Future Cities and Environment

Alternative to PCM: Recycling Plastic Waste for Affordable Thermal Insulation in Building Envelopes: An Experimental Analysis

TECHNICAL ARTICLE

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ABSTRACT

In the building sector, the low thermal conductivity of plastics makes them a viable option to increase the thermal resistance of construction materials. Incorporating recycled plastic in concrete panels can not only enhance the sustainability and circular economy of the buildings but also provide an affordable alternative to phase change materials (PCM) for thermal insulation. To evaluate the potential of waste plastic as a thermal insulation material, nine samples with varying thicknesses (1 mm, 2 mm, and 3 mm) and portions of shredded waste plastic were tested to determine their thermal and physical properties. The properties under investigation, such as density, water absorption, porosity, compressiveness, and thermal conductivity, have been tested. Upon completion of the physical and thermal assessments, it was determined that the PL.SH.layer.10% and PL.SH.layer.20% insulation samples exhibited higher thermal effective alternatives compared to the PCM samples. Additionally, the latter two options are deemed to be more cost-effective. Only the samples with with a melted plastic layer of 1 or 2 mm failed to boost their thermal efficiency in terms of heat insulation until the melted plastic was increased by more than 3 mm. The research emphasizes the capacity of recycled plastic to act as a cost-efficient substitute for thermal insulation. This substitution to boost the insulation of building envelopes, preserve energy, and enhance thermal comfort, boost increase the insulation of building envelopes, preserve maintain energy, and enhance thermal comfort, especially in hot developing countries. The results may provide valuable is for future investigations and advancements in sustainable construction materials, facilitating the shift towards a circular economic model.

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1. INTRODUCTION

In 2018, the building envelope accounted for 36% of final energy usage and 39% of carbon dioxide(CO_2)emissions. By 2060, the rapidly increasing rate of urbanisation is predicted to raise CO_2 emissions from the construction industry by 10%, (IEA international Energy Agency,2019). The concrete business is primarily focused on research on sustainable building components that are alternative and on minimising greenhouse gas emissions and other associated impacts from infrastructure development projects (Mistri et al., 2021). Those numbers present that the construction sector relies heavily on building envelopes to control heat transfer within structures. The building envelope comprises the building's exterior walls, roof, and floor. They prevent heat from entering during the summer and departing during the winter by acting as a barrier between the interior and exterior of the building (Kumar et al., 2023; Udawattha and Halwatura, 2018).

Thermal insulation provides a choice that could assist in reducing the amount of energy used, especially in buildings, by limiting the amount of heat that comes in from the outside. Insulation works by slowing down the movement of heat through a material. For heat slowing, several materials that could be used as insulation materials, such as fiberglass, cellulose, and spray foam. Phase change materials (PCMs) have been suggested as a viable substitute for conventional insulation materials in the field of insulation. PCMs are capable of both storing and releasing thermal energy. Consequently, they can absorb heat in warm environments and discharge it in cold ones. Given this characteristic, PCMs are an efficient means of controlling the temperature within a structure. Nevertheless, the considerable cost of PCMs has hindered their extensive implementation. Consequently, there is a demand for alternative phase change materials (PCMs) that are more cost-effective while still providing the beneficial properties of thermal insulation. Each of these has pros and cons, like being expensive, adding an extra layer to a building, being complicated, needing special care during and after installation, needing skilled labor, having a high thermal resistance, etc., but using waste materials as additives to traditional materials could be a cheaper way to insulate (Kalbasi and Afrand, 2022; Sabapathy and Gedupudi, 2022). So, instead of making new materials, additives are already available that can make them better at insulating heat. Adding waste materials as heat insulation made from salvaged trash is a big step toward sustainability and circularity at the same time (Ahmad et al., 2022).

