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RESEARCH

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Optimization of plastic waste integration in cement bricks

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Abstract

Implementing plastic waste in construction materials is a sustainable disposal method to overcome plastic pollution. The current study aims to optimize the integration of plastic waste in cement bricks regarding their thermomechanical properties in order to develop an eco-friendly building material. Polyethylene terephthalate (PET) and high-density polyethylene (HDPE) partially substituted cement with different ratios (0, 2.5, 5, 7.5, 10, 20%). The type that achieved better thermomechanical performance further replaced the other brick components; sand and coarse aggregates to determine the optimum replacement scenario and best design mix. Laboratory experiments have been carried out to measure the compressive strength, indirect tensile strength, bulk density, and thermal conductivity of the new composites. The measured results revealed better performance for the samples with HDPE than PET. A boost in the compressive strength and indirect tensile strength was noticed for the samples obtaining a limited amount (up to 7.5%) of HDPE. However, a reduction in the tested mechanical properties occurs with higher substitution levels. With respect to thermal conductivity and bulk density, they decreased with the increase of plastic waste. The best mechanical behavior and the highest thermal resistance were obtained by partial replacement of coarse aggregates with 7.5% and 20% HDPE respectively. The results represent a good contribution to energy conservation, waste management and sustainability.

Keywords: Cement bricks, Plastic waste, Thermomechanical

Introduction

Energy consumption, CO_2 emissions, depletion of natural resources and plastic waste are major environmental issues. Recent studies promote using plastic waste material in the construction sector and consider it as a valuable resource that may solve several environmental problems. Despite the low biodegradability of plastics [1], they have a variety of significant qualities; they are durable, corrosion, and moisture-resistant, lightweight, flexible, and cheap. Besides, they have high thermal resistance, which may enhance the building's thermal performance [2]. Economically, replacing aggregates with cheaper, lighter materials will be cost-efficient in production and transportation [3]. This practice also saves natural resources from depletion. In addition, developing lightweight construction material minimizes the building deadload and structure volume. These multi-sustainable benefits promote the idea of using plastics as an alternative building material [4].

The most common plastic types are polyethylene (PE) which is mainly classified into high-density PE (HDPE), medium-density PE (MDPE) and low-density PE (LDPE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyurethane (PUR). PE forms the largest share, followed by PET, PVC, and PP [5].

Concrete is one of the most demanded construction materials and is mainly dependent on natural resources. Around 65% of its composites consist of fine (sand) and coarse aggregates (gravel, limestone etc.) that are added to cement [6].

Several studies investigated the mechanical behavior of concrete after partially replacing their aggregates with plastic waste. Concrete has relatively high compressive strength and low tensile strength [7]. All reviewed studies agreed on the decrease of the compressive strength with high replacement levels of plastic waste [8–14]. However, not all studies have the same agreement for the case of low replacement levels; some pointed out a positive influence on the compressive strength by replacing sand with 3% PET [8], 10% PET [9] and 0.6% of mixed plastic [10]. Others detected a decrease in the compressive strength even with limited amounts of PET [11–13, 15]. The thermal resistance was proportional to the amount of plastic waste [12, 13, 15, 16]. Other properties were tested as the speed of ultrasound transmission which was reduced with the increase of PET in concrete. This gives the opportunity to develop an eco-friendly material with high sound resistance [9].

Another study by Saleh et al. intended to produce an eco-friendly economical cementitious composite that can be utilized for the immobilization of radioactive waste or radiation shielding construction. They employed PVC as an additive with different ratios (10–50%). The results achieved an increase in the neutron removal cross-section with an acceptable compressive strength [17]. Eskander et al. tested the behavior of cementitious composites that were integrated with chemically recycled polystyrene foam. The developed composites were soaked in plain, ground and sea water for 420 days. The findings indicate an enhancement in the mechanical properties especially compressive strength and corrosion resistance with adequate heat insulation [14].

From the reviewed studies, it can be demonstrated that many factors may affect the results depending on the constituents of the composite, the types and the amount of plastics. However, they focused on replacing one of the concrete's component, nevertheless, no one has carried out a comparative study with different replacement scenarios for the same composite; e.g., cement, sand or coarse aggregates.

The present paper investigates the thermomechanical behavior of cement brick containing different types of plastic waste with different replacement scenarios aiming to determine the optimum design with the highest thermal resistance and adequate compressive strength. Comparing two types of plastic waste with different recycled methods, namely manually cut PET and mechanically recycled HDPE. Different ratios of PET and HDPE were used to partially substitute cement (0, 2.5, 5, 7.5, 10, 20%). Other scenarios were proposed and compared, namely replacing sand and coarse aggregates with the plastic type that provides higher thermomechanical performance.

