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Studying The Effects of Polyester Resin Added as a Binder in Manufacturing Tiles from Different Plastic Waste: Materials Characterization and Assessment of Mechanical Qualities

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ABSTRACT: The conversion of plastic waste into construction materials with properties comparable to those of conventional building materials, as well as the identification of practical applications for recycled plastics, represents an important strategy for reducing environmental pollution. In this study, plastic waste comprising high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyvinyl chloride (PVC), polycarbonate (PC), polystyrene (PS), and polyethylene terephthalate (PET) was extruded, compressed, and moulded to produce tiles. Before compression, polyester resin was added as a binder at a concentration of 7.2% (v/w), along with a few drops of hardener.

Mechanical and environmental resistance tests showed that the tiles manufactured using polyester resin as a binder exhibited higher compressive strength, along with excellent tensile and flexural strength. Furthermore, the polyester binder improved the cohesion and hardness of the tiles and enhanced their resistance to bending. The manufactured tiles were characterized using Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and field-emission scanning electron microscopy (FESEM). Thermal analysis (TGA and DSC) indicated that the addition of polyester resin enhanced the thermal stability of the tiles. XRD analysis revealed a highly crystalline structure in the tiles prepared with polyester resin, a finding further supported by FESEM observations.

INTRODUCTION

Accumulated plastic waste is considered a wealth that can be exploited and recycled into its constituent raw materials or converted into new materials [1]. The accumulation of plastic waste is now considered a global problem because it represents a significant portion of industrial solid waste, which gives rise to environmental pollution [2, 3]. Generally, plastics are hydrocarbons made from finite sources, mostly petroleum, which must be used wisely rather than wastefully [4]. Therefore, recycling plastic waste has become imperative to retain its raw materials first and then to reduce environmental pollution from its accumulation secondly [5, 6]. Recently, plastic waste has been recycled using many methods as it has been designed and established to utilize different polymer composite materials [7]. One of the most widespread methods is the conversion of polymer into alternative construction materials for bricks, blocks, or floor tiles. The plastic alternatives are manufactured by inserting polymer waste into molds and applying heat and pressure to the molds to form construction materials [8]. Plastic tiles manufactured from waste are characterized by good specifications, the most important of which are less flammability and their

tensile strength; besides, they are light and cheap too [9]. In comparison with conventional tiles or bricks, plastic has better durability and more strength; besides, the plastic pavers and tiles have fast curing properties and lack water absorption [10].

Plastic is a highly useful alternative construction material such as fine aggregate, binder, sand, and modifiers in cement used in conventional tiles, pavers, bricks, and concrete [3]. Plastic tiles need a binder to hold their polymer materials together, as conventional tiles use a cement binder. However, binders hold the tile materials together through cohesive and adhesive forces. The cohesive force shows its effect within the binder molecules themselves, while the adhesive force shows its effect within the bonding forces at the interface between the binder and the connected materials [11, 12]. Binders are present in different types according to their modes of action and effective operating temperature [13], such as permanent binders (hydraulic or chemical) or temporary binders (organic). Some binders cause chemical reactions with material components which show a great influence on their properties, such as thermal properties, strength, and resistance to chemical attack, including erosion, corrosion, wear, etc. [14].

In this study, seven types of plastic waste -HDPE, LDPE, PP, PVC, PS, PC, and PET- were used for manufacturing plastic tiles with dimensions of (30 x 30 x 5) cm^3. The binder polyester was added to the plastic particles to form tiles. The cast tiles were characterized using different mechanical and climate resistance tests, and their components were analyzed by FTIR, XRD, thermal analysis (TGA, DSC), and FESEM techniques.

EXPERIMENTAL

The plastic waste of different polymers, including HDPE, LDPE, PP, PVC, PS, PC, and PET were purchased from the industrial region in Mosul, Iraq. The factories in the industrial region collected the plastic waste through their agents from different landfills in Mosul and classified each according to its type, washed it with detergent and water, and then ground it into small pieces; this was done for their own different manufacturing processes. The binder polyester was purchased from Marble Adhesive Sarlsson, Stone Contact Company, China. A hydraulic press with a maximum pressure of 32.0 tons was assembled in Mosul, Iraq. A tile mold of (30 x 30 x 5) cm^3 size was formed in Mosul, Iraq, using 10 mm steel plates and manufactured with a cover. Finally, an extrusion machine containing a heater of 2000 W was designed and assembled by a local factory in Mosul, Iraq.