Rapid rises in the global generation of solid waste, particularly plastic waste, are caused by growing urbanization, increasing populations, and shifting consumption patterns (Abbood and Al Slik, 2022; Meijer et al., 2021; Tayeh et al., 2021). Each year, 330 million metric tonnes of plastic are produced worldwide; around 9% are recycled, 12% are burned, and 79% end up in landfills (Abbood and Al Slik 2022). The drawback is that plastic is not biodegradable and remains in the environment for a long time. Consequently, plastic waste is accumulating at an alarming rate worldwide. Locally, Egypt has a persistent issue with the disposal of plastic garbage. Egypt produced over half of the improperly handled garbage among the Mediterranean nations in 2016. With 12.6% of plastic garbage generated, it was ranked fourth (Abbood and Al Slik, 2022; Morgado Simões and Stanicek, 2023). The local ecosystem, economics, and public health are constantly at risk due to the haphazard dumping of plastic garbage (Meijer et al., 2021). Additionally, that small sector recycles plastic trash as part of the circular economy strategy. According to previous data, solid waste disposal in Egypt is a persistent problem that causes several environmental and economic issues.

Several scholars endorse the feasibility of incorporating recycling and reusing plastic waste within the construction sector (Adnan and Dawood, 2021; Awoyera and Adesina, 2020; Datta et al., 2022). They explore several possibilities for utilizing plastic waste as a cost-effective and ecologically sustainable substitute for traditional construction materials. Examples include employing plastic waste as a substitute for aggregates in concrete production or as a binding agent. Accordingly, an industrial strategy for the Sustainable Development Goals (SDGs) involves using sustainable construction practices. This approach strives to minimize waste generation, enhance resource efficiency, and promote environmental protection.

2. LITERATURE REVIEW

Concrete is a combined material composed of a diverse range of particles that exhibit various types, shapes, dimensions, and characteristics. The components consist of binders, which serve the purpose of maintaining the cohesion of particles, in conjunction with fine aggregates. The impact resistance, ductility, energy absorption, and thermal conductivity of concrete are significantly influenced by these components. The enhancement of a building's thermal insulation performance is a focused objective due to the extensive utilization of this material in construction, with particular attention given to its thermal conductivity (TC). The overall thermal conductivity of concrete, being a composite material, is primarily influenced by the characteristics of its constituent elements. A multitude of scholarly articles have been written with the aim of examining the enhancement in thermal performance achieved via the use of various particles into the concrete mixture.

The TC of concrete may be effectively decreased by using materials with low thermal conductivity, such as fly ash, bamboo, plastic, and foam. Moreover, they may be used for the purpose of waste recycling, making them economically advantageous resources. A multitude of research investigations have been undertaken with the aim of ascertaining methods to improve the thermal properties of concrete composites. Hamed et al., 2016, suggested a novel kind of concrete known as wood bio-concrete. This innovative concrete formulation included the use of wood shaving waste as aggregates, in contrast to the conventional use of mineral aggregates such as sand and gravel. The use of bio-based aggregates and cementitious components, as discussed by (Amziane, 2016), is a viable approach for the development of lightweight concrete that exhibits commendable thermal and acoustical properties. Bamboo bio-concrete has emerged as a viable option for mitigating the environmental impact of buildings in Brazil, as shown in a study conducted by (Rosse Caldas et al., 2020). This alternative is characterized by a decreased carbon footprint and enhanced thermal performance, making it a promising solution for addressing the challenges posed by climate change. (Mohammadhosseini et al., 2018).

