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Strength Properties and Sustainability of Recycled Plastic Tiles: Flammability, Water Absorption, and Chemical Tolerance

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Abstract

The cost of construction materials, as well as the natural resources needed to manufacture the materials in an enabling climate, is affecting the world's construction industry, which is expanding at an unprecedented pace. Plastic wastes are a significant environmental concern due to their widespread use, non-biodegradability, and contamination from incineration and landfill, recycling these wastes into tiles would be a significant benefit. This investigation's goal is to study the mechanical qualities of tiles made from PET (Polyethylene Terephthalate) wastes, fly ash, and river sand aggregates. PET wastes were added to other aggregates in various percentages of 100 percent, 90 percent, 70 percent, 50 percent, and 30 percent by weight. The assessment of physical and mechanical properties reveals that, in terms of material density, weight, and flammability resistance, the tiles containing 30% plastic waste outperforms the other proportion of waste. According to the results, this composite tile has a very low percent porosity value (2.9 - 0.11 percent) as compared to cement or ceramic tiles. In addition, the composite tile (PT1) with 30% PET and 35% fly ash and sand demonstrated decreased flammability with a linear burning rate of 7.68 mm/min and enhanced compressive strength of 11.07 N/mm^2. There was no significant difference in weight after soaked in different acid and base solutions for seven days. Finally, as tile products, PET plastic tiles have good strength, chemical tolerance, low flammability, low water absorption, and are environmentally friendly. This possibility would not only reduce the cost of construction materials, but it would also serve as a waste diversion, reducing the environmental impact of plastic waste disposal.

Keywords: Polyethylene terephthalate • Fly ash • Compressive strength • Porosity • Flammability

Introduction

Plastic waste's high rate of production and non-biodegradability has created a global pandemic threat in our climate. Global demand for plastics continues to increase, resulting in unsustainable waste generation. By 2030, the volume of plastic in use is expected to have grown from 236 million to 417 million tons per year [1]. Over the last few decades, annual plastic intake has gradually risen, because of hereditary qualities such as low cost, user-friendly designs, production capabilities, high durability, lightweight, and strength. Plastic waste is a very common form of solid waste, posing a direct challenge to the wellbeing of our planet [2]. Plastic waste has been shown to have an effect on the climate, economy, and aesthetics as it enters the oceans [3]. Annual plastic waste production is projected to be about 300 million metric tons [4]. In 2017, plastics were produced in 8.3 billion metric tons around the world, with 80 percent of them being after usage, thrown in landfills, or polluting the environment [5-7]. Because of their lightweight, soft design, versatility, non-corrosiveness, and resilience, plastics are widely used. Plastics are convenient packaging materials and containers, but their waste is a significant source of pollution; when incinerated, they release toxic gases and are not biodegradable. Plastic products are allegedly carcinogenic due to the presence of chlorine and other carcinogens. As plastic waste is burned, toxic dioxins such as phosgene, carbon monoxide, arsenic, others are emitted into the air, as well. Since plastic waste accounts for most of the waste generated globally, there is a need to ensure proper waste management. Plastics are widely used as packaging materials, but their waste can be used to make construction materials such as floor tiles, roof tiles, building blocks, and so on. This will reduce building costs while also reducing environmental emissions. Plastic waste, for example, maybe combined with sand and other additives to create building materials [2,7]. Now, recycled plastic waste is increasingly replacing natural materials such as fiber, metal, wood/timber, and sand, protecting the natural environment. Fly ash is a fine powder that is produced when pulverized coal is burned in power plants. Proper solid waste management by recycling into new goods would aid in the promotion of a sustainable climate, the protection of natural resources, and the availability of low-cost raw materials [2,8]. On the other hand, inadequate solid waste disposal would exacerbate the current environmental problem; hence, solid wastes must be properly handled by recycling them into new usable items [9,10]. Since plastic wastes are difficult to decompose and are created in large amounts, their disposal in landfills may not be a permanent solution [2,3,11]. Recycling is currently not a simple management technique for plastic materials due to the labor and capital-intensive nature of the process [3,12]. Plastics were previously thought to be environmentally friendly products that save resources, reduce raw material extraction, and combat climate change. However, the rate of plastic waste production has skyrocketed, and management has become a major concern. As a result, researchers have proposed using plastic wastes in concrete production for two main reasons: first, to address the environmental issue associated with their disposal and second, to minimize construction costs because they are abundant [10]. Cement is commonly used as a binder in the construction industry; however, the high cost of cement has stopped many people from constructing their homes and has slowed the construction industry's progress [13,14]. As a result, it is critical to find a suitable substitute for this costly and necessary building material [15,16].

