RESEARCH ARTICLE

Polymer tiles from polyethylene terephthalate (PET) wastes and fly ash: mechanical properties and durability [version 1; peer review: awaiting peer review]

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Abstract

Background: Plastic waste (PW) is becoming increasingly hazardous to the environment as a result of its massive production, causing significant damage to both the ecosystem and its inhabitants. Managing plastic waste is a global concern due to its non-biodegradable nature. However, it is important to handle PWs properly to curtail the environmental emissions associated with their incineration and dumping into landfills. This research investigates the possibility of producing tiles from polyethylene terephthalate (PET) waste bottles and fly ash. The mechanical properties, as well as the chemical resistance of the manufactured PET polymer tiles, are reported in this study.

Methods: PET waste was used in varying proportions (from 30% to 100%) by sand weight. The shredded PET waste was heated at 230 °C before being suitably blended with fly ash. It was then poured into the designated mold, removed after one hour, and cooled for 24 hours before testing.

Results: The assessment of the physical and mechanical properties of the materials revealed that the tiles produced with 30% PET content performed better in terms of material density and strength compared to the samples with higher PET content. The highest compressive strength being 6.88 MPa. Based on the results of the tests, the produced PET tiles have a low water absorption efficiency of 80% lower when compare to cement and ceramic tiles (the water absorption values are between 0.98% and 0.09%).

Conclusions: The results from this study indicate that PET waste bottles can be used to produce long-lasting, durable, and extremely low water absorption eco-friendly tiles for both residential and commercial applications. This prospect of tile production using polyethylene terephthalate (PET) waste and fly ash would not only minimize the cost of building products but will also act as a waste diversion to mitigate environmental emissions caused by plastic waste

disposal.

Keywords

plastic wastes, pollution, aggregates, mechanical properties, polymer tiles

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Introduction

Plastic is a synthetic, solid, hydrocarbon-based polymer; it can either be a thermoplastic or thermosetting material. Thermoplastic is a plastic material that can soften upon heating and harden when cooled; hence, it can be molded into different shapes. Thermosetting materials cannot be remelted when they solidify; they are mainly used as Bakelite.¹ Plastics are in common use due to their lightweight, soft nature, flexibility, non-corrosiveness, and durability. Plastics are comfortable packing materials and containers but wastes from plastics are a major cause of environmental pollution; they emit poisonous gases upon incineration and are not biodegradable.² Plastic materials are reportedly carcinogenic as they contain chlorine and other carcinogens. The burning of plastic waste produces toxic gases such as phosgene, carbon monoxide, chlorine, sulfur dioxide, nitrogen oxide, and other deadly dioxins that are harmful to the environment. Since plastic wastes account for the highest percentage of waste produced globally, there is a need to ensure proper management of such waste.^{3,4} Plastics are commonly used as packing materials, but their wastes can be used in the construction industries to produce construction materials, such as floor tiles, roof tiles, building blocks, etc. This can reduce construction costs and minimize environmental pollution. For instance, plastic wastes can be mixed with sand and other additives to produce constructional materials.⁵ Presently, recycled plastic wastes are gradually replacing natural materials such as fiber, metal, wood/timber, and sand, thereby preserving the natural environment. Proper management of solid wastes through recycling into new products will help to promote a sustainable environment, conservation of natural resources, and cheap raw materials.⁴ On the other hand, the lack of adequate management of solid wastes will add to the existing environmental problem; hence, solid wastes must be properly managed by recycling them into new useful products.⁶ Being that plastic wastes cannot decompose easily and are produced in huge quantities, their deposition into landfills may not be a permanent solution.^{7,8}

Recycling is currently not an easy management strategy for plastic materials because it is a labor and capital-intensive process.⁹ Previously, plastics were considered environmentally friendly materials that save energy, reduce raw material extraction, and fight climate change. However, the rate of plastic waste generation has increased tremendously, and management has become a serious issue. Consequently, researchers have suggested the use of plastic wastes in concrete production for two major reasons: first, to resolve the environmental problem associated with their disposal and second, to reduce construction costs since they are available in great quantities.⁹ Cement is generally used as a binder in the construction industry; however, the high cost of cement has prevented many people from building their houses and has hindered the advancement of the construction sector.^{10,11} Hence, it is important to find a suitable replacement for this expensive and essential building material.^{12,13}

