

Original article

Utilizing the High-Density Polyethylene Waste in Mosaic Floor Tiles as a Partial Replacement for Marble Aggregate

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Abstract

This research aimed to evaluate the use of recycled high-density polyethylene (HDPE) waste as a partial replacement for natural marble aggregate in the manufacture of mosaic floor tiles. A laboratory study was conducted involving the preparation of four concrete mixes for the floor tiles: a reference mix (free of HDPE) and three mixes with volumetric replacement percentages of 10%, 20%, and 30% HDPE. Mechanical and physical tests were performed on the samples after 7 days of curing, including flexural strength, abrasion resistance, water absorption, and density. The results showed that the addition of polyethylene led to a gradual decrease in flexural strength with increasing substitution percentage. The reference mix recorded a flexural strength of 7.02 MPa, compared to 6.28 MPa for the mix containing 30% polyethylene. However, the increase contributed to improving the cracking behavior and increasing the flexibility of the samples under loads. Conversely, abrasion resistance improved significantly, with thickness loss decreasing from 0.046 mm in the reference sample to 0.016 mm in the sample containing 30% polyethylene. A decrease in overall density was observed with increasing polyethylene content, contributing to a reduction in tile weight. Absorption decreased to 7.11% with a 30% increase in the HDPE content, compared to 7.43% for the reference mix. All samples-maintained absorption levels within acceptable limits (less than 10%). The study concluded that using up to 20% HDPE waste offers a promising solution for achieving environmental sustainability, reducing weight, and improving the abrasion resistance of floor tiles.

Keywords. High-Density Polyethylene, Waste, Partial Replacement, Marble Aggregate.

Introduction

The building materials sector is witnessing rapid advancements focused on enhancing product performance and improving economic and environmental efficiency. Mosaic floor tiles are a fundamental element in the construction of buildings and facilities, constantly subjected to mechanical loads and abrasive factors that necessitate developing their properties to ensure their durability and lifespan. In this context, the trend towards introducing innovative materials that contribute to improving tile performance is prominent, and among these materials, plastic waste stands out as a promising option, with its production reaching only 430 million tons in 2024, of which only 10% is recycled [1]. High-density polyethylene (HDPE) is one of the most widely used types of plastic in the world, accounting for approximately 12% of all plastic produced. This waste poses a significant environmental challenge due to its slow decomposition and accumulation in the environment, necessitating the search for innovative and sustainable solutions for recycling and reusing it in various sectors, most notably the construction industry [2].

Polyethylene possesses unique properties that make it a suitable candidate for use in floor tile manufacturing, most notably its lightweight nature, high abrasion resistance, and flexibility, which can contribute to improved tile performance under load. Using this alternative is expected to enhance tile properties such as abrasion resistance and thermal insulation, in addition to reducing overall weight, thus positively impacting the load on structures and lowering transportation and installation costs. The steady increase in polyethylene waste resulting from the expansion of plastic product use poses a growing environmental threat that necessitates practical recycling solutions. Furthermore, the lack of available studies addressing the use of this waste as an unconventional additive in the floor tile industry warrants attention, particularly regarding its integrated impact on mechanical and physical properties such as flexural strength, abrasion resistance, and water absorption. This research aims to study the effect of partial replacement of natural aggregate with high-density polyethylene waste at volumetric ratios (10%, 20%, and 30%) on the performance of mosaic floor tiles.

The study evaluates the flexural strength of the tiles, measuring abrasion resistance and determining the amount of loss, determining the water absorption ratio and density of the samples, analyzing the cracking behavior under flexural loads, and reaching the optimal replacement ratio that achieves a balance between the different mechanical properties. This study is significant because it offers a practical solution for utilizing recycled polyethylene waste in the construction industry. Moreover, contributing to environmental sustainability and reducing the negative impact of plastic waste accumulation. The study also provides experimental data on the effect of these additives on the performance of mosaic tiles, helping manufacturers and engineers make informed decisions regarding the use of these materials in various applications.