PET bottles are also used as binders in the manufacture of a wide range of construction materials, including tiles. Shredded plastic waste is a recycled material that has sparked a lot of interest in the building industry [17]. Several studies have identified the possible suitability of plastic waste as building materials. Mehdi et al. [18] stated that when mixed with sand, high-density polythene (HDPE) plastics can be used to make roof tiles. After research, the results of their study showed that composite tiles made with 70% HDPE performed and were of higher quality. Several experimental studies of PET bottles that have been recycled as a replacement for natural aggregates in concrete and as resin in polymer concrete [19] have recently been released.

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Akinwumi et al. [20] demonstrated the development of stabilized soil blocks from shredded plastic waste, concluding that 1% finely shredded PET waste (size 6.3 microns) by weight could be used for effective block stabilization. Mustafa et al. looked at using PET waste as a partial substitute for fine aggregates in the manufacture of high-impact resistance building materials. The impact resistance of mortars made with a 20% plastic content increased by 39%. Kumi-Larbi et al. [21] reported on the efficient production of sand blocks from plastic waste, and their findings demonstrated that using only plastic waste, solid and long-lasting sand blocks can be manufactured without the usage of extra water. Yang et al. [22] explored the possibility of creating eco-friendly door panels by mixing plastic waste with wood dust. In one study, [23] used shredded PET waste to make roof tiles and discovered that the sample's compressive strength decreased as the PET volume increased. Borg et al. [24] used PET fibers in concrete and discovered that at higher PET fiber contents, the compressive strength of the sample was substantially reduced. Al-Hadithi and Hilal [23] investigated the construction of self-compacting concrete using plastic wastes and it was discovered that the sample's compressive strength decreased with an increase in plastic waste content. This research would examine the feasibility of manufacturing tiles out of PET bottle trash as a binder in place of cement. The sole purpose of this research is to develop and produce long-lasting and dependable tiles made from recycled PET bottles, river sand, and fly ash.

Figure 1. PET wastes sample.

Experimental Investigation

Materials

The following items were used in the experiment: a metal mold, a gas cylinder, a burner, a measuring scale, a measuring cup, lubricating oil, a plier, a metal bowl, a screwdriver, a brush, a fire source, a stirrer, and protective clothing such as a hand glove, a nose mask, a boot, an eye shield, and so on. The shredded plastic bottle waste and fly ash used in this study were collected from a waste Resource Management company in 14000 Bukit Mertajam, Malaysia, and a palm oil processing company in Penang, Malaysia, respectively. While the river sand used was supplied to the School of Housing Building and Planning Resource Laboratory (Figures 1–3) display bags of shredded PET waste, a sample of fly ash, and river sand, respectively. The School of Housing, Building, and Planning Resource Laboratory provided different chemical reagents of technical grade such as sodium carbonate (Na_2CO_3), acetic acid, hydrochloric acid (HCl), acetone, nitric acid (HNO_3), benzene, and sodium chloride (NaCl) needed to evaluate composite tiles' chemical resistance.

Figure 2. Sample of fly ash.

Method

The shredded PET wastes were heated in the aluminum pot to 230°C before adding the Fly ash and the fine river sand to the melted plastic wastes, as shown in Figure 4. The mixture was homogenized and poured into an iron mold lubricated with engine oil for quick removal; the mold's edge was banged continuously for a few minutes to ensure proper compassion. After one hour, the samples were de-molded, cooled, and cured for forty-eight hours at room temperature before testing. The composition of the aggregates (Tables 1 and 2) displays the chemical makeup of fly ash while (Figure 5) shows the sample of the PET roofing tiles produced.