The primary thermal contribution to energy savings documented in the literature for PCMs is a reduction in heating loads and the maintenance of year-round thermal comfort. The integration of PCM into geopolymer concrete and the addition of pure PCM to multilayer walls resulted in a notable improvement in thermal performance. To evaluate the thermal performance of adding a layer of PCM to concrete, a single-family home in the climatic conditions of Oslo (Norway) was employed in this research (Cao et al., 2019). As an extra layer in the multi-layer walls, the phase change material RT21 (PCM21), has been tested in Rubitherm, Germany, with a melting point of around 21 degrees Celsius and a high latent heat of 148 J/g was used to increase the thermal performance (Cao et al., 2019). Considering the thermal performance, which is made up of a thick layer of phase change material (PCM) and a thin layer of insulation, was put into place, energy use dropped by up to 28% per year. The study revealed that the proximity of PCM to the external environment positively correlated with its effectiveness. The multilayer walls demonstrated superior performance throughout the summer season, resulting in a significant decrease of up to 32% in energy consumption within the lower range of the specified human comfort zones (18°C). Testing PCM under hot conditions has been reported in a study (Al-Yasiri and Szabó, 2023) conducted in Al Amarah city, Iraq, with two cubical boxes of 1 m^3. Paraffin wax (44°C mT) has been tested on walls and roofs, and it was found that the maximum indoor temperature was reduced by 2.18°C and the maximum cooling load reduction was 20.9% at a 1 cm PCM thickness. And for the economic achievement, the maximum enhancement of 1.35 USD/day was attained at 1 cm PCM thickness combined with walls. In Australia (Melbourne), BioPCM with (18–32°C mT) has been tested on walls and roofs, found that PCM with 25°C melting temperature and 2.5 cm thickness was optimal (Jayalath et al., 2016; Kumar et al., 2023). The main conclusions for this study where the discomfort hours were reduced by 82%. Additionally, reduction of energy use, peak cooling demand, CO_2 emissions, and energy cost by about 40%, 65%, 64%, and 35%, respectively. In Morocco (Benguerir city) (Salihi et al., 2022), after testing various types of PCM, found that PCM RT-28 HC is optimal for the location under study. The highest annual energy saving was 13.77% were attained at 15 mm thickness of PCM RT-28 HC.

Concerning the potential of PCMs to increase heating energy savings when included in the building envelope, several problems are identified. While several investigations have shown that Paraffin Wax (PW) has excellent high-temperature behaviour, the comparatively high melting point of PW indicates that only PW can achieve thermal improvement because the sample temperature was lower than PW's melting point. This is one of the issues associated with the use of PCM in building materials (Methode Kalombe et al., 2023).

In Egypt (Cairo and Aswan), Abd El-Raheim et al. (Abd El-Raheim et al., 2022) used specialised building modelling software to evaluate six phase transition materials with melting temperatures between 21 and 31°C have been evaluated and verified against both the current interior experiment and an outdoor experiment that has been published. The PCM with 29°C melting temperature and 2 cm thickness performed the best. When the phase change material is incorporated into a wall with a thermal resistance of 0.5 m2 K/W.It results in a reduction of 373 exceedance hours compared to the thermal insulation. As the thermal resistance of the building envelope increases from 0.3 to 1.02 m2 K/W, there is a consistent decrease in the efficacy of the PCM. Moreover, there is a notable decrease in the number of exceedance hours, with a decline ranging from 52.8% to 9.24%, as the climate transitions from a hot-dry state to an extremely hot-dry state. The integration of a 1 cm layer of phase change material and a 3 cm thermal insulation layer yields significant results. Specifically, this combination (Kocher and Kamil. M. Yousif, 2022) adds to a reduction of exceedance hours by 65.5%, a decrease in air conditioning energy consumption by 27.2%, and a shortened payback period by 54%. It is noticed that number of numerical studies are much higher than the experimental studies mainly due to a variety of simulation tools and complexity of incorporation techniques, especially the active ones (Al-Yasiri and Szabó, 2021).

According to scholarly literature review, adding waste plastic to concrete may improve thermal performance. (Kocher and Kamil. M. Yousif, 2022) examine and compared the mechanical, acoustical, and thermal characteristics of sustainable concrete that incorporates plastic waste to conventional concrete, or normal concrete. The range of plastic waste percentages employed in this investigation is 0–25%. The overall outcomes demonstrate that the compressive strength decreased by approximately 40–51% as a result. Additionally, the concrete with plastic's thermal conductivity was reduced by roughly 50%. On the other hand, the ultrasonic pulse velocity and sound intensity travelling through concrete with plastic were found to decrease as the plastic content of concrete increased.

