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Upcycling Recycled High-Density Polyethylene (HDPE) as Sustainable Aggregate in Concrete Paving Blocks: Experimental Performance and Predictive Modeling

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ABSTRACT

Purpose: This study evaluates the feasibility of using recycled high-density polyethylene (HDPE) waste as a partial volumetric replacement for natural aggregate in concrete paving blocks and assesses its effects on mechanical performance, density, and water absorption.

Materials and Methods: Concrete paving blocks were produced using crushed recycled HDPE granules as volumetric aggregate replacements at 10%, 20%, and 30% (CP10, CP20, and CP30, respectively), with a control mixture (R0). Fresh concrete workability was maintained at an 80 mm slump to isolate the effect of HDPE content on hardened-state properties. Compressive strength, flexural strength, bulk density, and water absorption were evaluated, and linear regression models were developed to examine relationships between HDPE content, density, and mechanical performance.

Results: Increasing HDPE content progressively reduced compressive strength from 65.66 MPa for R0 to 48.67–39.36 MPa for the HDPE mixtures, corresponding to reductions of 26–40%. Flexural strength decreased from 7.94 MPa to 6.91–4.49 MPa, representing reductions of 13–44%. In contrast, bulk density decreased from 2206.6 to 1926.7 kg/m³, corresponding to a maximum reduction of 12.7%. Water absorption also decreased, with all mixtures remaining below the 6.5% limit specified by LNCSM-7:2025. The regression models showed strong predictive relationships, with R^2 values up to 0.98 and a density–strength correlation of $R^2 = 0.97$.

Conclusions: Recycled HDPE can effectively produce lighter paving units while maintaining compliance with the specified water-absorption requirement. Although increasing HDPE content reduces mechanical strength, the 10% replacement level provides the most favorable balance between weight reduction and mechanical performance. This approach offers a practical route for valorizing urban HDPE waste in non-structural pedestrian paving applications. *(J Multidiscip Eng 2026;1:59-67)*

Keywords: High-density polyethylene (HDPE), recycled plastic aggregate, paving blocks, compressive strength, flexural strength, water absorption.

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1. INTRODUCTION

The rapid increase in global plastic waste poses a significant environmental challenge, pushing the construction sector towards sustainable solutions within a circular economy. Structural frameworks have been created for paving materials that consist entirely of alternative waste materials, thus eliminating the necessity for Portland cement.[1] Conventional concrete paving units frequently

experience surface cracking and particle detachment due to ongoing pedestrian friction. Substituting rigid natural aggregates with ductile, viscoelastic polymers presents an innovative solution to improve energy absorption and surface durability. The incorporation of agricultural and rubber waste alongside advanced sustainable formulations has successfully utilized coal char-based materials, specifically for road paving and pedestrian walkway applications.[2] This runs parallel to pioneering work that integrated fly ash to enhance the surface performance and durability of conventional concrete paving blocks.[3,4,5]

High-Density Polyethylene (HDPE) makes up a large portion of municipal solid waste, and its non-biodegradable nature contributes to serious landfill issues. Upcycling HDPE into concrete composites as a partial replacement for aggregates presents a practical approach to reducing the depletion of natural resources and lowering the carbon footprint associated with concrete production.[6,7,8]

Interlocking concrete paving blocks and pedestrian tiles are ideal for plastic upcycling because these non-structural elements primarily face surface friction, weathering, and light loads instead of major structural forces [9, 10]. While adding polymers to concrete often results in a decrease in compressive strength due to the hydrophobic nature of plastics and the subsequent weak interfacial transition zone (ITZ),[11,12] strong compressive strength is not the only factor to consider for pedestrian infrastructure. Instead, there is a growing emphasis on properties such as weight reduction, energy absorption, and durability.[13]

While extensive literature discusses the mechanical degradation of plastic-modified concrete, there has been limited focus on optimizing the secondary benefits of including HDPE specifically, its potential for weight reduction and water absorption behavior in paving units. Building on previous findings that HDPE enhances surface abrasion resistance in mosaic tiles,[14] this study evaluates the experimental performance of concrete paving blocks that incorporate recycled HDPE granules as aggregate replacements at 10%, 20%, and 30% by volume.