Methods

Materials used

The mosaic tiles consist of a face layer (surface) made from a mixture of white or colored cement with crushed marble (or quartz), and a back layer (base) composed of cement and fine aggregate to ensure adhesion. The 10 mm thick back layer is made of cement mortar using ordinary Portland cement (CEM I 42.5N) produced by the Arab Union Factory in Zliten city, conforming to Libyan standard LNCSM-340 [3]. The fine aggregate consists of sand sourced locally from Misrata city, with an absorption rate of 0.355%, in addition to gravel supplied from the Al-Alous area east of Tripoli. The aggregate particle size distribution conforms to Libyan standard LNCSM-49 [4]. The face layer, 15 mm thick, is made of white cement produced by the Biskra Company in Algeria to improve the tile surface appearance.

Crushed marble was supplied from Italy (from marble quarries) with a specific gravity of 2.6 and an absorption rate of 0.005%, available in two colors, white and black, to enhance the aesthetic appeal of the mosaic tiles. Marble powder with a maximum nominal particle size of less than 500 micrometers was added, in accordance with Libyan specifications (LNCSM-7, 2006) [5]. As a filler to improve the mechanical properties of tiles, high-density polyethylene (HDPE) waste was obtained to replace the aggregate in the face layer. This waste was sourced from plastic recycling plants in the city of Qarabulli and shredded using a mechanical granule machine (Retsch SR 300). The particle size can be controlled by using sieves on the bottom. The produced granules have diameters ranging from 0.15 to 4.75 mm. Figure 1 shows the materials used in the production of the two-layer tile. Potable water, conforming to specification (LNCSM-294) [6], was used in both layers.



Figure 1. Materials used in mixtures

Preparing mixtures and designing ratios

Four mixes of the tiles were prepared: a reference mix (R0) free of polyethylene, and three mixes with volumetric replacement ratios of coarse aggregate of 10%, 20%, and 30%, referred to as (FP10), (FP20), and (FP30), respectively. (Table 1) shows the quantities of materials used for the face and back layer per square meter.

Table 1. Proportions of components of floor tile mixes (kg/m²)

| Face Layer | Mix Type | White Cement | Water | Coarse Aggregate | Polyethylene Aggregate | Marble Powder |
|------------|-------------|--------------|-------|------------------|------------------------|---------------|
| | R0 | 5.6 | 4.5 | 21.714 | 0 | 10.850 |
| | FP10 | 5.6 | 4.835 | 19.542 | 0.650 | 10.850 |
| | FP20 | 5.6 | 4.38 | 17.37 | 1.30 | 10.850 |
| | FP30 | 5.6 | 4.368 | 15.2 | 1.950 | 10.850 |
| Back Layer | Mix | Black cement | Water | Sand | gravel | |
| | All Samples | 2.4 | 1.63 | 5.76 | 3.84 | |

Experimental program

Four mixtures are prepared for tile production, including the reference mixture and three other mixtures with the mentioned replacement ratios.

Mixing, Casting, and Curing Procedure

The materials (cement of both types, aggregates, marble powder, and polyethylene granules) were prepared and weighed using a sensitive balance (0.1 g accuracy). The tiles were manufactured in a specially equipped factory under laboratory conditions according to the procedures followed in tile manufacturing, as shown in (Figure 2) and as stipulated in Libyan Standard No. 7-2006 [5]. After mixing the dry ingredients and adding water, the first layer was cast into molds designed for tile production with dimensions of (250×250×25) mm. Eight molds were prepared for each mix, totaling 32 molds for the four mixes. The mixture was compacted using a mechanical vibrator for two minutes to remove air voids. The back layer, made of cement mortar, was then mechanically compacted to a pressure proportional to the surface area. The samples were left to dry in a location away from sunlight and then underwent wet curing for several days at a temperature of 20±2°C. After 72 hours, they were polished and smooth using a sanding machine to achieve the final tile shape. They remained under curing for seven days after casting. (Figure 3) shows the tiles after being poured into the molds, prior to the sanding process, while (Figure 4) displays the finished tile samples after polishing.