Characterization

The composite tiles' compressive strength was computed with the help of an Instron Universal Testing Machine (UTM 5967) at a crosshead speed of 5 mm/min in accordance with ASTM D638. To test the tensile strength, the gauge length, width, and thickness of the samples were all 50 mm. The densities of different composite tiles were determined. The rate of burning was tested for flammability using the ASTM D 635 process. Waste plastic composite tiles were chopped into 100 mm x 25 mm x 10 mm bar-shaped test samples. Each composite tile had at least three specimens, and the burning rate was calculated in millimeters per minute. ASTM D543-14 was used to test these composite tiles' tolerability to various chemical solutions. The rate at which these plastic tiles absorb water after being immersed for a set period of time was tested using the ASTM D570 standard; all experiments were carried out at ambient temperature.

Figure 3. River sand sample.

Figure 4. Melted PET mixed with sand and fly ash.

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

Sample (wt. %)	PET waste content (wt. %)	Fly ash (wt. %)	Sand (wt. %)
PFSRT1	30	35	35
PFSRT2	50	25	25
PSFRT3	70	15	15
PSFRT4	90	5	10
PRT	100	0	0

Table 2. Chemical composition of Fly Ash used.

Composition	Mass (%)
TiO_2	0.85
Na_2O	1.71
MgO	1.74
K_2O	2.46
CaO	4.28
Fe_2O_3	6.35
Al_2O_3	24.01
SiO_2	58.6

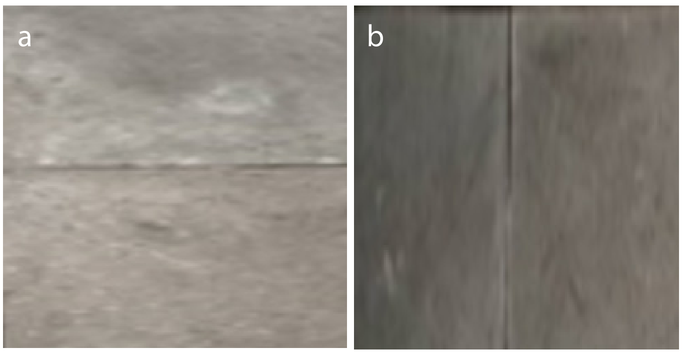

Figure 5. (a and b) Samples of plastic roof tiles.

Results and Discussion

Physical properties

Test results for sand particle size distribution: The aggregate gradation of fine sand was assessed using sieve analysis. According to Figure 6 and Table 3, the fine sand sample is properly graded. The aggregate was found to be well-selected and suitable for building work, with a uniformity coefficient of 0.2 to 0.6 and a fineness modulus of 1.93. [25] Was used to rate the sample.

Sand aggregate's relative density and water absorption: The relative density and water absorption of the sand were determined by weighing 500 g of sample sand and soaking it in water for 24 hours before pouring it into a conical flask filled with water and weighing it. The sand was then sieved, sun-dried, and weighed at the surface dried. It was returned to the oven for another 24 hours to dry. The test on the river sand used yielded an average relative density of 2.38 and 0.07 percent water absorption, as illustrated in Table 4 it falls within the fine aggregates range described by British Standard. The relative density of natural aggregates, according to Kosmatka et al. [26], is between 2.4 and 2.

Where,

A represents the mass of the Saturated Surface Dry sample in air.