This paper emphasizes the balance between potential strength reduction, decreased density, and water absorption compliance with international standards. Additionally, it proposes empirical predictive models to support sustainable pavement mix designs.

2. MATERIALS AND METHODS

2.1 Research Context

Despite the environmental inducements of utilizing recycled HDPE in concrete, a critical material drawback is the hydrophobic surface profile and lower surface energy of the polymers systematically lead to a weakened interfacial transition zone (ITZ) and a subsequent reduction in conventional compressive performance. However, conventional studies often classify this reduction in strength as terminal failure, overlooking the potential structural benefits in applications where continuous surface friction, impact resistance, and lightweight construction are prioritized over high load-bearing capacity. Concrete paving blocks are predominantly prone to surface wear, micro-cracking, and aggregate separation under the influence of pedestrian and light vehicular movement.

Subsequently, the significance of this study lies in transitioning from traditional strength to a surface-durability and eco-efficiency optimization outline. By studying how ductile recycled HDPE granules can function as internal shock absorbers to arrest micro-cracks and suppress abrasive wear, this research establishes a viable structural pathway for the commercial upcycling of global urban plastic waste (which reached approximately 220 million tons in 2024).

To methodically address this engineering challenge, the research plan is executed across three interconnected phases: (i) Preparing and substituting natural aggregates with crushed recycled HDPE granules at distinct ratios (10%, 20%, and 30% by volume); (ii) Manufacturing two distinct structural lines comprising four paving block mixtures (R0, CP10, CP20, CP30); (iii) Conducting thorough testing on fresh concrete (slump) and hardened-state properties, focusing on the positive correlations regarding density reduction and water absorption alongside conventional compressive and flexural strength thresholds.

2.2 Materials and Characterization

Ordinary Portland Cement (OPC) CEM I 42,5R, conforming to standard international specifications was utilized as the primary binder. The water used is drinkable and free of organic matter, in accordance with Libyan Standard Specifications (LNCSM 249),[15] which specifies chloride content to ≤ 500 ppm, sulfate content to ≤ 1000 ppm and requires carbonate/bicarbonate content ≥ 1000 ppm. A combined fine aggregate consisting of 60% natural fine sand (Misrata) with an absorption ratio of 0.355% and 40% crushed marble sand (Italy) with an absorption rate of 2.02% was used. The specific weight of the marble was 2.63. The grain size distribution of both types was highly graded in accordance with the Libyan standard (LNCSM 49-2002).[16] Recycled HDPE waste was collected, commercially washed, and crushed into granules suitable for aggregate use. According to the partial replacement of natural aggregate sizes, the physical properties and shape configurations of the HDPE granules were selected. Sika Plastocrete-N KE, a liquid chemical admixture based on modified lignosulphonate, was used to enhance the workability of fresh concrete and reduce the water/cement. The admixture is a dark brown liquid with a density of 1.09–1.195 kg/L at 25 °C, a pH of about 5.0–7.0, a dry solids content of 33.5–36.5%, and a chloride ion content ≤ 0.2%.

2.3 Concrete Proportions and Mixing Design

Different mixing ratios were used for the paving blocks based on the volumetric equation. Various proportions of gravel and fine aggregates were replaced with HDPE aggregate according to their particle size distribution. Additionally, Sika Plastocrete-N KE was incorporated into the mixtures to offset the expected decrease in resistance due to the addition of plastic.

As shown in Table 1, a total of four concrete mixtures were created: a control mix (R0) and three modified mixes with 10%, 20%, and 30% volumetric replacements of HDPE (CP10, CP20, and CP30). Forty paving blocks molds with dimensions of 200×100×60 mm were prepared.

The workability of the fresh concrete was immediately checked using a standard slump test. The mixes were then cast into molds. Using vibrating tables, compacting was applied to ensure the proper matrix consolidation around the hydrophobic plastic granules. All samples were demolded after 24 hours and fully immersed in water curing tanks at lab temperature ($23 \pm 2°C$) until they reached their specified test ages.

Table 1. Types of mixes for paving blocks and material ratios in the mix (kg/m³).