Polyethylene terephthalate (PET) bottles are now used as binders in the manufacture of a wide range of building materials, including tiles. Shredded plastic waste is a recycled material that has received a lot of attention in the construction industry.¹¹ Several studies have documented the potential suitability of plastic waste as construction materials. For example, Mehdi *et al.*¹⁴ reported that high-density polythene (HDPE) plastics can be used to make roof tiles when combined with sand. The results of their study revealed that composite tiles made with 70% HDPE had better performance and quality after analysis. Several experimental studies on the use of recycled PET bottles as a substitute for natural aggregates in concrete have recently been published,¹⁴ and as resin in polymer concrete.¹⁵ Akinwumi *et al.*¹⁶ documented the production of stabilized soil blocks from shredded plastic waste and their study opined that 1% finely shredded PET waste (size 6.3 microns) by weight could be used for successful block stabilization. Mustafa *et al.* [2019], investigated the use of PET waste as a partial replacement for fine aggregates in the production of high-impact resistance building materials. The impact resistance increased by 39% in mortars made with a 20% plastic material. Kumi-Larbi *et al.*¹⁷ reported the successful production of sand blocks using plastic waste and the findings of their study revealed that solid and durable sand blocks can be produced without the use of extra water, using only plastic waste.

Yang *et al.*¹⁸ also investigated the feasibility of producing eco-friendly door panels by combining plastic waste with wood dust. In a particular study, Al-Hadithi and Hilal²¹ used shredded PET waste to make roof tiles and discovered that the compressive strength of the sample decreased as the PET volume increased. Borg *et al.*²⁰ used PET fibers in concrete and discovered that at higher PET fiber contents, PET fibers significantly decreased the compressive strength of the sample. Al-Hadithi and Hilal²¹ tested the use of plastic waste fibers in the construction of self-compacting concrete and discovered that the compressive strength of the sample increased as the plastic waste content increased. This study aims to examine the viability of utilizing PET waste as a binder in full replacement of cement to produce tiles. The main objectives of this study are to evaluate the possibility of recycling PET waste to produce tiles, as well as to examine the physical and mechanical performance of the PET polymer tiles.

Methods

Materials

The materials used in making the composite tiles were sourced locally; the locally sourced materials included plastic wastes, metal mold, wood stirrer, sieve, hand gloves, coal pot, face mask, and engine oil. The PET wastes used in this

study were shredded plastic bottle wastes collected from a Waste Resource Management Company located at 14000 Bukit Mertajam, Penang, Malaysia. The fly ash used was supplied to the School of Housing, Building, and Planning Resource Laboratory, Universiti Sains Malaysia. The shredded PET wastes were heated and melted inside an aluminum pot at a temperature of 230 °C before the addition of fine dried fly ash into the melted plastic wastes at different percentages. The mixture was homogenized and poured into a 5 cm thick iron mold that had been lubricated with engine oil for easy removal. The edge of the mold was banged continuously for proper compression. After one hour, the samples were de-molded, cooled, and cured at ambient temperature for forty-eight hours before testing (see Table 1). Table 2 shows the chemical composition of the obtained fly ash. The following chemicals: acetone, benzene, acetic acid, hydrochloric acid (HCl), carbon tetrachloride (CCl₄), sodium carbonate, and sodium chloride were used and supplied by the School of Housing, Building, and Planning to determine the chemical tolerance of the polymer tiles produced.

Characterization

The compressive strength of plastic composite tiles was determined using the Instron Universal Testing Machine (UTM 5967) (Instron Norwood, USA) and the ASTM D638 specification which involved casting of the homogenously mixed PET paste and fly ash into a standard cube for compression testing of size 50 × 50 × 50 mm. Samples with lengths of 50 mm, widths of 50 mm, and thicknesses of 50 mm were prepared for strength testing for this test, the samples were tested on the Instron Universal Machine after de-molding and cooling for 48 hours at room temperature to determine their compressive strength.