Compare the results after adding waste plastic in different cases to the results after adding phase change materials (PCM) in the same concrete mixture. Instead of PCM, plastic waste could be used for thermally enhanced concrete. Reusing plastic waste in the building and construction industry may improve material thermal efficiency on a budget. As mentioned, this strategy greatly affects how these countries manage plastic waste and housing. This method is inexpensive, eco-friendly, and requires little equipment. Instead, a waste plastic recycling system for building materials could improve thermal properties and the environment.

For the environmental impacts, the entire cement production process is accountable for the emission of several polluting gases, such as CO_2, methane, and nitrous oxide, as well as other pollutants, such as particulate particles (Danish et al., 2021). The building envelope comprises the building's exterior walls, roof, and floor for exposing the sun heat and using concrete within buildings. The implementation of measures to decrease the quantity of plastic waste generated would lead to a reduction in the release of dangerous chemicals and emission of carbon dioxide (CO_2) emissions arising from the incineration of plastic garbage (Journal et al., n.d.). Consequently, this would contribute to a decrease in air pollution, so safeguarding the well-being of humans, animals, plants, and the whole ecosystem.

Therefore, this study examines the economic viability of using plastic waste as insulation material within the context of the circular economy. Aiming to reduce the expenses associated with landfilling plastic waste and the energy consumption involved in the incineration procedure. The aim is to decrease the amount of energy used in the production of conventional construction materials and the energy expended during the operation of buildings by using recycled plastic-based materials with effective thermal insulation qualities instead of high-costed materials.

This research investigated the incorporation of waste plastic into normal concrete in diverse proportions and types. Thermophysical qualities were evaluated experimentally, and a correlation matrix was constructed to illustrate the compounds' efficacy on both the physical and thermal levels. Finally, use equations to compute the expected energy savings for cooling and heating purposes during the summer and winter seasons.

3. MATERIALS AND METHODS

3.1. MATERIALS

Concrete panels for the building envelope were made by Ordinary Portland Cement (OPC) CEM 11 (A-P 42.5 N). For aggregates, Grade II with 12.5 mm coarse was mixed with mortar mixture. Table 2 provides descriptions of the characteristics of course and fine aggregate. Based on (ASTM C33/C33M – 18, 2018), the values for aggregate properties listed in Table 1 are based. Regarding to the plastic bottles waste, recycled Polyethylene Terephthalate (PET), crushed to reuse them as a thermal insulation. The process of turning the crushed PET into the shreds of plastic seen in Figure 1. Two phases of plastic waste have been used in this paper, melting and shredded plastic. Accordingly, the scenarios have been designed as shown in Figure 3.

3.2. EXPERIMENTAL METHOD

A concrete mixture was created using cement, sand, and aggregates in a 1:2:3 ratio and mixed with a 0.51

Figure 1 Images of the shredded waste plastic before and after melting to convert to solid layer or use it as shredded layer.

water-to-cement ratio. To eliminate the air gaps, the produced material was put into the moulds in two layers and crushed in between as shown in Figure 2. The concrete specimens were prepared according to BS 1881–125 2013. The specimens as presented in Figure 3 and Table 2, were maintained at room temperature

AGGREGATE	GRADE II	SAND
Bulk SSD SG	2.633	2.625
Apparent SG	2.721	2.630
Bulk dry SG	2.582	2.623
Bulk Density-Dry (Kg/m)	1234	1238
Absorption %	2	0.1
Moisture Content %	2.1	5.2
% Voids	48.6	52.7

Table 1 Coarse and fine aggregate according to (ASTM C150/C150M – 20, 2020).