Manufacturing of tiles from plastic waste

Different weight ratios of plastic waste with a total weight of 900 g were found sufficient to press inside the mold of (30 x 30 x 5) cm^3 area. Therefore, the plastic wastes with total weights and their weight ratios (Table 1) are transferred into the extrusion machine for extrusion at 200°C. The molten plastic coming out of the extrusion machine is transferred into the mold and 7.0 % v/ w polyester binder is added to the plastic melt with a few drops of its hardener. The mold is then covered with a lid and moved to the hydraulic press, applying 207 MPa or 15 ton in^{-2} pressure for 15 min. The tile is extracted from the mold and subjected to mechanical and physical checks.

Table 1: The weight and weight ratio of plastic waste used for preparing (30 x 30 x 5) cm^3 tiles.

Plastic waste	Weight ratio %	Weight g
HDPE	20.6	185
LDPE	20.6	185
PP	17.2	155
PVC	19.4	175
PC	10.0	90
PET	10.0	90
PS	2.2	20
Total	100 %	900

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Mechanical tests

Compression strength test

The test is a structural element that resists loads and provides a reduction in the size of the measured material. In other words, it is a force applied to the test sample from its top and bottom until it is deformed or fractured. A universal testing machine was used for the compression strength test, and the following Eq. (1) was used:

$$\text{Compressive strength } (\sigma) = \frac{P}{A} \quad (1)$$

Where (P) is the maximum load in (N); and (A) is the cross-sectional area of the sample (m^2).

Tensile strength test

Ultimate tensile strength is the maximum stress applied to a sample that it can resist while being stretched or pulled before breaking. A universal tensile testing machine was used for tensile strength determination with the following Eq. (2):

$$\text{Tensile strength } (S) = \frac{P}{A} \quad (2)$$

Where (P) is the force required to break (N), and (A) is the cross-sectional area (m^2).

In addition, the elongation, which represents the change in the length of the sample from its original length before breaking, can be calculated from tensile strength parameters according to the following Eq. (3):

$$\text{Elongation } (\%) = \frac{L_f - L_0}{L_0} \text{ x100} \quad (3)$$

Where (L_f) is the final length, and (L_0) is the original length of the sample.

Flexural strength test

Flexural strength is a mechanical parameter that shows the material can withstand deformation under a certain load. The Toni ZEM-Model 1548 is the machine used for the test, and the following Eq. (4) was used:

$$\text{Flexural strength } (f) = 3PL/2bd^2 \quad (4)$$

Where (P) is the maximum load applied in (N), (L) is the supported length in (m), (b) is the width in (m), and (d) is the failure point depth in (m).

Impact test

The Charpy impact test is a standardized high stress rate test that can measure the energy absorbed by the sample while breaking under a fixed load. The Charpy impact test is conducted using an advanced universal pendulum tester, and the following Eq. (5) is used:

$$\text{Impact test} = W.\ L\ (\cos\alpha - \cos\beta) \quad (5)$$

Where (W) is the weight of the pendulum, (L) is the length of the pendulum, (α) is the angle, and (β) is a constant.

The impact test value can be used for the calculation of toughness Eq. (6), which represents the material's ability to absorb energy and deform without fracturing.

$$\text{Toughness} = \frac{\textit{impact energy}}{\textit{area of the specimen}} * 100 \quad (6)$$

Rockwell hardness test

The Rockwell hardness test is a method that gives the resistance of a material to indentation. The KARL KOLB Rockwell hardness tester from Germany was used, and the following Eq. (7) was used:

$$HR = N - \left(\frac{d}{D}\right) \quad (7)$$

Where (N) is the load applied in (N); (d) is the depth of the indentation in (m), and (D) is the diameter of the ball in (m)

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Climate resistance tests

Relative humidity (RH) test

The test includes drying the examined sample in an oven at 80°C for 6 h, and then transferring it into a desiccator to cool and weight. The sample is prolonged exposure to high humidity at 25°C for 24 h. Finally, the sample is weighted, and the following Eq. (8) was depended:

$$\text{Relative humidity (RH) (\%)} = \frac{W_f - W_0}{W_0} * 100 \quad (8)$$

Where (W_f) is the final weight, and (W_0) is the initial weight of the sample.