The chemical resistance test was performed on the samples in accordance with ASTM D543-14 by cutting the sample tiles into 20 × 20 × 20 mm sizes and soaking them in a different chemical solution for a period of seven days. The purpose of this test was to evaluate the sample's resistance to various chemical reagents. The chemicals used for this study were acetone, benzene, acetic acid, hydrochloric acid (HCl), carbon tetrachloride (CCl₄), sodium carbonate, and sodium chloride with 5% dilution.

Furthermore, the ASTM D570 standard method was used to determine the relative water absorption rate of the polymer tiles sample after immersion in water for 72 hours. The percentage change in weight of the sample was calculated and recorded, all experiments were carried out at room temperature.

The flexural strength of the PET polymer tiles was determined using ASTM D 72-64-15. For the testing, three prisms measuring 40 × 40 × 160 mm³ were made from each batch of PET polymer paste. The prism specimen was placed on the

Table 1. Different contents of PET waste and Fly ash used in this study.

Sample	PET waste content (wt. %)	Fly ash content (wt. %)
PT1	30	70
PT2	50	50
PT3	70	30
PT4	90	10
PT5	100	0

Table 2. Chemical composition of fly ash used.

Composition	Mass percentage
SiO ₂	58.60
Al ₂ O ₃	24.01
Fe ₂ O ₃	6.35
CaO	4.28
MgO	1.74
K ₂ O	2.46
TiO ₂	0.85
Na ₂ O	1.71

ELE International Flexural Testing Machine loading frame with the assurance that the specimen to be examined is centered and parallel with the two longitudinal levers located below and above the machine arms. The specimens were subjected to bending tests using a bending test machine loaded at a continuous rate of 50 N/s until they failed, and the failure load was recorded. The ultimate flexural strength was calculated by taking the average of three specimens from the same batch.

The average density of tile specimens was discovered by taking the measurement of the weight of sample of the polymer tiles and the diameter of the specimen. The polymer tile is prepared and poured into a prism cube size 50×50 mm. Three to five samples of each mix are selected for the test. The weight of each sample was recorded. The density was calculated using the equation:

$$\frac{j}{d^3} \times 1000^3 (\text{kg/m}^3)$$

Where j is the sample weight and d is the diameter of the sample size.

While the porosity was measured in accordance with the RILEM guidelines.²² Cylinder specimens with diameters of 50 mm and heights varying from 35 to 40 mm were cast. The samples were dried in an oven for 78 hours at 105 ± 2 degrees Celsius. They were then cooled in a desiccator for 24 hours. The weight of the oven dried samples was calculated and denoted as W_d . The sample was then placed in a dissector filled with de-aired and de-ionized water until it was completely immersed in water. The samples were held under a steady vacuum for 78 hours before being allowed to equilibrate. The weight of the samples was determined in both the air (W_a) and the water (W_w). The absolute porosity, P for the samples is calculated using:

$$P(\%) = \frac{W_a - W_d}{W_a - W_w} \times 100$$

Results and discussion

Water absorption

PET polymer tiles produced with 30% PET and 70% fly ash achieved the highest value (0.98%) while those produced with 100% PET and 90% PET + 10% fly ash presented the lowest values (see Figure 1). This means that the water absorption of the PET polymer tiles is directly a function of the PET content but inversely related to the fly ash content.

Density

The density of the PET polymer tile was determined, and the result showed PT1, PT2, PT3, PT4, and PT5 (Table 1) are 1688, 1575.2, 1370.4, 1181.6, and 1070.3 kg/m^3 respectively. The PET polymer tiles produced with 100% PET had the lowest density (1070.3 kg/m^3) while those produced with 30% PET content had the highest density (1688.0 kg/m^3) as shown in Figure 2. Therefore, increases in the PET content decreased the density of the PET polymer tile. Notably, other studies previously indicated that an increase in PET content reduced the density of the resulting composites.^{19,23}

Porosity

The PET plastic composites produced with 30% PET content presented the highest porosity value (4.14%) while those containing 90% PET achieved the lowest porosity value of 0.39% (see Figure 3). The porosity values fall consistently as

Figure 1. Water absorption of the composite tile samples.