Laboratory tests have been carried out to determine the novel composites' compressive strength, indirect tensile strength, bulk density, and thermal conductivity.

Experimental program

A series of laboratory experiments have been conducted on various composite mixtures of cement bricks. Cement, fine aggregates (sand), and coarse aggregates (limestone) have been partially replaced by volume with different ratios of HDPE, one at a time, to identify the optimal replacement limit. A comparison between HDPE and PET is carried out by partially replacing cement once again with PET. Thus, four sets were prepared with five different replacement ratios (2.5, 5, 7.5, 10, 20%) giving an overall 21 different mixtures including the control sample. The mixtures were named according to the replaced component and plastic type; e.g., CEPET is the set in which PET replaces cement, in CEPE cement was replaced with PE. Coarse aggregates and sand were only replaced with PE; hence, their samples were named CAPE and SAPE respectively. All samples were tested for bulk density, compressive strength, indirect tensile strength, and thermal conductivity. Figure 1 presents the experimental programme of this research.

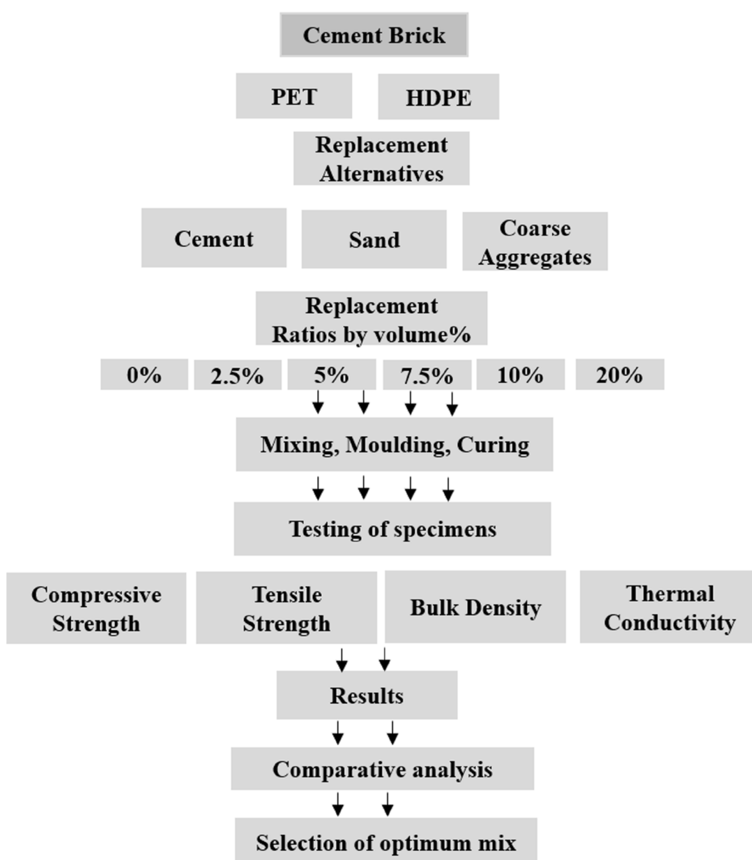

Fig. 1 Experimental program

Materials design mix

- Ordinary Portland cement with a fineness of 42.5 N and a relative specific gravity of 3.1. The specific gravity was used to determine weight-volume relationships.
- Limestone as coarse aggregate with a size $4.75 \leq \times \leq 9$ mm and specific gravity of 2.6 and sand as fine aggregate with a specific gravity of 2.55.
- PET that was collected from water bottles and was manually cut into small pieces (1.5–2.5 mm). HDPE bought from the manufacturing industry. The HDPE is mechanically recycled under a heat of 140 °C till melting and shaped into long thin rods that were cut into a length of 2 mm and a diameter of 1.5 mm. The specific gravity of PET is 1.38 and that of HDPE is 0.97.
- A superplasticizer (MasterRheobuild 1100) was used as a water reducer admixture, with a ratio of 1000 ml per 100 kg cement.
- Water: the used water/cement ratio was 0.5 and remained constant.