Mixture	Cement	Water	Aggregate	HDPE	Plastocrete-N KE
R0	350	296.6	1040.1	0.0	2.1
CP10	350	289.7	935.3	24.7	2.1
CP20	350	270.9	831.5	49.3	2.1
CP30	350	260.0	727.7	73.2	2.1

3. TESTING PROCEDURES

3.1 Compressive and Flexural Strength Testing

Compressive and flexural strength tests were carried out on the reference (R0) and HDPE-modified (CP10, CP20, CP30) paving block specimens (200×100×60 mm) at 28 days of curing using an AUTOTEST testing machine. Each sample was loaded to failure, and its compressive and flexural strength values were calculated based on the recorded failure load, the sample's cross-sectional area, and the cross-sectional modulus. The final compressive and flexural strength values were extracted directly from the instrument screen. The average of the values for three samples of each mixture was used in the final evaluation.

3.2 Water Absorption Testing

Water absorption was determined in accordance with Libyan Standard LNCSM-7-2025,[17] on an

average of five specimens per mix. Specimens were oven-dried to constant mass and weighed, then fully immersed in water for the period specified by the standard, after which surface moisture was removed and the specimens re-weighed. Water absorption was calculated as the percentage gain relative to the oven-dry mass.

3.3 Density Measurement

The bulk density of the hardened paving blocks was determined by calculating the ratio of the specimen's mass to its volume, which was derived from the measured external dimensions of each specimen. An average of five specimens was analyzed for each mix.

4. RESULTS AND DISCUSSION

Slump tests were performed on fresh concrete to validate the experimental plan. Hardened concrete samples were then tested after 28 days for compressive strength, flexural strength, bulk density, and water absorption, with results shown in Table 2.

Table 2. Concrete mixes test results.

Concrete mixes	Density (Kg/m³)	Compression (MPa)	Flexural (MPa)	Absorption (%)
R0	2206.6	65.66	7.94	5.96
CP10	2063.0	48.67	6.91	5.59
CP20	1977.0	40.39	5.25	5.51
CP30	1926.7	39.36	4.49	5.44

4.1 Fresh Concrete Properties (Workability)

The slump value was controlled at 80 mm for all mixes by adjusting the mix water content, ensuring that workability remained constant across the study and isolating the effect of HDPE content on hardened-state properties.

4.2 Compressive Strength

Compressive strength testing was performed on both the reference paving block mix and the HDPE-modified mixes at 28 days of age. The results, along with standard deviations, are presented in Figure 1.

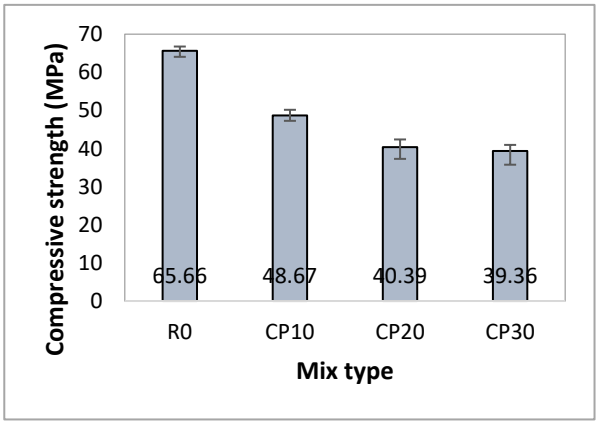


Fig. 1: Compressive strength of paving blocks versus HDPE replacement ratio (28 days).

Compressive strength decreased progressively with increasing HDPE content, from 65.66 MPa for the control mix (R0) to 48.67 MPa, 40.39 MPa, and 39.36 MPa for CP10, CP20, and CP30, respectively, corresponding to reductions of approximately 26%, 38%, and 40% comparative to the control mix. Despite this decrease, the compressive strength values remained high thanks to the addition of the aforementioned Sika Plastocrete. This trend is attributed to the weak interfacial bond between the smooth, hydrophobic HDPE particles and the surrounding cement paste, which limits stress transfer across the matrix and reduces the load-bearing capacity of the composite.

A similar fracture pattern progression was visually observed, with control samples showing a brittle and granular fracture pattern, while HDPE-modified samples showed increasingly splintered fracture with an increasing substitution ratio, consistent with the progressive weakening of the aggregate-paste interface. The failure pattern illustrated in Figure 2.