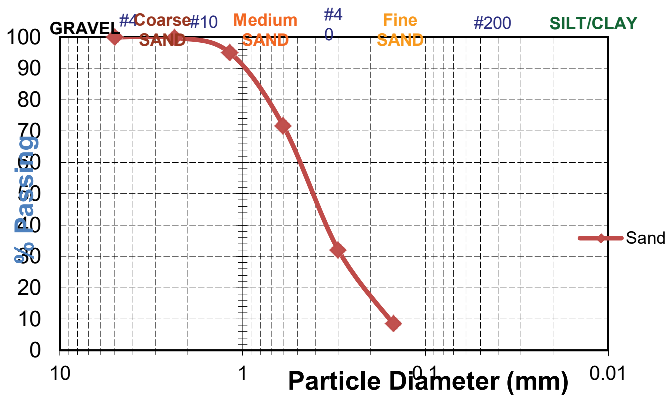

Figure 6. Particle size distribution of river sand.

Table 3. Sand particle size distribution; Weight of dry sample (g):500.0.

Sieve Number	Diameter (mm)	Soil Retained (g)	Soil Retained (%)	Soil Passing (%)
5.00 mm	5	0	0	100
2.36 mm	2.36	1	0.2	99.8
1.18 mm	1.18	23	4.7	95.1
600 µm	0.6	113	23.4	71.7
300 µm	0.3	191	39.6	32.1
150 µm	0.15	114	23.6	8.5
Pan		41	8.5	0
	TOTAL:	483		

Table 4. Determination of sand aggregate relative density and water absorption.

Test no:	A (g)	B (g)	C (g)	D (g)	Relative Density (Oven-Dried Basis)	Relative Density (Saturated Surface Dried)	Water Absorption % of Dry Mass
1	471	1,801	1,540	471	2.24	2.24	0
2	498	1,819.3	1,508.1	497	2.66	2.67	0.20
3	497	1,822.2	1,506.6	497	2.74	2.24	0
Average					2.55	2.38	0.70

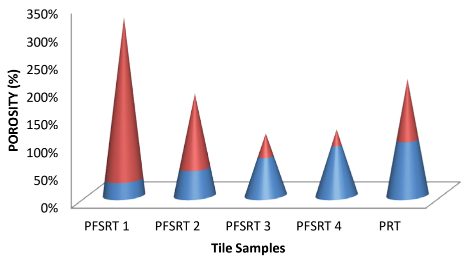

Figure 7. Porosity of sample.

B denotes the mass of the water-filled cylinder containing the sample.

D is the mass of the oven-dried sample in the air.

C is the mass of the Cylinder filled with water only.

Porosity: The amount of void space in a material is measured by porosity, also known as a void fraction. According to (Figure 7) and Table 5, the highest percent porosity for the PET composite tiles was 30 percent PET (2.83 percent) and the lowest percent porosity was 90 percent PET (0.11 percent). The percentage porosity of the composite tiles gradually decreased down to 90% PET, all of which fell within the 2% range defined by the norm. [7]. Except for the 100 percent PET tile, this means that when the PET material density grows, so does the porosity of the PET tiles.

Mechanical properties

Density: The density of the PET wall tile was determined, and the results showed that PFSRT1, PFSRT2, PFSRT3, PFSRT4, and PRT5 were 1764.7, 1534.3, 1301.5, 1082.3, and 1070.1 kg/m3, respectively. The manufactured composite tiles with 100% PET possessed the lowest density (1070.2 kg/m^3), while those produced with 30% PET content had the highest density (1764.7 kg/m^3), as shown in Figure 8. Increases in PET material, on the other hand, decreased the density of the composite tile. Notably, as previously mentioned, the density of the resulting composites was decreased as the PET material was increased [27,28].

Compressive strength: The PET composites with the highest compressive values were those with 30% PET (11.07 MPa). Although 100 percent PET had the lowest strength value (0.02 MPa). This value was greater than the compressive strength of other common tiles. The compressive strength values for PFSRT1, PFSRT2, PFSRT3, PFSRT4, and PRT are 11.07, 10.01, 7.10, 2.78, and 0.02 MPa, respectively, and increase steadily with increasing sand and fly ash content but decrease with increasing PET content (Figure 9). The findings show that increasing the PET waste content decreases the composite's compressive strength [27-29].