Figure 2. Tile manufacturing

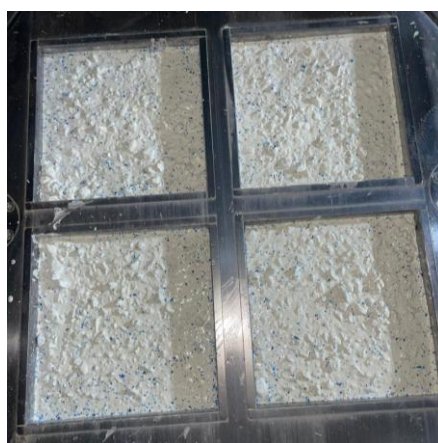


Figure 3. Cast the tile in the molds

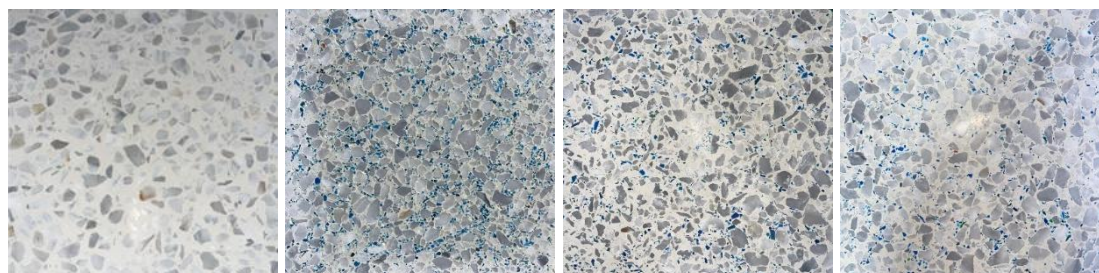


Figure 4. Final texture of the samples produced

Laboratory tests

Seven days after treatment, the mosaic tile samples were subjected to a comprehensive series of mechanical and physical evaluations in accordance with established standards. Flexural strength was determined using the Tecnotest device, applying a central load to specimens measuring 250 × 100 × 25 mm at a loading rate of 0.5 mm/min until failure, following ASTM C293 guidelines. For each mixture, three samples were tested, and the average failure load was used to calculate the bending stress. Abrasion resistance was assessed with a specialized device designed to simulate wear from continuous friction in high-traffic conditions. Samples of 60 × 60 × 25 mm were prepared and exposed to 500 operating cycles, with mass loss and surface changes recorded according to specification [5]. Water absorption was measured in line with ASTM C642. Samples were oven-dried at 105 ± 5 °C until weight stabilization, then immersed in water for 24 hours, with absorption ratios calculated as the mean of three specimens per mixture. Apparent density was determined by dividing the mass of saturated samples by their volume, using a sensitive balance and digital caliper for precise dimensional measurements. Finally, fracture patterns resulting from the flexural strength test were documented through digital imaging, enabling detailed analysis of crack propagation and failure behavior under load.

Results And Discussion

The aforementioned tests were statistically analyzed using Excel. The results were compared to the reference mix and approved standards. The results of the various tests are recorded in (Table 2).

Table 2. The average test results for the different mixtures

| Mix | Flexural Strength MPa | Abrasion Resistance mm | Water Absorption % | Density kg/m ³ |
|------|--------------------------|---------------------------|-----------------------|------------------------------|
| R0 | 7.02 | 0.046 | 7.43 | 2476 |
| FP10 | 6.85 | 0.05 | 7.43 | 2279 |
| FP20 | 6.43 | 0.03 | 7.15 | 2229 |
| FP30 | 6.28 | 0.016 | 7.11 | 2208 |

Flexural resistance test

The flexural strength test in this research was performed on all tiles seven days after casting. The samples were placed in the device under the load arm, then the load was gradually applied to the middle of the sample until collapse, as in (Figure 5). The results of flexural stress for different mixes mentioned in (Table 2) are displayed in Figure 6. The figure illustrates the relationship between the mix type and the flexural strength for each sample, along with the standard deviation of the results.