Each mixture was cast into six moulds, one cubical specimen for 7th curing day compressive strength test and three specimens for the 28th, one cylinder for the indirect tensile strength, and one for the thermal conductivity, having a total of 126 samples. The used quantity of materials for the control sample was calculated according to the design Mix 1:3:5. Table 1 presents the ratios of the components that were used for the different cementitious mixtures per 1.0 m^3.

Table 1 Materials design mix

Mixtures	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregates (kg/m^3)	Plastic (kg/m^3)	Water (ml/m^3)
Control	250	750	1250	0	125
CEPET 2.5%	244	750	1250	2.79	122
CEPET 5%	237	750	1250	5.7	118.5
CEPET 7.5%	231	750	1250	8.25	115.5
CEPET 10%	225	750	1250	11.12	112.5
CEPET 20%	200	750	1250	22.26	100
CEPE 2.5	244	750	1250	1.96	122
CEPE 5%	237	750	1250	3.9	118.5
CEPE 7.5%	231	750	1250	5.86	115.5
CEPE 10%	225	750	1250	7.8	112.5
CEPE 20%	200	750	1250	15.6	100
CAPE 2.5%	250	750	1218	11.66	125
CAPE 5%	250	750	1187	23.31	125
CAPE 7.5%	250	750	1156	34.97	125
CAPE 10%	250	750	1125	46.6	125
CAPE 20%	250	750	1000	93	125
SAPE 2.5%	250	731	1250	7.13	125
SAPE 5%	250	713	1250	14.25	125
SAPE 7.5%	250	693	1250	21.38	125
SAPE 10%	250	675	1250	28.5	125
SAPE 20%	250	600	1250	57	125

Test procedures

All tests were conducted in the British University Laboratory except the thermal conductivity test, which was conducted in the Housing and Building National Research Center in Cairo.

1. All ingredients were measured and mixed in a concrete mixer, as shown in Fig. 2.
2. All components of each mix were mixed, in a rotary concrete mixer. Each mixture was cast into four cubes with a dimension of 10 × 10 × 10 cm, one cylindrical with a diameter of 10 cm and a height of 20 cm and one wooden mould with a dimension of 25 × 12 × 6 cm. With a tamping rod the concrete was compacted, then the surface was flattened and smoothed with a steel float as shown in Fig. 3.
3. The samples were left to dry for 24 h before demoulding and then were immersed into a curing water tank (Fig. 4).
4. After 7 days, a cube of each mixture was removed from the curing tank and left to dry before weighing and testing its compressive strength. The same procedure was conducted for the other three cubes of each mixture on the 28th day, an average was taken to determine the bulk density and the compressive strength of the composite.

Fig. 2 Materials preparations

Fig. 3 Concrete compaction

Fig. 4 Samples demoulding and curing

Test instruments

Compressive strength and indirect tensile strength

Compression strength was determined by using a load control testing machine, as illustrated in Fig. 5. For the compressive strength test, only one sample of each mix was measured on the 7th day; however, three specimens were tested on the 28th day and an average was taken. The indirect tensile strength was measured using split tension test for one sample of each mix on the 28th day.

Thermal conductivity

A laser comp heat flow meter fox instrument (Fig. 6), was used for the thermal conductivity test according to standard specification ASTM C-518–21. The sample with a known thickness x and area A is set between a hot and a cold plate for 24 h to determine the heat flow in order to measure the thermal conductivity.

Results and discussion

Dry bulk density

The results of the bulk density are illustrated in Fig. 7, which indicates a decrease in the density with the increase of plastic waste content. CAPE samples obtained the lowest densities, followed by SAPE, CEPE, and finally CEPET. The sample of CAPE with 20% replacement recorded a bulk density of 2097 kg/m^3, which is 11% lower than the control

Fig. 5 Compression test machine

Fig. 6 Laser heat flow meter

sample. The density of SAPE with 20% PE was reduced by 10%, the CEPE by 5.7% and the CEPET by 5.2%. The reason relies in the lower specific gravity of plastic compared to the other components. In addition, coarse aggregates share the highest ratio of weight