Figure 2. Density of the composite tile samples.

Figure 3. Porosity of the composite tile samples.

the fly ash percentage decreases, yet the percent porosity of PT 5, which contains pure PET (no fly ash), is higher than PT 3 and PT 4, which contain 30% and 10% fly ash, respectively. This means that the presence of fly ash in the PET tiles has an effect on the porosity value of the PET polymer tiles but should not exceed 10% in a particular mix. Rilem²³ made a similar observation.

Compressive strength

PET composite that contains 100% PET exhibited the lowest compressive strength value (0.012 MPa) while those produced with 30% PET content had the highest compressive strength value (6.88 MPa) as shown in Figure 4. The compressive strength values (6.88, 5.49, 4.36, 2.94, and 0.012 MPa respectively) steadily increased with the fly ash content but decreased with increasing PET content. The results show that increasing the PET waste content reduces the compressive strength of the composite.^{18,19,21,23}

Flexural strength

The flexural strength of the PET polymer tiles was calculated in accordance with ASTM D 72-64-15, and the results are shown in Figure 5. The sample with 100% PET content had the lowest flexural strength, while the sample with 30% PET

Figure 4. Compressive strength of the composite tile samples.

Figure 5. Flexural strength of the composite tile samples.

content had the highest (6.75 MPa). This shows that the flexural strength improved as PET content decreased but increased as fly ash content increased. Because of this behavioral adjustment, the flexural strength of the PET polymer tile is dependent on the PET material. A similar observation was also previously reported and showed that flexural strength decreased as the amount of plastic waste in a structure increased.¹⁹⁻²¹

Chemical resistance

Chemical resistance tests were performed on the samples in accordance with ASTM D543-14 guidelines. The samples were prepared with length = 20 mm, width = 20 mm, and thickness = 10 mm, then weighed and immersed in various chemicals: hydrochloric acid (HCl), sodium chloride (NaCl), sodium carbonate (Na₂CO₃), acetone, benzene, acetic acid, and carbon tetrachloride (CCl₄). The experiment was carried out at room temperature for 168 hours. Following the soaking time, the samples were removed, rinsed with distilled water, and air-dried before measuring the weight and dimensions of the soaked samples and comparing them to the weight and size of the non-soaked samples. Comparative findings revealed no significant changes in sample weights or measurements after seven days of soaking in different chemicals; this finding is consistent with Dhawan *et al.*²³

Conclusions

Based on the experimental results, the following conclusions were reached:

- A higher PET content in the tile reduces water absorption. The percentage of water absorption decreased from 0.98% to 0.1%.

- Samples with 100% PET content had the lowest average density (1070.3 kg/m^3), while samples with 30% PET content had the highest density (1688.0 kg/m^3). When compared to control samples, density increased steadily with increasing fly ash content but decreased with an increasing percentage of PET waste.
- The compressive and flexural strength of the PET polymer tiles decreased as the PET content increased. The compressive strength decreased from 6.88 MPa for samples with 30% PET content to 0.012 MPa for samples with 100% PET content, while the flexural strength decreased from 6.75 MPa for samples with 30% PET content to 0 (brittle) for samples with 100% and 90% PET content.
- PET polymer tile tolerance in different chemical solutions has been demonstrated, with no significant changes in weight or dimensions found after seven days of soaking in different chemicals.

These results from this study indicate that PET waste bottles can be used to produce long-lasting, good strength, minimal water absorption, and eco-friendly tiles for both residential and commercial applications. This prospect of tile production using polyethylene terephthalate (PET) waste and fly ash would not only minimize the cost of building products but will also act as a waste diversion to mitigate environmental emissions caused by plastic waste disposal.

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Data availability

All data underlying the results are available as part of the article and no additional source data are required.

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