SAMPLE NAME	SAMPLE DESCRIPTION
Con Ref.	Plain concrete sample
PL.MEL.1 mm	1 mm melted layer of plastic
PL.MEL.2 mm	2 mm melted layer of plastic
PL.MEL.3 mm	3 mm melted layer of plastic
PL.SH.Layer.10%	10% shredded plastic as a middle layer
PL.SH.Layer.20%	20% shredded plastic as a middle layer
PL.SH.Layer.30%	30% shredded plastic as a middle layer
PL.SH.Mix.10%	10% shredded plastic mixed with cement
PL.SH.Mix.20%	20% shredded plastic mixed with cement
PL.SH.Mix.30%	30% shredded plastic mixed with cement
PCM 10%	10 MM PCM of 29°C melting temperature (recommended in previous study in Egypt)
PCM.20%	20 MM PCM of 29°C melting temperature (recommended in previous study in Egypt).

Table 2 Various concrete samples with waste plastic.

Figure 2 Images of the shredded waste plastic and combing them with concrete to have concrete samples with plastic.

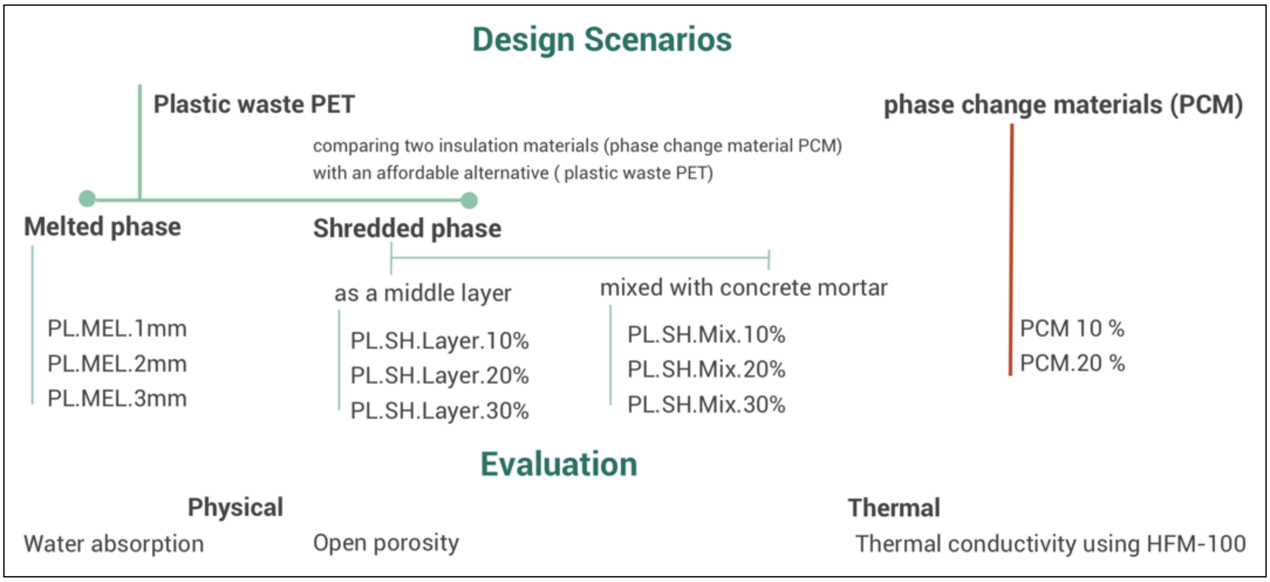

Figure 3 Planning the experimental scenarios.

for 24 hours before being immersed in clean water for 28 days of curing. To assess the effect of PET on the behaviour of concrete physically and thermally, three substitution levels in three different plastic phases (melted, crushed, mixed) were applied and compered with with one reference concrete mix (Ref.CM) without plastic. With the following replacement ratios, concrete mixtures were prepared by mass: 10%, 20% and 30%. Table 3 shows examples made from each plastic condition: shredded plastic in the middle or mixed with the concrete mixture, or melted to form a solid layer in 1 mm, 2 mm, and 3 mm.