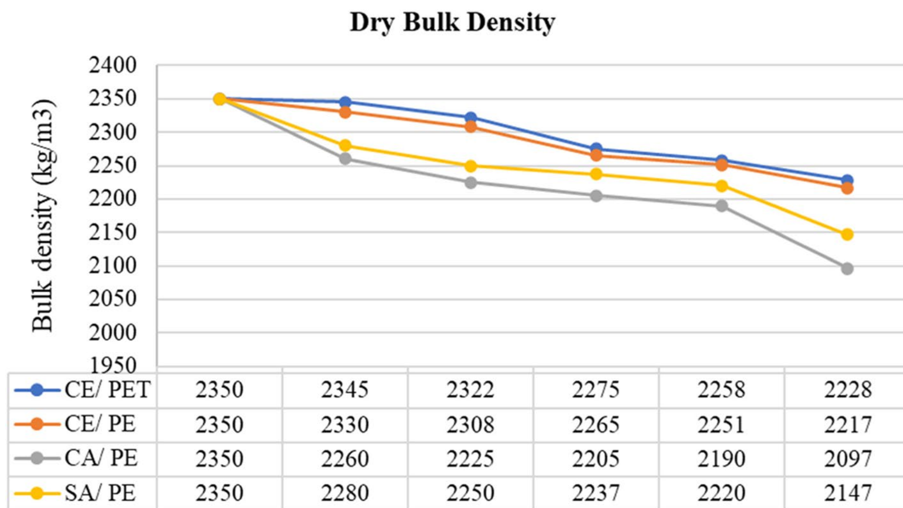

Fig. 7 Dry bulk density

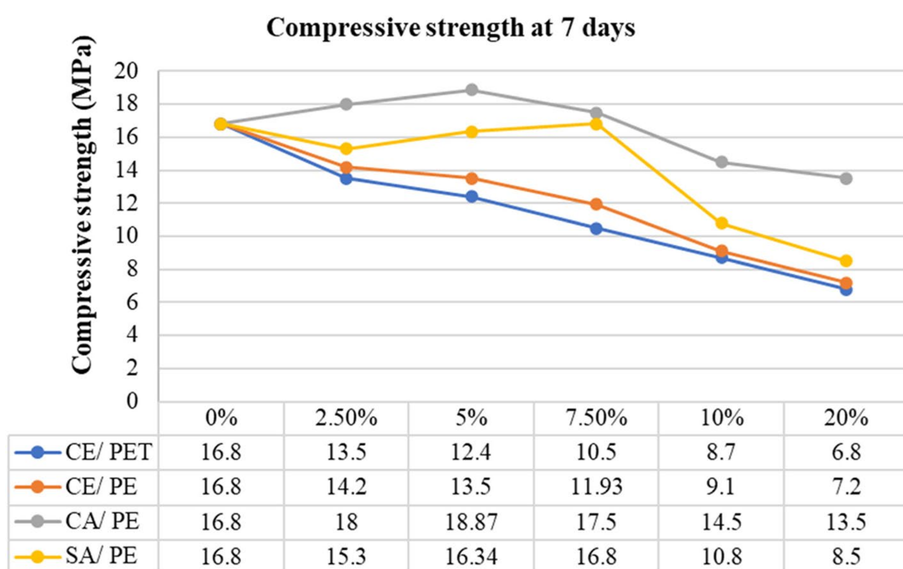

Fig. 8 Compressive strength at 7th day

reduction in relation to sand and cement; 20% replacement represents 11% of the total composite weight, while 20% of sand represents 6.7% and 20% of cement represents only 2%. Therefore, a higher reduction in weight occurs due to coarse aggregate substitution.

Compressive strength

The compressive strength results of all samples on the 7th day and the average of the three samples of each mixture on the 28th day are presented in Figs. 8 and 9. Upon comparing the four sets, it was found that the CAPE set showed the best results on the 7th and 28th day, while the CEPET set showed the least compressive strength. The results show an increasing trend for compressive strength with a limited replacement level for

