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Producing Eco-friendly Tiles from Recycled Plastic Generated from Municipal Solid Waste

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Plastic waste is considered one of the most problematic components of solid waste. Recycled high-density polyethylene (HDPE) plastic was selected to produce plastic tiles as a binding material. In this study, to produce plastic tiles, mold with dimensions (15×15×2.5) cm was manufactured, and different mixture percentages of plastic, sand, and gravel were tested experimentally, focusing on flexural strength, chemical abrasion, absorption, and density. The results illustrated that the optimum mixture was (70, 30, 0) % of (plastic, sand, gravel), respectively, which achieved maximum flexural strength equal to 15.4 MPa. Also, chemical abrasion was less than ordinary cement tile standards, water absorption was zero, and the plastic tile density was 1075 kg/m^3, which was classified as light tile compared with the ordinary cement tiles. The most significant conclusion is that the recycled plastic tile is a promising type since it has good engineering characteristics, and it could be a suitable eco-friendly product as well as an alternative to ordinary cement tile. Also, the research can be the starting point for using recycled plastic as binding material.

Keywords: recycled plastic, HDPE, plastic tile, eco-friendly.

Introduction

Municipal solid waste (MSW) is defined as the solid waste that is produced from households, commercial, institutional municipal services, and treatment plants. The composition of MSW incorporates food waste, wood, plastic, textiles, glass, and metal, paper, rubber, yard waste, etc.

Plastic, which is one of the main compositions of MSW, causes a significant environmental problem in the world; the reasons behind that plastic are multi-use material that can be used either for industrial or daily activities, the daily huge generated quantities, and the long-time decomposition (Evode et al., 2021). Furthermore, plastic has a noticeable impact on MSW volume; however, it has a small effect on the MSW weight (composition) due to the low density of plastic. In general, annually, the world produced 415 million tonnes of plastic (Azoulay et al., 2019).

There are different types of plastic; for instance, in Europe there are three common plastic types: polypropylene (PP), low-density polyethylene (LDPE) and high-density polyethylene (HDPE). These three types represent about 49.1% of the total used plastic in Europe (Plastics Europe, 2017).

Many researchers were focused on checking the ability of using recycled plastic as binding material for producing different construction products such as plastic tiles, bricks, etc. For instance, Balamurugan and Rafi used recycled plastic with quarry dust and bitumen to produce tile. The results of this study showed that 55% PET bottles with quarry dust give maximum compressive strengths, which were 3.48 and 3.38 MPa at normal temperature and after thermo shock, respectively (Balamurugan and Rafi, 2021). Also, Ghude et al. studied manufacturing plastic bricks from mixing recycled plastic (60%) with laterite soil and bitumen. The maximum compressive strength for the plastic brick was 11.1 MPa. Also, the experiments proved that when the plastic percentage increased, the compressive strength decreased (Ghude et al., 2019). Aiswaria et al investigated producing plastic soil bricks from PET plastic and manufactured sand (M-sand) with different mixture proportions. The results showed that proportion 1:4 achieved the maximum compressive strength of 18.13 MPa, which means that the brick can be used in building (Aiswaria et al., 2018).

In addition, Puttaraj et al. studied the capability of manufacturing plastic tile by mixing recycled plastic as binding material with fly ash. The study focused on the mechanical and physical properties of the tile. The results found that the transverse strength was 10.8 MPa, which makes the tiles suitable for use as construction material (Puttaraj et al., 2020).

Furthermore, using recycled plastic and ceramic wastes in constructing materials, seven self-compacting concrete mixtures with constant binding material were studied. In these mixtures, the density was 473 kg/m^3, and the water-to-binder ratio was 0.37. The sand was replaced by ceramic waste while the gravel by plastic waste at various percentages (0, 5, 10, 15, 20, 25, and 30% by weight). The tests showed that the workability was within the standards. They proved that using recycled materials of both wastes up to 30% in self-compacting concrete is allowed (Blaifi et al., 2023).

Others used polyethylene terephthalate (PET) fiber waste and Linear low-density polyethylene (LLDPE) powder plastic in concrete and mortar instead of disposing of them. The sand was replaced with different percentages of powdered recycled LLDPE, and the PET fibers were added to the mixture. The results proved that mechanical and physical properties were developed by adding these types of recycled plastics, as well as that the absorption of the mortal was decreased clearly (Benimam et al., 2021).