3.3. EXPERIMENTAL TESTS

3.3.1 Physical properties

The experimental determination of three physical properties, including bulk density, water absorption, and open porosity, has been conducted as shown in Table 4. To establish the bulk density of the samples, it was essential to determine the dry weight of the specimens. In order to do this, each specimen was weighed on an electronic scale with a 0.01 gm resolution. As indicated in Table 2, the bulk density was calculated using the specimen's dry weight (W) and volume (V). After determining water absorption by immersing the dry specimens in water at 25°C for 24 hours, their saturated weights were measured until they reached a consistent value. Then, water absorption was determined using the specimen's dry weight (Wdry) and volume (V), the bulk density was determined as follows in Eq (1):

$$\text{Absorption of Water} = (W_{sat}\_\ W_{dry}) / (W_{dry})$$

The open porosity of material may be determined by calculating the ratio of the volume of surface-attached open pores to the volume of the specimen (Mawra et al. 2023a; Hamed et al. 2016). The open porosity may alternatively be computed as the ratio of the volume

MIX TYPE	CEMENT	SAND	PLASTIC	WATER (w/c = 0.51)	PCM
Con Ref.	350	619	–	178	–
PL.MEL.1 mm	350	619		178	–
PL.MEL.2 mm	350	619		178	–
PL.MEL.3 mm	350	619		178	–
PL.SH.Layer.10%	350	619	35	178	–
PL.SH.Layer.20%	350	619	70	178	–
PL.SH.Layer.30%	350	619	105	178	–
PL.SH.Mix.10%	350	619	35	178	–
PL.SH.Mix.20%	350	619	70	178	–
PL.SH.Mix.30%	350	619	105	178	–
PCM 10%	350	619	–	178	35
PCM.20%	350	619	–	178	70

Table 3 Concrete mixture composition.

	BULK DENSITY (KG/M³)	OPEN POROSITY %	WATER ABSORPTION
Plain concrete	2036.7	11.52	5.66
PL.MEL.1 mm	1667.1	13.29	9.72
PL.MEL.2 mm	1733.0	10.76	7.51
PL.MEL.3 mm	1932.9	14.71	7.61
PL.SH.Layer.10%	1802.1	16.21	8.99
PL.SH.Layer.20%	1655.9	17.86	10.78
PL.SH.Layer.30%	1979.0	22.22	11.23
PL.SH.Mix.10%	1929.7	17.04	8.83
PL.SH.Mix.20%	1891.9	18.53	9.79
PL.SH.Mix.30%	1986	19.48	10.62
PCM 10%	2021	11.92	5.79
PCM 20%	1997	12.02	5.97

Table 4 Relationship of water absorption with bulk density and porosity.

of water absorbed, provided by the difference between the saturated and dry weight of a specimen, to the total volume of the specimen using the following equation, where w is the density of water (1 g/cm^3) at 20°C.

3.3.1.1 Bulk density

The density of concrete plays a crucial role in construction since it directly affects its durability, porosity, and permeability (Kearsley et al., 2002). The density of concrete varies based on the relative amounts of its constituent elements. Hence, the decrease in density of the concrete mixes can be attributed to the integration of lightweight waste aggregates in place of the dense natural aggregates (cement, sand and gravel), as well as the capture of air voids on the surfaces of the waste aggregates during the mixing process. This leads to an increase in the number of air voids, resulting in a reduction in concrete density. The lowered density of the concrete mixes was notably influenced by the percentage of the recycled waste aggregates. As the amount of recycled waste aggregates increases, the density decreases. The decrease in the strength of the concrete may also be attributed to the makeup of the pores, which affects the drying process (Robalo et al., 2021). This research aims to investigate the extent to which the addition of waste plastic may improve the heat resistance of concrete, while still meeting the established standards for both the construction material and non-loaded concrete.

ASTM C90 categorises loading-bearing concrete units into three weight classifications: light weight (1680 kg/m^3), medium weight (1680–2000 kg/m^3), and normal weight (2000 kg/m^3 or more). The studied densities may be classified as typical concrete due to their dry densities above 2000 kg/m^3 (Mawra et al., 2023a). Figure 4 shows that samples with plastic waste cause a drop in bulk density, as PL.SH.20 and PL.SH.30 cause the least drop, at 1955.9 and 1597 kg/m^3, respectively. Almost all the samples were classified as medium weight except PL.SH. Layer. 30% has a low-density of 1597 kg/m^3 and belongs to the lightweight category. On the other side, PL.SH. Mix.10 and 20% have density values of 1929.7 and 1986 kg/m^3, which are near the recommended normal values of 2000 kg/m^3.