Fig. 2: The failure patterns in different mixtures.

4.3 Flexural Strength

Flexural strength testing was performed on all paving block specimens after 28 days. The results presented in Table 2 are also graphically displayed in Figure 3, including the standard deviation.

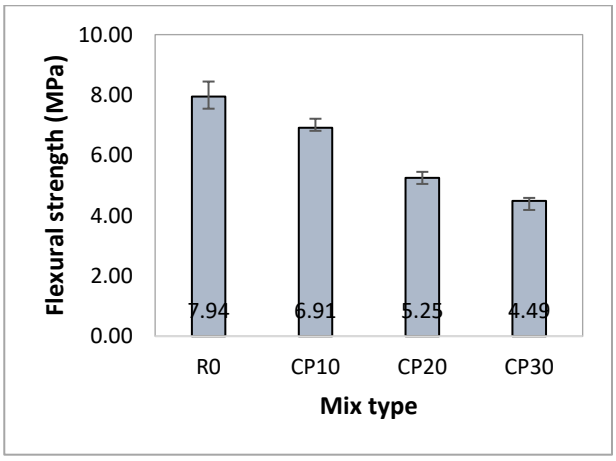


Fig. 3: Flexural strength of paving blocks versus HDPE replacement ratio.

Flexural strength decreased modestly and progressively with increasing HDPE content, from 7.94 MPa (R0) to 6.91, 5.25, and 4.49 MPa for CP10, CP20, and CP30, respectively, reductions of approximately 13.0%, 33.9%, and 43.5% relative to the control. The flexural strength values establish 12.1%, 14.2%, 13.0%, and 11.4% of the compression value. Although the reduction in flexural strength was proportionally smaller than that of compressive strength, it suggests a similar weakening mechanism at the HDPE paste interface under flexural stress. This indicates a mechanical degradation mechanism linked to the low bond strength at the interfacial transition zone (ITZ) between HDPE and paste.

Notably, the development of crack became progressively less severe with increasing HDPE content: the control specimen failed by complete fracture into two halves, while the CP30 specimen exhibited only limited cracking, indicating that HDPE particles give the composite a degree of flexibility and ductility after cracking, consistent with the elastomeric nature of the polymer.

4.4 Water Absorption

The water absorption results for paving blocks for an average of 5 samples are summarized in Table 2. All these results are within the limits of Libyan Standard LNCSM-7-2025 [17], which indicates that the absorption rate of paving blocks should not exceed 6.5% by weight for an average of 5 samples. The control mix (R0) achieved an absorption of 5.96%, however, all HDPE-modified mixes decreased as HDPE content increased from 10% to 30% with absorption of 5.59%, 5.51%, and 5.44% for CP10, CP20, and CP30, respectively. This behavior suggests that the reduced absorption associated with the addition of HDPE is due to its non-absorbency, leading to a decrease in absorption with increasing substitution of HDPE particles. This natural result reinforces previous studies indicating this reduction.

4.5 Density

The paving block density results shown in Table 2 indicate a gradual decrease with increasing high-density polyethylene (HDPE) content, which is normal given HDPE's lighter weight compared to natural aggregates. The paving blocks density decreased from 2206.6 kg/m³ (R0) to 1926.7 kg/m³ (CP30), representing reductions of 6.5%, 10.4%, and 12.7% for samples CP10, CP20, and CP30, respectively. This overall density reduction is beneficial for applications requiring a decrease in self-weight and associated structural loads.

4.6 General Discussion

The four measured properties, when considered together, create a consistent and coherent understanding of how recycled HDPE alters the paving-block matrix. Compressive and flexural strength decreased in close proportion in all four mixes. This indicates that the addition of HDPE does not significantly alter the brittleness or ductility of the composite compared to the reference mix. Rather, it uniformly weakens one key mechanism: the poor adhesion between the smooth, hydrophobic surface of the HDPE and the

surrounding cement paste. This interpretation is further supported by the strong linear correlation observed between bulk density and both compressive and flexural strength (Next section). As the replacement ratio of HDPE granules with lower specific gravity increases, they occupy a larger portion of the mix volume. This reduces the overall packing density of the matrix and introduces a consistent proportion of poorly bonded interfaces. Both factors affect strength through essentially the same physical mechanism.