Figure 5. A fracture pattern in the samples due to flexural load

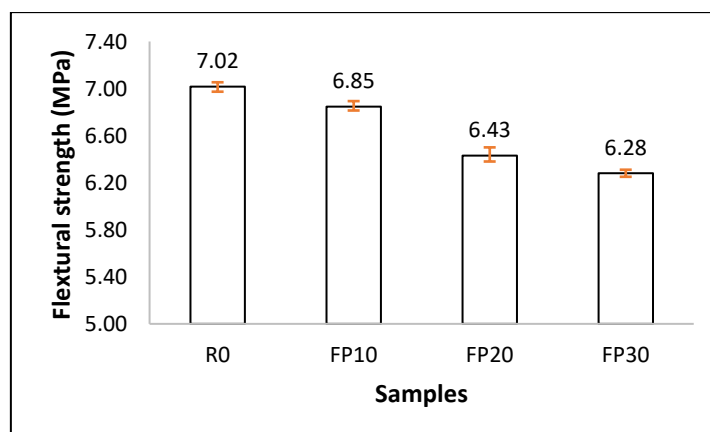


Figure 6. Flexural resistance of the different samples

It is evident from the data that as the amount of polyethylene in the mix increases, flexural strength steadily declines. This layout shows how the mechanical characteristics of the tiles are directly impacted by the addition of plastic. When 10% polyethylene (FP10) was added, the resistance dropped by 2.4%, from 7.02 MPa for reference (R0) to 6.85 MPa. After adding 20% polyethylene (FP20), the resistance dropped to 6.43 MPa, which is 8.4% less than the R0. The resistance dropped to 6.28 MPa, or 10.5% less than the R0, when 30% polyethylene (FP30) was added. This decrease in bending resistance is due to several factors, including the weak bonding between the polyethylene granules (which are hydrophobic) and the cement paste, which creates weak areas known as the Interfacial Transition Zone (ITZ). Additionally, the polyethylene has a lower modulus of elasticity compared to natural aggregate, which reduces the overall stiffness of the tiles under bending loads. Despite a decline in flexural strength, the study demonstrated a notable improvement in flexural cracking behavior.

It is noted that sample R0 developed a large crack, resulting in it splitting in two (brittle behavior). Sample FP10 exhibited a moderate crack without complete splitting, due to the flexibility of the polyethylene. Compared to the R0, sample FP20 displayed a smaller crack, while sample FP30 exhibited a very limited crack, confirming the improved flexibility and the tile's ability to absorb energy without complete collapse. This behavior is consistent with a previous study by the researcher using HDPE in concrete [9]. According to the LNCSM-7 specification [5]. All samples attained acceptable bending resistance ratings for widespread use, which indicates the bending fracture standard is no less than 4.0 MPa for each test piece and 4.5 MPa for the average results of 5 pieces. The reduction in the studied mixtures did not fall below 6.0 MPa, even at a rate of 30%.

Abrasion resistance

The test specimen was placed in the apparatus so that it was tangential to the rotating disc. Abrasive material was fed uniformly into the grinding zone at a rate of (500 ± 10) g/500 revolutions. The amount of loss in thickness was measured in accordance with approved standards and procedures to ensure the reliability and comparability of the results. According to the LNCSM-7 specification [5]. The amount of abrasion loss in the face layer thickness of a single tile does not exceed 0.5 mm, and the average for four tiles does not exceed 0.4 mm. The results shown in (Table 2) are for the abrasion test, which is for an average of five samples. These results are represented in (Figure 7) with an illustration of the standard deviation coefficient of the test results.