Dimensional stability of resilient tile test

Dimensional stability test of resilient tile covers the determination of the changes in their linear dimensions after exposure to heat. The test includes measuring the exact length, width, and height of the sample. Thereafter, the sample is placed in an oven at 82°C for 6 h. The sample is taken out and kept at room temperature for 24 h. The following Eq. (9) was used:

$$\text{Dimensional stability (\%)} = \frac{V_f - V_i}{V_i} * 100 \quad (9)$$

Where (V_f) is the final volume, and (V_i) is the initial volume of the sample.

Characterization of tiles

The manufactured tiles were characterized by the following techniques:

FT-IR using a Shimadzu FT-IR 8400 s spectrometer, Japan. XRD using a Philips X-ray diffractometer (PW1730). TESEM using a TESCAN MIRAFSEM, Czech Republic. TGA and DSC using TA Instruments DSC SDT Q600 V 20.9 build 20, USA. Heat rate: 80°C. min^{-1} for 700°C, Ref. Al_2O_3.

RESULTS AND DISCUSSION

Polymers face challenges including plastic waste, environmental impact, performance limitations, health, and safety concerns. Therefore, developing recycling technologies is the goal of many studies, and aiming to reach effective, cheap, and simple methods; otherwise, huge quantities of plastic waste will fill landfills and make environmental pollution worse. The most common plastics in the world such as HDPE, LDPE, PP, PVC, PS, PC, and PET, were used in their native form for the manufacturing of tiles used in floor paving.

Characterization of tiles

FT-IR spectroscopy

The FT-IR analyses of the tiles were studied, and their absorption frequencies of the main functional groups are given in (Table 2).

Table 2: FT-IR absorption frequencies of the main functional groups of control and tile prepared with binder.

Specimen	ϒ(O-H) str	ϒ(C-H) str aliph	ϒ(C-H) str arom	ϒ(C=O) str	ϒ(C=C) str arom	ϒ(-CH2)	ϒ(-CH3)	ϒ(C-O) str	ϒ(C-O-C) asymm	ϒ(C-H) str arom	ϒ(C-Cl)
Control without binder	3431	2918 2849	3057	1730	1647	1468	1375	1267	1074	721	633
Tile With binder	3433	2918 2849	2959	1709	1649	1460	1373	1263	1070	723	671

The control sample, which represents a tile prepared without binder, shows its FT-IR spectrum (Fig. 1, Table 2) with the main functional groups of different plastics that the tile contains. The low absorption frequency peak at 3431 cm^{-1} is of the γ(O-H) str group, which represents the end groups of PET and PC [15]. The peaks at 2918 cm^{-1} and 2849 cm^{-1} belong to γ(C-H) str of aliphatic methine groups, and the peak at 3057 cm^{-1} is of γ(C-H) str of aromatic methine groups. The carbonyl group γ(C=O) str is shown at 1730 cm^{-1}, which comes from PET and PC polymers. The peak at 1647 cm^{-1} belongs to γ(C=C) str of the aromatic ring of PET, PC, and PS polymers. The peak at 633 cm^{-1} is of the (C-Cl) group from PVC plastic. On the other hand, the FT-IR spectroscopy of the tile prepared with polyester binder shows (Table 2, Fig. 1) all the peaks of the control sample, besides a strong peak at 3433 cm^{-1} representing γ(O-H) str of the polyester binder.