Compared with previous studies on plastic-modified paving units, the observed trend and magnitude of resistance reduction are consistent with published findings. A similar gradual decrease in compressive and flexural resistance with increasing plastic content, rather than a constant decrease in resistance, has been reported in paving blocks modified with polyethylene terephthalate (PET), where the best resistance was obtained near the lowest tested replacement level,[13] a trend generally consistent with the resistance-durability trade-offs reported in paving blocks modified with wheat straw and crumb rubber/coconut fiber.[10,18] This convergence across independent studies using various waste materials indicates that hydrophobicity and surface smoothness, rather than the specific polymer chemistry, are the primary mechanisms limiting strength shared by recycled thermoplastic and elastomeric aggregates in cementitious composites. The water absorption results are arguably the most significant finding of the study from an application perspective. All four mixes, including CP30, surpass the 6.5% LNCSM-7-2025 threshold, and absorption actually improves as the HDPE content increases. Since paving blocks used in pedestrian areas and light landscape settings must endure wet-drying cycles as much as they need to support peak load capacities, this decrease in absorption is a genuine benefit that is verified by standards, rather than a mere secondary observation. The case for substituting HDPE relies heavily on a 6.5-12.7% reduction in self-weight, which lowers transport, handling, and installation costs for large-area paving projects, rather than primarily on strength enhancement.

Balancing these trade-offs, the 10% replacement ratio (CP10) stands out as the most practical recommendation based on the current dataset. This ratio maintains approximately 75% of the reference compressive strength (48.67 MPa compared to 65.66 MPa) while providing a noticeable reduction in density and improved water resistance. The 20% and 30% replacement ratios are also acceptable for lighter applications, such as garden paths and non-vehicular courtyards. These ratios yield a residual compressive strength of around 40 MPa, which is sufficient for typical pedestrian-block design requirements. However, they should not be used for applications that involve vehicular loading without independent structural verification. A direct limitation of this study is that abrasion resistance was not measured directly; therefore, the conclusions drawn are based on indirect reasoning. Future research should focus on standardized abrasion testing, such as the Böhme or wide-wheel methods, applied consistently across the same four mixes. Additionally, conducting freeze-thaw cycles and long-term water absorption testing would help validate the durability claims suggested by the observed trends in density and absorption.

4.7 Empirical Predictive Models

To prepare the experimental dataset for initial mix design screening, we constructed linear regression models that relate the high-density polyethylene (HDPE) substitution ratio (x, expressed as a percentage by volume) to the percentage decrease in each measured hardened-state property relative to the control mix (y). These relationships are illustrated in Figure 4, based on the four mixes detailed in Table 2 and expressed through Equations 1 to 4:

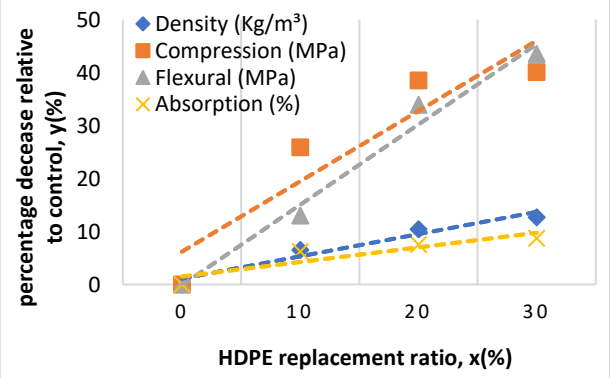


Fig. 4: The linear relationship between the percentage decrease in properties as a function of the HDPE ratio.