In addition, polyethylene terephthalate (PET) and low-density polyethylene (LDPE) were utilized as a partial replacement of fine aggregate in concrete. The replacement ratios are (10, 20, 20, 40%) by volume, and different plastic fibers (0.5, 1, 1.5, 2%) were added to the concrete mixtures. The results illustrated that replacing sand with plastic led to minimizing the bulk density and air content, while the compressive and flexural strengths were increased clearly, especially at 10% and 20% (Guendouz et al., 2016).

As mentioned before, many materials can be used as eco-friendly construction materials, which have fewer harmful effects on the environment. One of these eco-friendly materials is recycled plastic.

In this study, recycled HDPE plastic was used in producing eco-friendly plastic tiles as binding material by mixing it with sand and gravel or one of them and determining the capability of this plastic waste to act as a binding material for plastic tiles as an alternative material of cement.

Materials and Methods

The used HDPE waste is one of the most significant pollutants in the world due to several reasons, including its widespread and large produced quantities. These reasons encouraged us to investigate using recycled plastic as construction material.

The main goal of this study is to produce eco-friendly plastic tiles from recycled HDPE plastic. To achieve the research goal, an experimental research approach was applied. Different tests were examined for the tiles, including flexural strength of the recycled plastic tiles, physical and chemical properties. Moreover, different sand, gravel, and plastic proportions were determined to get the optimum mixing ratio.

Materials

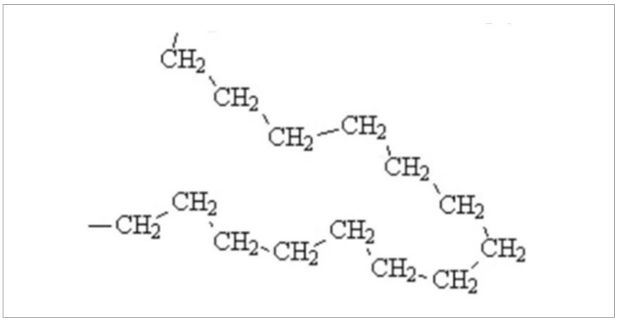
Plastic waste

There are different types of plastic waste that can be recycled. In this study, high-density polyethylene (HDPE) was selected to generate recycled plastic, which was used as binding material, due to the chemical stability of the polymer and the huge quantities produced from daily life. *Table 1* shows the characteristics of used HDPE wastes (Thakare et al., 2015). Also, *Fig. 1* shows the chemical structure of HDPE (Roslan, 2013). *Fig. 2-a* shows the used recycled HDPE particles.

Table 1. *HDPE thermophysical properties (Thakare et al., 2015)*

Mechanical properties	Value
Density (kg/m^3)	940
Melting point (°C)	130.8
Crystallization temperature (°C)	111.9
Latent heat of fusion (kJ/kg)	178.6
Thermal conductivity (W/m. °C at °C)	0.44
Specific heat Capacity (J/kg-K)	1330–2400
Specific heat (Solid) (kJ/kg °C)	1.9
Crystallinity	60%

Fig. 1. *HDPE structure (Roslan, 2013)*



Gravel

The used gravel for the plastic tile mixture has a grading zone (5 mm) according to Iraqi specifications as shown in *Table 3* (Iraqi Standard, No. 45, 1984).

Table 3. *Specifications of used gravel vs. Iraqi specifications (Iraqi Standard, No. 45, 1984)*

Sieve size (mm)	% Passing	
	Used gravel	Grading zone
10	100	100
5	56.1	45-100
2.36	24.2	0-30

Sand

The sand used to produce the mixture of the plastic tile was passing through a 10 mm sieve. *Table 2* illustrates the grading of used sand. The test results indicated the sand conformed to the Iraqi specification (No 45/ 1984 - grading zone 1), which is considered coarse sand (Iraqi Standard, No.45, 1984).

Molds

Stainless steel molds were manufactured with dimensions (15×15×2.5) cm. Also, a stainless-steel compactor with dimension (15×15) cm was used to compact the heated liquified mixture. *Fig. 2-b* illustrates the used mold and compactor.