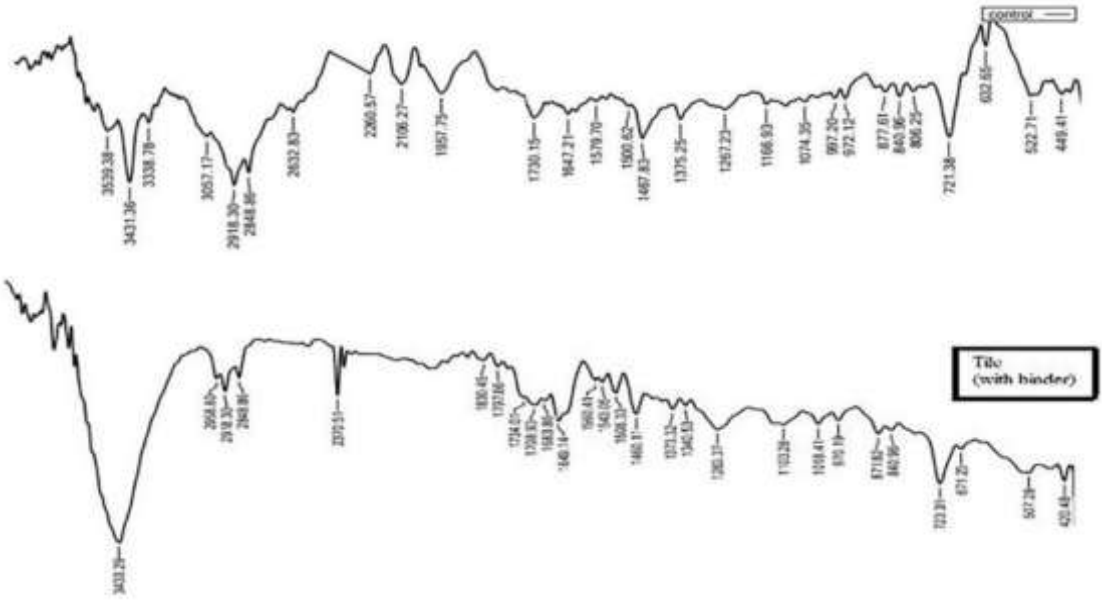


Fig. 1: FT-IR spectrum of control and tile prepared with binder.

Thermal analysis (TGA and DSC)

The TGA and DSC thermograms of control and tile with binder samples give a general indication that the prepared tiles are thermally stable. The control sample shows initial decomposition temperature (IDT), final decomposition temperature (FDT), maximum decomposition temperature (Tmax) and crystalline decomposition temperature (Tcr) from TGA thermograms (Fig. 2, Table 3), which have higher weight loss (%) at lower temperatures compared with the tile sample of polyester binder, which indicates that adding binder to the tile will elevate its thermal stability.

Table 3: TGA and DSC thermal analysis data of control and tile prepared with binder.

Specimen	TGA weight loss %				DSC W g^{-1}	
	IDT	FDT	Tmax	Tcr	Tg°C	Δ Hf J g^{-1}
Control	0.1	82.0	41.0	78.0	96.0	922.2; 996.1; 81.57
(without binder)	45°C	620°C	450°C	500°C		94.1°C; 357.7°C; 498.0°C
Tile	0.05	77.0	34.0	68.0	110.0	553.7; 62.84; 285.2; 26.46
(with binder)	50°C	620°C	460°C	520°C		57.5°C;213.4°C; 370.2°C; 568.3°C

Similarly, the glass transition temperature (Tg) calculated from DSC thermograms of the control sample is 96.0°C, whereas it is 110.0°C for the tile sample with binder. The heat of fusion (ΔHf) from the DSC thermogram shows (Fig. 2 and 3, Table 3) that both have endothermic behavior maxima, with three (ΔHf) for the control sample, while the tile sample with binder shows four

(ΔHf), where the fourth one belongs to the polyester binder. As a result, the TGA and DSC data show that the tile sample with polyester has high thermal stability compared to the control sample [16].

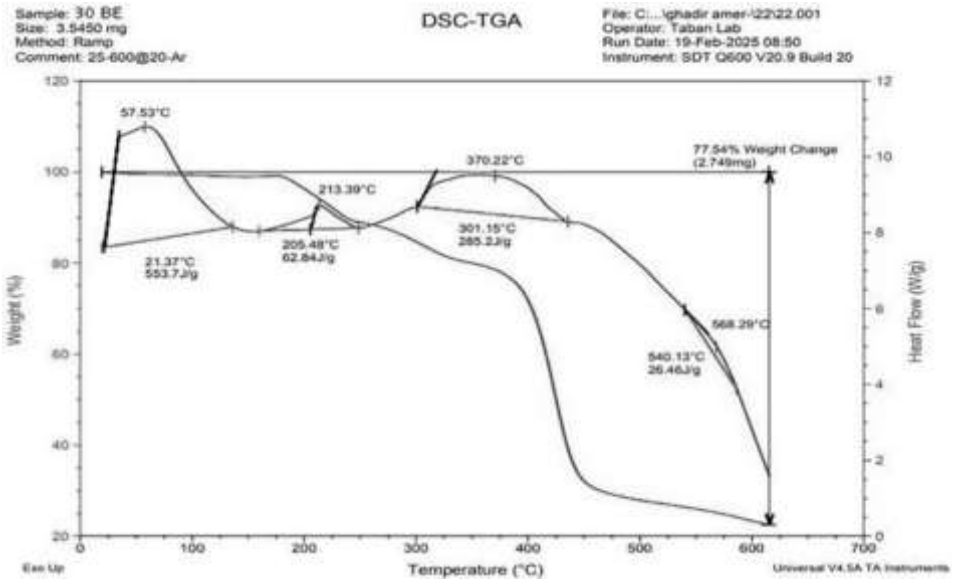


Fig. 2: TGA and DSC thermogram of control sample.