3.3.1.2 Water absorption

Water absorption represents the amount or air gap inside each specimen in comparison with their respective. In general, the water absorption of all the samples with plastic waste exhibited an increase ranging from 7.6 to 9.7, while the plain basic concrete sample shows absorption with 5.7. However, it shows that most increasing rate is for samples with plastic waste in shredded condition, ranging from 9 to 11.2, more than plastic waste in melted condition (PL.MEL.10, PL.MEL.20, PL.MEL.30).

3.3.1.3 Open porosity

Porosity refers to the ability of each specimen to absorb water internally in relation to their various capacities (Mawra et al. 2023a; Hamed et al. 2016). Overall, the water absorption of all samples, including plastic waste, has shown an increase ranging from 13.3 to 22.2, while the simple basic concrete sample displayed an absorption rate of 11.5. It has been shown that the rate of increase is higher for samples containing plastic waste in a shredded state compared to those containing plastic waste in a melted state (PL. MEL10, PL. MEL20, PL. MEL30).

The addition of another ingredients to concrete mixture leads to changes in their structural composition. Those materials are porous constructions that generate empty spaces. The existence of voids leads to a reduction in densities and an increase in the porosity of the material

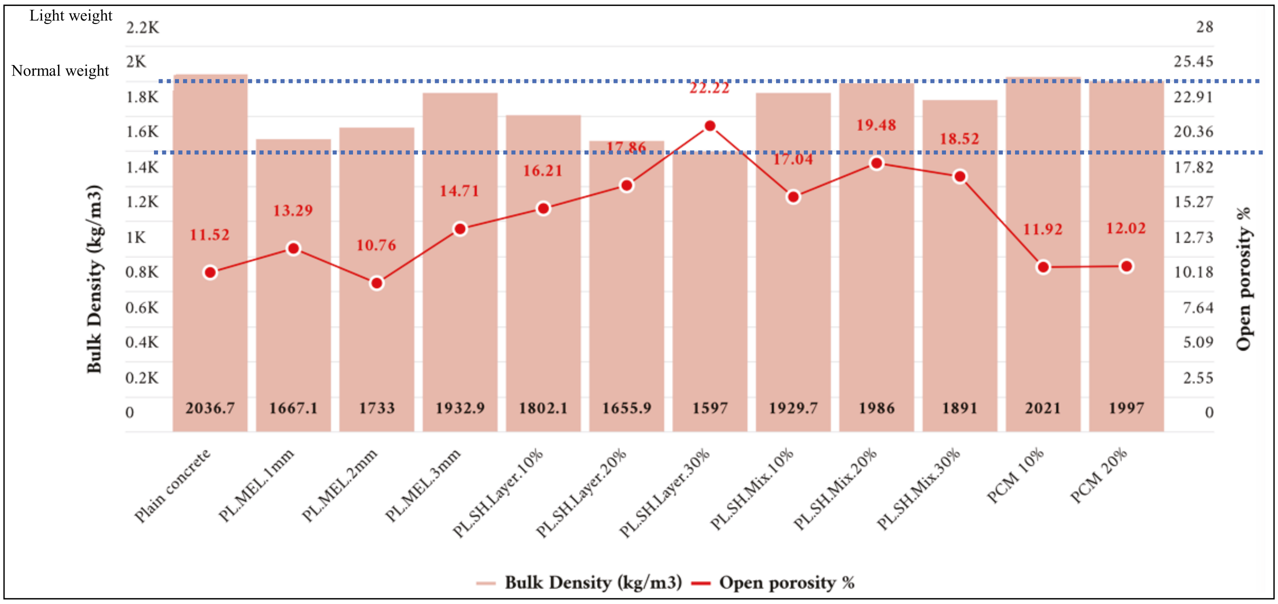

Figure 4 Relationship of bulk density with porosity.