Table 2. *Grading of used sand vs. Iraqi specifications (Iraqi Standard, No.45, 1984)*

Sieve No.	% Passing				
	Used sand	Grading zone 1	Grading zone 2	Grading zone 3	Grading zone 4
10 mm	100	100	100	100	100
4.75 mm	90.3	90–100	90–100	90–100	90–100
2.36 mm	63.6	60–95	75–100	85–100	95–100
1.18 mm	52	30–70	55–90	75–100	90–100
600 μm	33.4	15–34	35–59	60–79	80–100
300 μm	17.7	5–20	8–30	12–40	15–50
150 μm	4.5	0–10	0–10	0–10	0–15

Methods

A) Producing HDPE particles

The following six stages were used to produce the recycled HDPE plastic particles:

1 Collecting: Plastic (HDPE) wastes were collected from different MSW sources inside the Mosul city in Iraq. The plastic was separated and collected at the source.

2 Sorting: Each plastic waste type was separated from the others, so HDPE plastic was sorted from other types of plastic such as LDPE, PVC, etc. Unwanted materials were removed from the waste manually, such as bottle caps.

3 Shredding: After the separation process, the HDPE waste was shredded into smaller pieces (chips) (approximately 1 square centimeter each).

4 Cleaning: The produced chips were cleaned mechanically by a special machine to get rid of any remaining glue, paper labels, dirt, and product residues. The next step of the machine is drying the washed plastic chips by heating drying.

5 Melting and producing plastic particles: The shredded plastic was melted at a high temperature and directly sent to a small tank filled with water to warm down the plastic threads, and then the machine started to cut down the threads to small and uniform HDPE particles.

6 The molds were filled with molten plastic, which was then let to cool at room temperature.

B) Producing recycled plastic (HDPE) tiles

1 Determining the mixture percentages and their corresponding weights, *Table 4* shows % mixture components.

2 Adding the mixture components (recycled plastic, sand, and gravel) to an appropriate volume pot, then mixing the components *Fig. 2-a*.

3 Starting to heat up the mixture till reaching the melting state at temperature (255 to 265) °C (Brydson, 1995).

4 Preparing the mold and covering it with oil *Fig. 2-b*.

5 Pouring the heated and liquified mixture into the prepared mold, and starting compacting the mixture by compactor immediately (before its cooling) to ensure getting compacted tile, *Fig. 2-c*.

6 Leaving the sample at room temperature until the tiles are solid.

7 Separating the tile from the mold. The tile is now ready to be tested *Fig. 2-d*.

Table 4. *Percentage of mixture components*

% HDPE	Sample No.	% Gravel: % Sand
30	$S1_{(30)}$	35:35
	$S2_{(30)}$	50:20
	$S3_{(30)}$	20:50
	$S4_{(30)}$	60:10
	$S5_{(30)}$	10:60
	$S6_{(30)}$	00:70
50	$S1_{(50)}$	25:25
	$S2_{(50)}$	30:20
	$S3_{(50)}$	40:10
	$S4_{(50)}$	20:30
	$S5_{(50)}$	10:40
	$S6_{(50)}$	50:00
	$S7_{(50)}$	00:50
70	$S1_{(70)}$	15:15
	$S2_{(70)}$	20:10
	$S3_{(70)}$	10:20
	$S4_{(70)}$	05:25
	$S6_{(70)}$	30:00
	$S7_{(70)}$	00:30

Fig. 2. *Producing plastic tile experiment. (a. Mixture components in a pot, b. Preparing the mold, c. Pouring the heated and liquified HDPE, d. Final HDPE tile)*

(a) (b) (c) (d)

Tests

Different tests were applied in this study to determine the HDPE tile characteristics and compare them with cement tile. *Table 5* shows the research tests and their code numbers.

Table 5. *Tests and specification code numbers*

Test	Code number
Flexural strength	ASTM D790
Chemical resistance	(Iraqi specification 1627, 1991)
Absorption	ASTM C1492-03
Sieving analysis	(Iraqi specification 1627, 1991)

Results and Discussion

Fig. 3 shows the flexural strength of the plastic tiles using 50% plastic and various ratios of gravel:sand. The flexural strength curve starts with the highest value, then decreases gradually, followed by increasing smoothly. The highest flexural strength was 137 kg/cm^2, which was achieved at a mixture percentage (gravel:sand) of 0:50. While the lowest value was 53 kg/cm^2, which was achieved at a percentage (20:30). The reason for this variation is the binding material (plastic) was sufficient to cover most of sand surface area and fill the voids which is normally limited because of the sand which minimizes the voids ratio.

When the percentage of used sand is increasing, the surface area of the mixture is also increasing, which maximizes the binding area between the plastic and sand (when the binding material is sufficient), which results in increasing flexural strength. This reason is similar to the principle that when the sand particles increase, the surface area increases clearly (Al-Thairy, 2018).