Compressive strength:

$$y = 1.328x + 6.19\ (\%), R^2 = 0.86 \quad (1)$$

Flexural strength:

$$y = 1.513x - 0.11\ (\%), R^2 = 0.98 \quad (2)$$

Bulk density:

$$y = 0.420x + 1.11\ (\%), R^2 = 0.95 \quad (3)$$

Water absorption:

$$y = 0.275x + 1.49\ (\%), R^2 = 0.84 \quad (4)$$

These equations provide a way to estimate the expected performance of an untested intermediate replacement ratio (x), such as 15% or 25%, without the need for additional casting tests. This makes them an efficient screening tool prior to conducting confirmatory testing. The four mix points offered are first-order approximations and are intended for interpolation within the tested range of 0-30%. However, it is important to note that extrapolation beyond 30% HDPE is not supported by the current data.

In addition to the ratio-based models, a more direct and practically useful relationship was discovered between bulk density (ρ) and mechanical strength. This relationship highlights their common physical origin, as discussed in the previous section. The connections are illustrated in Figure 5 and are represented by Equations 5 and 6.

Compressive strength:

$$fc = 0.0979\rho - 151.47\ (MPa), R^2 = 0.97 \quad (5)$$

Flexural strength:

$$ff = 0.0125\rho - 19.33\ (MPa), R^2 = 0.95 \quad (6)$$

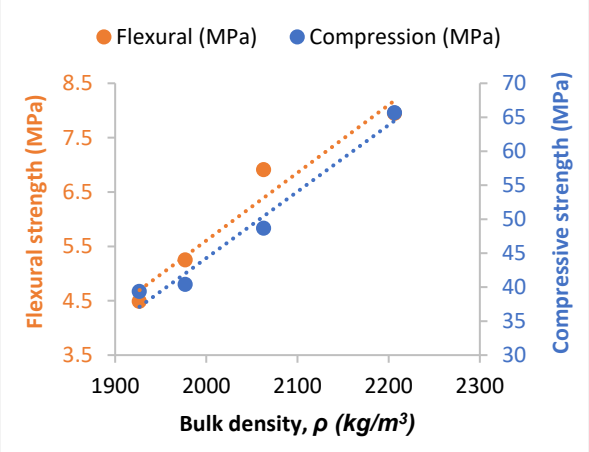


Fig. 5: The relationship between the mechanical properties of concrete and its density as a function of the percentage of HDPE replacement.

Bulk density can be measured quickly and non-destructively on a hardened paving unit using only dimensional and mass measurements. In contrast, compressive and flexural tests are both destructive and time-consuming. This density-strength relationship provides a practical quality control tool for in-plant operations. By measuring production density, it serves as a rapid proxy indicator to identify units that fall outside the expected strength range for their target mix, allowing for early detection before formal destructive testing is conducted.

5. CONCLUSION

This study evaluated the physical and mechanical performance of concrete paving blocks incorporating recycled high-density polyethylene (HDPE) as a partial volumetric replacement for natural aggregate at levels of 10%, 20%, and 30%. Experimental results demonstrated that increasing the HDPE content led to a progressive decline in both compressive and flexural strengths; this is primarily attributed to the hydrophobic nature of the polymer particles and the resulting weakness in the interfacial transition zone within the cementitious matrix. Despite this reduction in strength, the addition of HDPE significantly lowered the bulk density of the paving blocks, yielding lightweight units that effectively reduce self-weight and structural loads. Furthermore, water absorption values improved across all replacement levels compared to the control mix and remained within the permissible limits set by the LNCSM-7-2025 standard for paving tiles. Among the tested compositions, the 10% replacement level achieved the optimal balance between load-bearing capacity and weight reduction, making it a viable, eco-friendly strategy for recycling urban plastic waste in non-structural pedestrian paving applications. Linear regression models also revealed strong correlations between density and mechanical performance, offering a rapid, non-destructive tool for quality control in industrial production. However, a notable limitation of this study is the absence of direct abrasion resistance testing; Therefore, future research should focus on evaluating abrasion resistance in accordance with standard specifications, as well as investigating long-term durability and performance under temperature fluctuations, to fully verify the practical

feasibility of HDPE-modified paving composites.

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AUTHOR CONTRIBUTIONS

Salhin Alaud: Conceptualization, methodology, writing – original draft, investigation, data curation, manuscript preparation, and final approval of the manuscript. **Abdulrahman A. Hussein:** Investigation, data curation, validation, manuscript preparation, critical review, writing – review & editing, and final approval of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest concerning the research, authorship, and publication of this article.

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