Flammability: The tiles were cut into 100 mm bars to calculate the linear burning rate ass shown in Figure 9 each composite sample's linear burning rate was determined using three specimens. In which at one end, 100mm sample bars are supported and ignited with specific scorching from the opposite end for about 30 seconds each and the time spent to reach the 100 mm mark from the lit end was recorded. The sample linear burning rate (V) was calculated by averaging the burning rates of three specimens. The following equation can be used to calculate the rate of burning of each sample, the time taken to reach 100 mm from the flame front:

$V = 60L/T$.

Where L denotes the period burned in millimeters and T denotes the time taken in minutes.

The linear burning rate of 21.21 mm/min is achieved by 100 percent plastic tile, which is compatible with published values. Furthermore, adding Fly ash and river sand to the plastic paste in various percentage weight loadings decreases the composite tiles burning rate by 17.78, 15.11, 9.82, and 7.96 mm/minutes, as shown in Figure 10. The results of the experiment revealed that the addition of river sand and fly ash aggregates to PET paste formed a barrier, causing the composite tiles to burn slower than the pure 100 percent PET plastic tile. This is a result of sand and fly ash content, which are non-conducting ceramics materials that are thermally stable up to 2000°C. These metal oxides inhibit polymer carbonization, resulting in a more durable and efficient layer of char that function as a barrier between surface burning and undecomposed content. Heat and fuel transfer to the burning front is reduced as a result. As a result, the linear burning rate decreases as sand and fly ash content increases [30].

Chemical resistance: Chemical resistance testing on the samples was carried out according to the ASTM D543-14 guideline. The samples were prepared with 20 mm in length, 20 mm in width, and 10 mm in thickness, then weighed and immersed in various chemicals Hydrochloric acid (HCL), Sodium chloride (NaCl), Sodium carbonate (Na_2CO_3), Acetone, Benzene,

Table 5. Density, compressive strength, porosity, and flammability resistance (Linear burning rate) of the PET composite tiles of different PET, fly ash, and sand contents.

Sample	Linear burning rate (mm/min)	Density (Kg/m^3)	Compressive strength (MPa)	Porosity (%)
PFSRT1	7.96	1764.7	11.07	2.92
PFSRT2	9.82	1534.3	10.01	1.34
PFSRT3	15.11	1301.5	7.10	0.42
PFSRT4	17.78	1082.3	2.78	0.29
PRT	21.21	1070.1	0.02	1.10

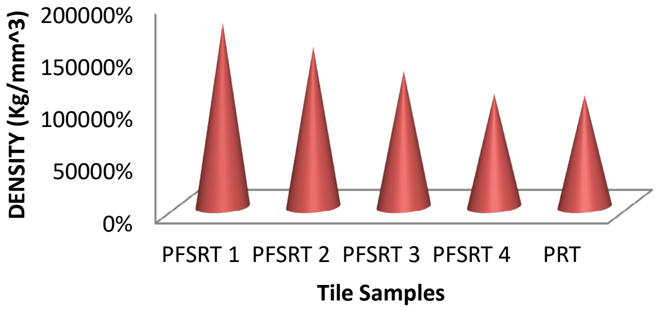

Figure 8. Average density of the sample.

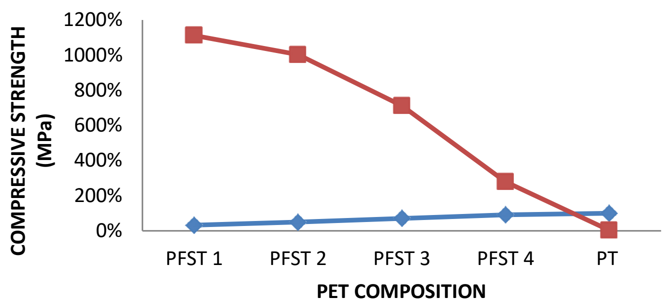

Figure 9. Average compressive strength values of the samples.