When the gravel percentage is increasing with the availability of sand, the void ratio among the mixture composition is increasing, which leads to decreasing the flexural strength. This concept is similar to the study, which shows that when the fiber particle size increases, the voids of cement mortar increase, which leads to a decrease in the interaction of binding material-sand (Soydan et al., 2018).

As well as the gravel percentage is increasing, it will lead to decreasing the binding area due to the reduction of surface area (even with the availability of enough binding material), which results in minimizing the flexural strength clearly.

To clarify the gradual flexural strength increasing after the minimum point in the curve (53 kg/cm^2) and becoming (77 kg/cm^2), the cause of this sudden increasing is the clear surface area reduction (due to increasing the gravel percentage in the mixture), which leads to covering the surface area completely with filling most of the mixture voids.

Fig. 3. *Variation of flexural strength using different gravel:sand ratios with a fixed plastic percentage of 50%*

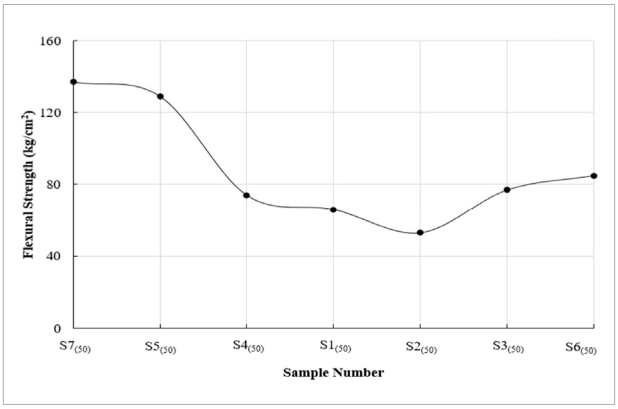
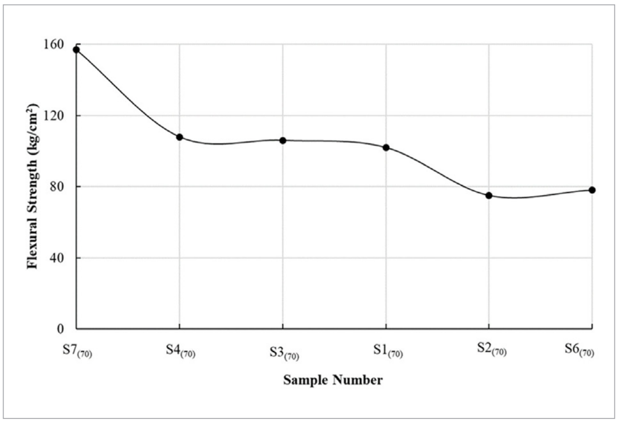


Fig. 4 illustrates the distinction of the flexural strength with various gravel:sand ratios with a fixed plastic percentage equal to 70%.

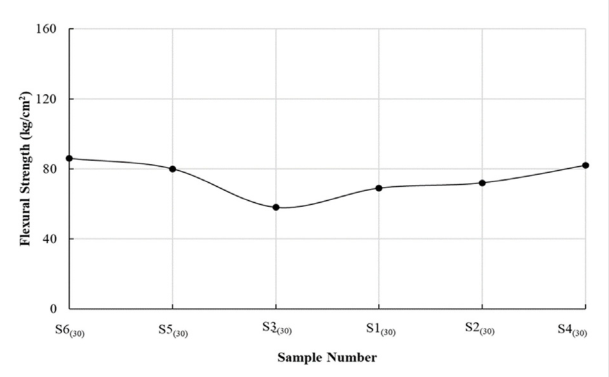
Fig. 4. *Variation of flexural strength using different gravel:sand ratios with fixed plastic percentage of 70%*



The curve starts with the highest flexural strength value (157 kg/cm^2) at a ratio of 30%:0%. Then the curve dropped gradually to reach the minimum point of the flexural strength (75, 78 kg/cm^2) at ratios (10%:20%, 0%:30%), respectively.

The reason for this clear dropping from the highest point is that the plastic was adequate to cover most of the sand surface area and fill the voids in the mixture, as well as increasing the binding area for the mixture. By increasing the gravel percentage, the voids start to increase, which led to decreasing the binding area due to the reduction of mixture surface area. For the plateau shape of the curve's last two points, the reason for being almost equal is filling the voids with binding material and the weakness effect of the binding material because the surface area of both mixtures was almost the same. *Fig. 5* illustrates the values of the flexural strength for different gravel:sand ratios with a fixed plastic percentage equal to 30%.