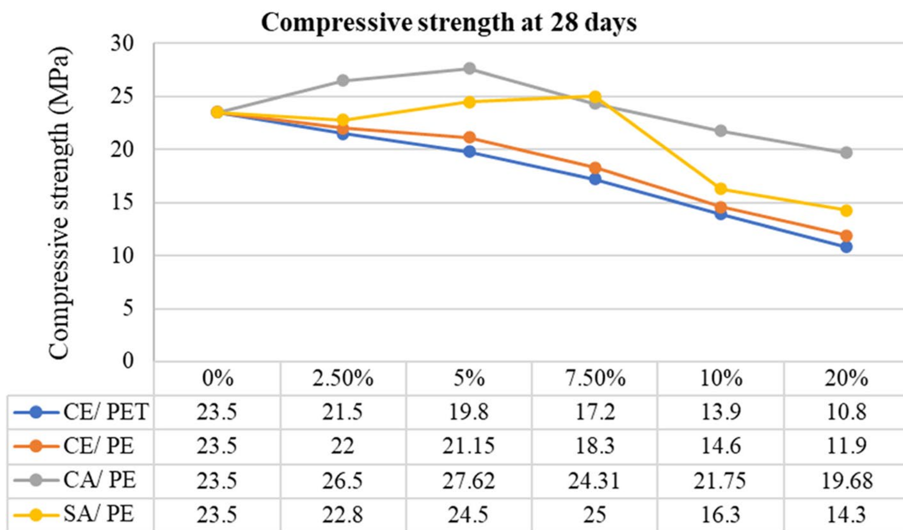

Fig. 9 Compressive strength at 28th day

SAPE and CAPE. The compressive strength increases gradually and reaches its peak at 5% replacement of coarse aggregates, recording 27.6 MPa on the 28th day which is 17% higher than the reference sample (23.5 MPa). The highest value for the SAPE samples was obtained with 7.5% replacement, recording 25 MPa which is 6% lower than the control. The reason for this increase may relate to the shape and size of PE that can be considered as microfibers that create bridges inside the composite giving it higher strength. In addition, replacing the coarse aggregates ($4.75 \geq \times \geq 9$ mm) with plastic particles (2 mm) provides better size distribution. However, the strength declines sharply for the SAPE for higher replacement ratios and declines gradually for the CAPE. Replacing cement with any of the two plastic types decreases the strength due to lowering the binding element. Manually recycled PET has lower strength than mechanically recycled HDPE which lowers the compressive strength of the CEPET than CEPE. All samples show a clear reduction with higher replacements level greater than 7.5%, as a result of the smooth surface of plastic which affects the adhesive strength between cement and plastic concrete's components. Besides, the hydrophobic nature of plastic hinders cement to obtain the required water for curing. All samples of CAPE satisfy the minimum strength required for structural concrete (> 17 MPa), while SAPE, CEPE, and CEPET with higher replacement (> 7.5%) do not fulfill structural loadbearing standard limits. However, they still meet non-loadbearing standards.

Figure 10 shows the failure of concrete samples containing PET and HDPE.

Indirect tensile strength

Figure 11 presents the results of the indirect tensile strength test, which indicate a slight increase for all samples till 5% substitution except for SAPE which exhibited a reduction in all its samples. CAPE tensile strength increased to 7.5% and obtained the highest value with 5% replacement (2.45 MPa) which is 16% higher than the control sample

Fig. 10 Compression failure for concrete samples with **a** PET and **b** HDPE

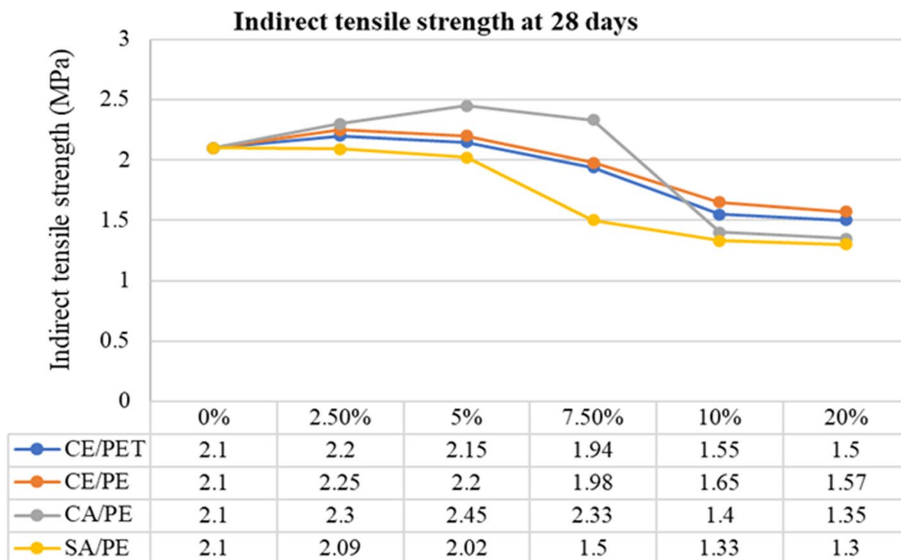

Fig. 11 Indirect tensile strength

Fig. 12 Tensile strength failure for samples **a** PET, **b** HDPE

(2.1 MPa). In general, adding a limited amount of plastic enhances the tensile strength of concrete.

