for paver blocks, which is 35N/mm². This result suggests a workable compromise between the inclusion of plastic aggregate and structural integrity. Our research also promotes resource conservation by using recycled plastic trash as a replacement for natural coarse aggregate, which lessens environmental stress. Future research should concentrate on evaluating the water quality and its toxicity analysis, as it permeates the ground through these permeable paver blocks, revealing their potential environmental effects in terms of groundwater. Also, the TRL assessment places the technology at TRL 4 (Experimental Validation in Lab Conditions), confirming its feasibility through laboratory testing. But, to transition to TRL 6-7, further research is needed on field trials, regulatory compliance, and cost-effectiveness evaluations. These findings encourage more study into environmentally friendly building materials and support sustainable construction methods.

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