Fig. 5. *Variation of flexural strength using different gravel:sand ratios with a fixed plastic percentage of 30%*

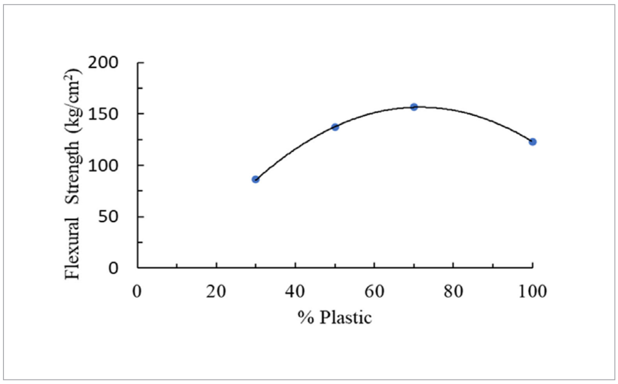


In this curve, 30% of plastic is considered not sufficient to work as mixture binding material and did not fill either the voids nor cover the surface area of the mixture particle. This reason led to making all the curve points close to each other, as well as the flexural strength of all points of the curve being generally weak compared to previous plastic percentages (70%, 50%).

Fig. 6 represents the effect of plastic percentage on tile flexural strength. The curve values represent the maximum flexural strength for the plastic tiles with varied plastic percentages (30, 50, 70, 100) % with different gravel:sand ratios.

The flexural strength is increased gradually by increasing the plastic percentages to reach maximum values

Fig. 6. *Effect of plastic percentage on flexural strength*



at 70% plastic (157 kg/cm^2), then the flexural strength start decreasing significantly.

The flexural strength for 100% plastic (0:0) gravel:sand ratio was 123 kg/cm^2, which is less than the maximum value (at 70% plastic), due to adding sand to the mixture, which made the plastic fill the mixture voids and cover the particles surface area, which led to an increase in the binding area and the interaction of sand-plastic.

Table 6 shows a comparison between plastic tile versus ordinary cement tile; all plastic tile information according to experimental study.

The maximum flexural strength achieved for the plastic tile was 15.4 MPa (for sample 70% plastic, 30% sand), which is much higher than ordinary cement tile (5-11.8) MPa (UNI EN 13748-1, 2005). This advantage for the plastic tiles increases its use such as walkways, room partitions, top roof isolation, etc.

The other important advantage of the plastic tile is having zero absorption for water, which makes it more resistant to corrosion with time compared with cement tile. The reason for this zero absorption is that the plastic (binding material) has a water-proof composition, and this material is filling the voids and coating the mixture particles and clogging their pores, which led to prevent water penetration through the sand and gravel structure.

Also, the plastic tiles have chemical resistance shown in *Table 6*, which is less than the Iraqi specifications (1.5%) for cement tiles (Iraqi specification 1627, 1991). This plastic resistance extends its long-life time due to the fact that the plastic composition has strong resistance to corrosion.

Table 6. *Comparison of plastic versus cement tiles*

Test	Plastic tiles				Cement tiles (Standard)			
Maximum flexural strength (MPa)	15.4				(5–11.8) (UNI EN 13748-1, 2005)			
Absorption	0				12.5% (ASTM C1492-03, 2016)			
Density (kg/m^3)	1075				2400–2600(EN 14617-1, 2005)			
Abrasion resistance (%)					(Iraqi specification 1627, 1991)			
	H_2SO_4 0.16	HNO_3 1.2	HCl 1.4	NaOH 0	H_2SO_4 1.5	HNO_3 1.5	HCl 1.5	NaOH 1.5

Conclusions

Recycled HDPE plastic tiles have good engineering properties, which make them an eco-friendly and alternative product of ordinary cement tiles. The flexural strength of recycled HDPE tiles was 15.4 MPa, which is greater than ordinary cement tile standard. The chemical abrasion of the recycled HDPE tiles was less than the standards of ordinary cement tiles. Recycled HDPE plastic tiles had zero adsorption, which makes them more resistant for the climate conditions and long lifetime compared with ordinary cement tile standards. The optimum mixture was (70, 30, 0) % of (plastic, gravel, sand), respectively, which achieved maximum flexural strength equal to 15.4 MPa. It is recommended to study recycled HDPE plastic with demolition waste. The produced tiles can be applied to walkways, roofs, and pathways in parks.

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