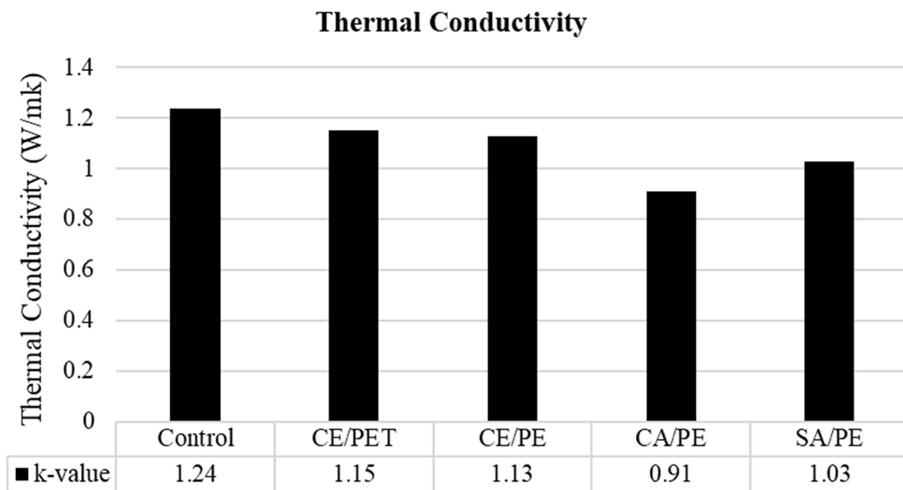

Fig. 13 Thermal conductivity with 20% replacement

Figure 12 shows the tensile strength failure of the samples with PET and PE.

Thermal conductivity

The results of thermal conductivity (*k* value) indicate a decrease for all samples containing 20% of plastic waste (Fig. 13). The factor that affected the thermal conductivity the most is the increase of air voids formation; plastics do not absorb water, which accumulates around the plastic particles creating cavities when water evaporates. The other factor is the low thermal conductivity of plastics (0.2–0.4 W/mk) which is lower than concrete components. CAPE has the lowest *k* value because it contained the highest amount of plastic in comparison to the other samples. Improving the thermal resistance of building materials helps to minimize the heat gain which lowers the energy consumption of buildings.

Upon comparing the results of all tests, it has been found that the mixture with 5% replacement of coarse aggregate (CAPE) showed the optimum results, as it has a highest compressive strength in comparison to other mixture, the highest indirect tensile strength and the lowest thermal conductivity and bulk density.

This study determines that incorporating limited amount of recycled plastic in cement brick is a sustainable method to create porous lightweight composites with improved thermal performance, which have a significant impact on the energy consumption and environment. However, the compressive strength declines with high substitution level due to the hydrophobic nature of plastics, as they are incapable of absorbing water which creates a porous composite. In addition, the smoothness of the plastic surface decreases the bond between the cement and the components. Though, chemical treatments can be applied to plastic surface by increasing the roughness of the particles and enhance the bonding properties.

The high porosity of the structure as well as the low weight of plastics reduces the density of the new composite.

Conclusions

This study explored the opportunity of optimizing plastic waste implementation in producing ecofriendly cement brick with high thermal resistance and proper compressive strength. The impact of its incorporation on the thermomechanical behavior of the developed composite. Various replacement ratios of PET and HDPE were integrated in the cement brick and tested in regard to compressive strength, indirect tensile strength, density, and thermal conductivity. The research revealed that the use of plastic waste in cement brick with limited amount is a promising sustainable method for plastic disposal. The main outcomes of this experiment, carried out here, are the enhancement of the compressive strength and tensile strength with low substitution level (up to 7.5%). HDPE showed better mechanical performance than PET. Replacing coarse aggregates with HDPE has shown the best results, followed by fine aggregates.

Partial replacement of concrete components, especially aggregates, with plastics reduced the thermal conductivity which increases the thermal resistance of the composite. This may improve the thermal performance of the building which in turn reduces the energy consumption.

This study introduced a promising application for plastic waste in the construction industry that has several environmental benefits. However, further studies should be conducted to investigate the influence of implementing plastic waste on other types of bricks such as hollow blocks. Besides, further properties should be evaluated such as behavior under fire.

Abbreviations

CO_2	Carbon dioxide
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PE	Polyethylene
MDPE	Medium-density polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane

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Authors' contributions
All four authors collaborated in the research. YE was responsible for the research itself including the literature review and empirical work. Authors KD, MI, and IE were responsible for revising, guiding, and advising throughout the research process. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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