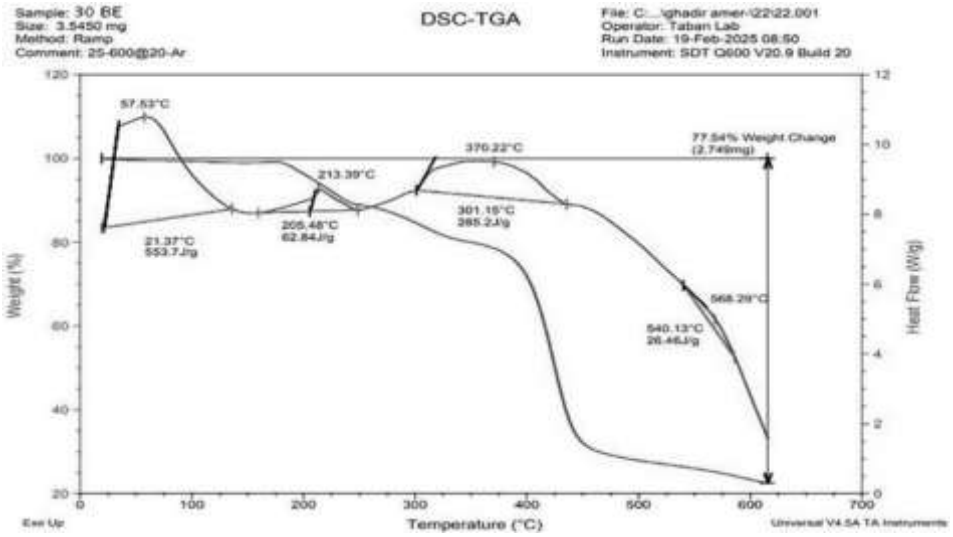


Fig. 3: TGA and DSC thermogram of tile prepared with binder.

FESEM study

The FESEM image of the control sample (Fig. 4) shows a little cohesion between the particles of the plastic material. The surface morphology of the control sample appears non-homogeneous with folds and some crystalline portions. On the other hand, the FESEM image of the tile sample with binder (Fig. 5) shows a homogeneous surface of the plastic material. The polyester binder worked to increase the cohesion of the composite and make the surface more crystalline, with frequent folds, entangled fibers, and the appearance of a non-smooth surface.

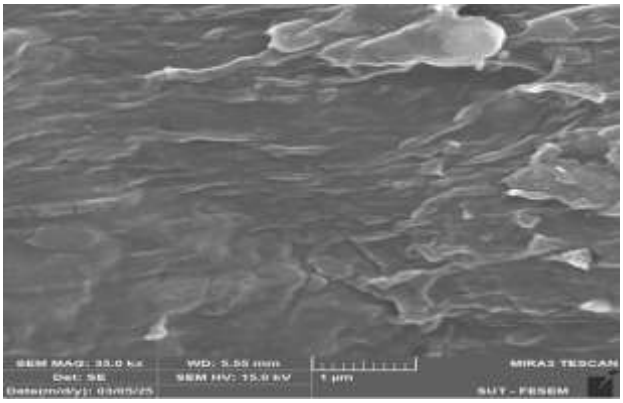


Fig. 4: FESEM image of control sample.

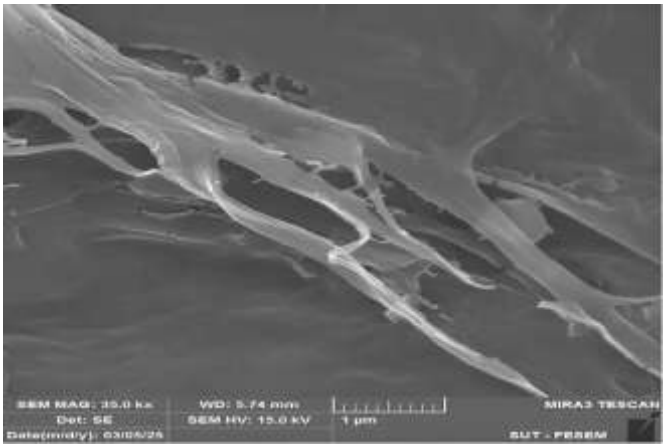


Fig. 5: FESEM image of tile prepared with binder.