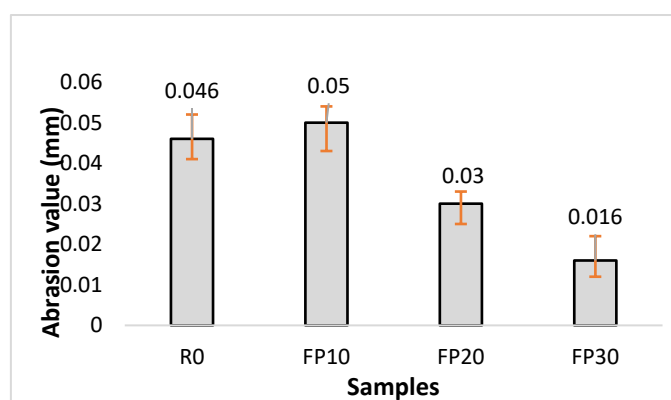


Figure 7. Abrasion values for the different samples

It is observed that the additive used led to a significant improvement in abrasion resistance, particularly as the additive percentage increased up to 30%. This is attributed to the inherent self-lubricating properties of HDPE, which reduce surface friction, as well as its flexibility, which helps absorb frictional energy without material loss. Sample FP10 exhibited a slight increase in loss (0.05 mm), which may indicate that a 10% yield is insufficient to form a continuous plastic network that improves abrasion resistance. Sample FP30 recorded the lowest loss (0.016 mm) at 65% compared to R0, indicating a clear improvement in abrasion resistance with increasing application rate. Furthermore, with an increase in application rate from 10% to 30%, a continuous decrease in loss was observed, demonstrating that the addition of HDPE was effective in enhancing abrasion resistance; compared to the reference sample (0.046 mm), all modified samples showed superior performance. The improved abrasion resistance partially compensates for the decrease in flexural strength, as the thickness loss decreased from 0.046 mm (R0) to 0.016 mm (FP30). All results obtained are within the limits of the required specifications.

Absorption ratio

The addition of HDPE aims to improve the physical and mechanical properties of the tiles, including reducing the absorption rate. According to the results, which are displayed in (Table 2), the average absorption rate of the three R0 specimens is almost the same as that of sample FP10, which reached 7.43%. The percentage decreased to 7.15% and 7.11% for the FP20 and FP30 samples, with the absorption rates slightly reduced

by 3.8% and 4.3%, respectively, compared to mix R0. FP10 did not improve absorption, confirming that 10% is insufficient to cause a significant change in the pore structure. All these absorption results are within the limits permitted for mosaic tiles in specification LNCSM-7 [5]. The requirement is that the mosaic tile's absorption rate not exceed 12 % by weight for all tiles and 10 % by weight for an average of 3 samples. The decrease in absorption with increasing HDPE is attributed to its water-repellent nature.

Density test

Density is a fundamental property, as it reflects the material's cohesion and rigidity after the hardening process is complete. The density test was performed on the average of three samples of Mosaic tiles with dimensions of (250×250×25), and the results were as recorded in (Table 2). A continuous decrease with increasing proportion of HDPE, as the density decreases steadily, as the replacement ratio increases from FP10 to FP30. The largest decrease was between R0 and FP10 (197 Kg/m³). Decreases between FP10 and FP20 (50 Kg/m³) and between FP20 and FP30 (21 kg/m³) are less pronounced, indicating a decreasing effect with increasing proportion. This trend is logical and inversely expected with HDPE content, given that the specific gravity of polyethylene ranges from 0.91 to 0.96 g/cm³, which is significantly lower than that of natural aggregates (2.6 to 2.7 g/cm³). Also, the replacement was based on volume, meaning that the same volume of aggregate was replaced by an equal volume of lighter polyethylene. The relationship between density and absorption rate can be linked, as a decrease in density is accompanied by a slight decrease in water absorption, and this relationship is direct, as shown in (Figure 8).