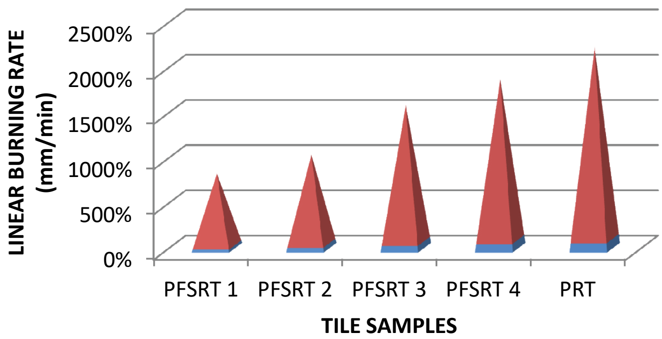

Figure 10. Flammability: Linear burning rate (mm/minute).

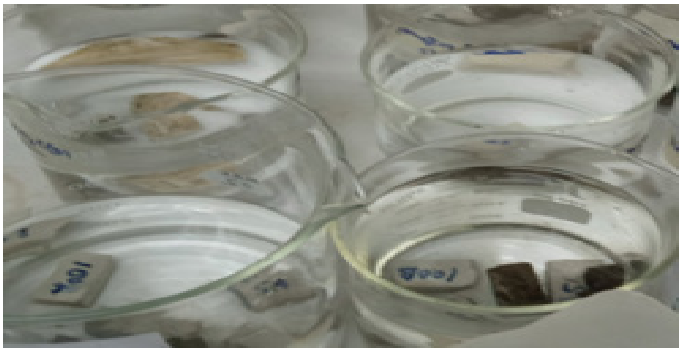

Figure 11. Sample soaked in different chemical for 7 days.

Acetic Acid, and Carbon Tetrachloride) (CCl_4). The experiment was carried out at room temperature for 168 hours, as shown in Figure 11. Following the soaking time, the samples were removed, rinsed in clean water, and air-dried prior to weighing and measuring the soaked samples then comparing them to the weight and size of the neon-soaked samples. Comparative findings revealed no significant changes in sample weights or measurements after 7 days of soaking in different chemicals; this finding is consistent with Ridham Dhawan, Brij Mohan Singh Bisht, Rajeev Kumar, Saroj Kumari, except for the samples which contain higher sand content has a slight change in weight in Hydrochloric acid and Nitric acid solution because of the presence of SiO_2 which is the main component of sand.

Conclusions

The experimental findings lead to the following conclusions:

- The tile specimen with the lowest measured density was 100 percent PET (1070.1 kg/m^3), samples with 30% PET exhibited the maximum density (1764.7 kg/m^3). As compared to composite tiles, the densities increase gradually as the sand and fly ash content increases but decrease as the percentage of PET waste increases.
- The percentage porosity decreases as the amount of PET waste in the composite tile increases from 30% to 90% PET but changes when 100% PET is used as a binder incomplete replacement of cement. The percentage porosity fell from 2.92 percent to 0.29 percent.
- The composite tiles' compressive strength decreased as the amount of PET waste used as a binder increased. The compressive intensity dropped from 11.07 MPa (at 30% PET) to 0.02 MPa (100 percent PET). A well-distributed aggregate distribution in polymer matrices increases compressive strength.
- The flammability resistance of composite tiles decreases as the amount of PET waste increases but increases as the amount of fly ash and sand increases. The linear burning rate increased from 7.96 mm/min to 21.21 mm/min. The results of the experiment revealed that adding river sand and fly ash to composite tiles formed a barrier, causing the tiles to burn slower than pure 100% PET plastic tiles. The sand and fly ash particles reduce polymer carbonization, resulting in a char layer that is more stable and efficient that serves as a barrier between the charred and uncharred surfaces. Consequently, a more durable and efficient layer of char between these two surfaces is created. As a result, as the sand and fly ash content increases, so does the linear burning rate.

PET waste bottles with fly ash and river sand, according to the findings of this study can be used to make long-lasting, high-strength, low-water-absorption, and eco-friendly roof tiles for both residential and commercial applications. This prospect of making tiles from polyethylene terephthalate (PET) waste, sand and fly ash would not only minimize building material costs but would also serve as a waste diversion to reduce environmental pollution caused by plastic waste disposal.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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