XRD study

The X-ray diffraction (XRD) pattern of the control sample (Fig. 6) shows that the sample has a crystalline structure. Different types of plastics, after being heated, compressed, and finally cooled, have produced tiles that show (Fig. 6) a number of peaks with different relative intensity percentages representing the crystalline structure of the participating plastics. The use of the polyester binder for the preparation of tiles will increase the cohesion of the tile, and its XRD pattern (Fig. 7) shows an increase in its crystalline morphology, where the number of XRD peaks and their intensities have increased. This means that the polyester binder could enhance the crystalline structure of the tile, which in turn increases its strength [17].

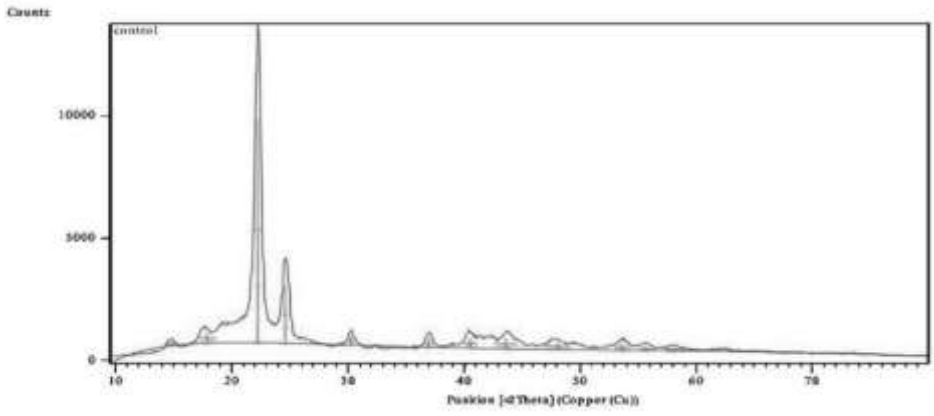


Fig. 6: XRD pattern of control sample.

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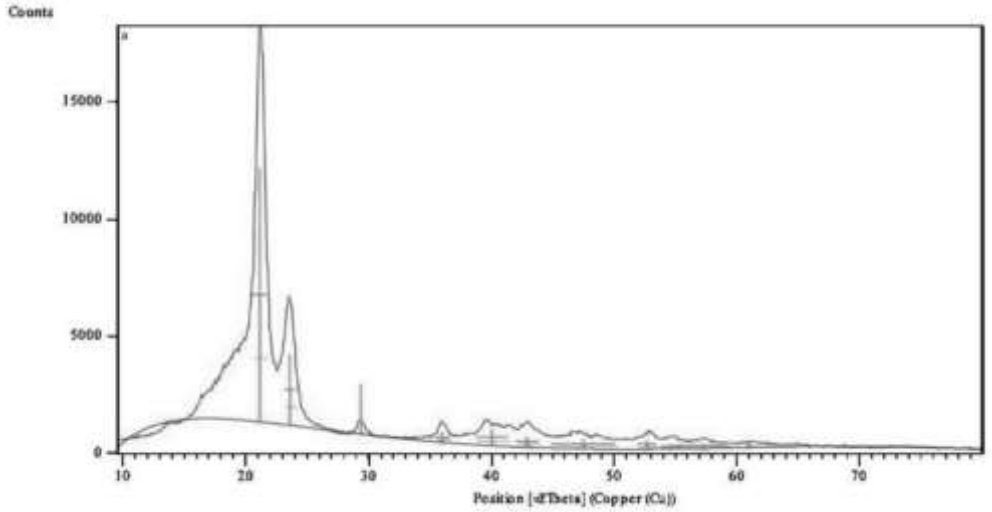


Fig. 7: XRD pattern of tile prepared with binder.

Mechanical tests

Different mechanical examinations of the control life and tiles prepared with a polyester binder have been done, and their data are shown in (Table 4). The compression strength (σ) of the tested samples, calculated from Eq. (1), shows that the control sample is 15.0 MPa, whereas the tile with binder is 27.4 MPa, which means that the latter has higher resistance to compression, and the polyester binder delivers excellent performance across a hardness range [18].

Table 4: Mechanical data of control and tile prepared with binder.