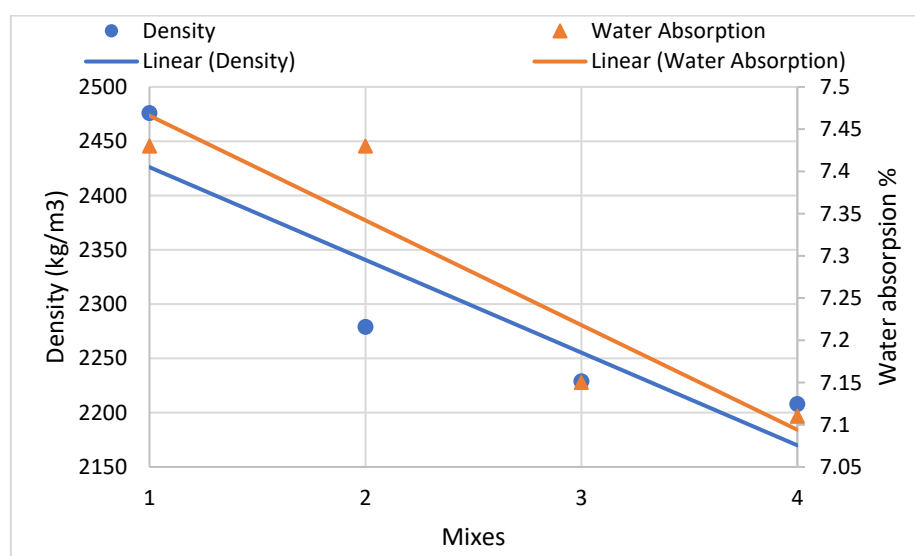


Figure 8. Relationship between density and absorption ratio versus increase in HDPE

The figure shows two linear curves. The lower curve represents the density values on the left axis (2150-2450 kg/m³), and the upper curve represents the water absorption values on the right axis (7.05-7.45%). The horizontal axis (X) represents the four mixtures: 1=R0, 2 =FP10, 3 =FP20, and 4 =FP30.

Density equation: $y = -85.4x + 2511.5$, and $R^2 = 0.812$

As we proceed from one combination to the next, the slope equation shows that the density decreases by 85.4 kg/m³. Additionally important is the coefficient of determination, or R^2 . This indicates that the change in the percentage of HDPE can account for 81.2% of the variation in density.

Water absorption equation: $y = -0.1255x + 7.5975$, and $R^2 = 0.8249$

The equation indicates a decrease in water absorption of 0.1255% with each step. Furthermore, the coefficient of determination R^2 means that 82.5% of the change in water absorption can be explained by the change in the polyethylene content. Conventional concrete with a lower density has more porosity, which increases water absorption. However, rather than greater porosity, the study's decrease in density is the result of substituting lightweight polyethylene for heavy aggregate. Moreover, even though polyethylene has a lower density, increasing its proportion decreases water absorption since it is hydrophobic.

Conclusion

This study concludes that incorporating high-density polyethylene (HDPE) waste as a partial volumetric replacement for natural coarse aggregate significantly alters the physical and mechanical profile of mosaic tiles. A clear trade-off is shown by the experimental data: while increasing the HDPE ratio up to 30% causes a systematic decrease in density, resulting in lighter tiles for structural load reduction, it also causes a decline in flexural strength because of the suboptimal interfacial bonding between the cementitious matrix and the hydrophobic polymer granules. Conversely, the FP30 sample showed a 65% decrease in thickness

loss when compared to the control (R0), indicating a notable improvement in abrasion resistance. This improvement is explained by HDPE's natural self-lubricating qualities and energy-absorption capability, which successfully changed the material's failure mode from brittle to ductile and lessened the severity of cracks under stress. Therefore, it is advised that the replacement ratio be kept below 20% in order to balance the benefits of lightweight with structural integrity. Applications where durability and wear resistance are more important than strong flexural demands are best suited for these modified mixes. To improve the HDPE granules' adherence to the cement paste and further improve the mechanical performance of the composite, future studies should look at surface functionalization.

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