Specimen	Compression Strength (σ) MPa	Flexural Strength (f) MPa	Tensile Strength Test		Hardness Rockwell	Hardness Impact	
			Ultimate Tensile Strength (σ) MPa	Elongation %		Charpy Impact energy J	Toughness J cm^{-3}
Control without binder	15.0	4.48	27.7	9.4	43HHR	25.5	77.6
Tile with binder	27.4	15.44	43.0	8.6	57HHR	32.0	123.7

The ultimate tensile strength (σ) and the elongation (%) of both samples have been calculated (Eq. (2) and (3)), and their data are given in (Table 4), where the control sample shows an ultimate tensile strength of 27.7 MPa and elongation of 9.4 %, and for the tile with binder, the value are 43.0 MPa and 8.6 %, respectively (Table 4). Similarly, the tile with binder has a higher ultimate tensile strength and slightly lower elongation (%) because of the non-linear behavior of the polyester, which delivers excellent performance to the tile through a hardness range [19]. In addition, both samples show good elongation (%), which means they are highly flexible and ductile and can stretch before they break [20].

One of the important mechanical tests is the flexural strength test, and Eq. (4) was used for the calculation of its magnitudes, which are 4.48 MPa for the control sample and 15.44 MPa for the tile prepared with binder (Table 4). The results show that the tile prepared with polyester binder has excellent flexural strength [21] because mixing plastic waste with polyester resin causes more cohesion, and the binder can resist bending under external force.

Charpy impact energy is calculated according to Eq. (5), which shows 25.5 J for the control sample and 32.0 J for the tile prepared with polyester (Table 4). The Charpy impact energy value is high for tile with polyester because the latter reinforces the plastic particles in the tile [22]. In addition, toughness is calculated from impact energy values according to Eq. (6), which shows 77.6 J cm^{-3} for the control sample and 123.7 J cm^{-3} for the tile prepared with polyester (Table 4). The toughness shows a high value for the tile with binder because the binder increases the strength of the tile and makes it not easily broken or damaged.

The last mechanical test was the Rockwell hardness test, which uses a depth differential method for hardness and the results were obtained from Eq. (7). The Rockwell hardness for the control sample is 43 HHR and for the tile with polyester binder, it is 57 HHR (Table 4). The Rockwell hardness values are higher for the tile with polyester, which means it is harder than the control tile, but still, it is ductile.

Climate resistance tests

Relative humidity (RH) test

The manufactured tiles have also been measured for physical properties, starting with the relative humidity test, and its percentages are calculated according to Eq. (8). The relative humidity (%) for the control sample is 1.863 % while for the tile with polyester binder it is 1.696 % (Table 5), which means the relative humidity (%) for both samples is very low because both are hydrophobic. In general, plastic materials absorb humidity to a limited degree and are ordinarily waterproof [23].

Table 5: Relative humidity (RH) (%), and dimensional stability (%) of control and tile prepared with binder.

Specimen	Relative humidity (RH) test %	Dimensional stability cm^3	
		Before	After
Control without binder	1.863	0.754	0.784
Tile with binder	1.696	0.726	0.729

Dimensional stability of resilient tile test

Other test was the dimensional stability test which is done after exposing the tiles to heat. The data are treated in Eq. (9). The dimensional stability values of both samples before and after treatment are very close (Table 5), and once again, the polyester binder shows that its tiles are more dimensionally stable due to its heat stability (Fig. 3, Table 3).

CONCLUSIONS

Different plastic wastes of the most consumed types of polymers were used for the manufacturing of tiles that could be used as alternative construction materials. Seven types of plastics were used in different weight ratios and selected according to their mechanical, cohesion, ductility, and physical properties. Tiles of (30 x 30 x 5) cm^3 size were manufactured using 900 g of plastic waste inside a stainless-steel mold after being extruded by an extrusion machine at 200°C and compressed by a hydraulic press at 15 ton in^{-2} pressure for 15 min. For comparison purposes, tiles were manufactured to which polyester resin was added in order to bond the plastic particles. The tiles manufactured with a polyester binder showed high mechanical and physical qualities in comparison with the control sample prepared without a binder.

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Authors' Contributions

Fawzi Habeeb Jabrail and Roua'a Kassim Al-Ojar: Supervision; Conceptualization; Methodology; Writing-Reviewing and Editing. Ghadeer Amer Muhamed: Investigation; Visualization.

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

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