(Mawra et al., 2023b). In general, the findings align with prior studies that have established a positive correlation between porosity and water absorption, while seeing an inverse relationship between porosity and bulk density. The alteration in physical characteristics is influenced by the varying diameters of waste plastic and its hue, whether melted or shredded as a layer in middle or mixed with a mortar mixture, which determines their interfacial bonding with the material mixture and the surface area for the air gap. The correlation between the physical characteristics of plastic waste adds and concrete mortar is shown in Table 4 and Figure 5. After 28 days of curing, the water absorption rate and porosity of the concrete mixture exhibit a strong linear correlation, as depicted in Figure 6.

3.3.1.4 Compressive strength breaks

To assess the effect of the waste aggregates on the strength of the concrete, cubes with dimensions of 10*10*10 cm have been prepared and tested after 14- and 28-days using compression test equipment with a maximum capacity of 3000 KN, following the guidelines of BS EN 12390-3. Concrete reaches its peak strength of around 90–99% after being cured over a period of 14 days.

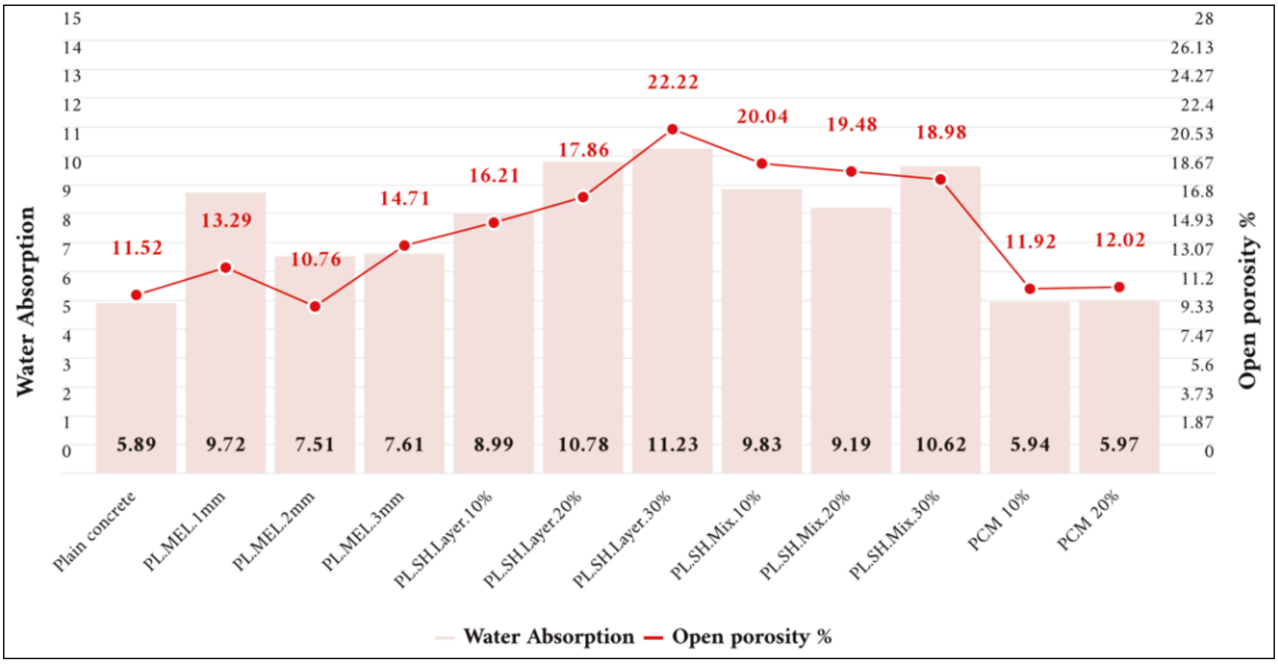

Figure 5 Relationship of water absorption with porosity.

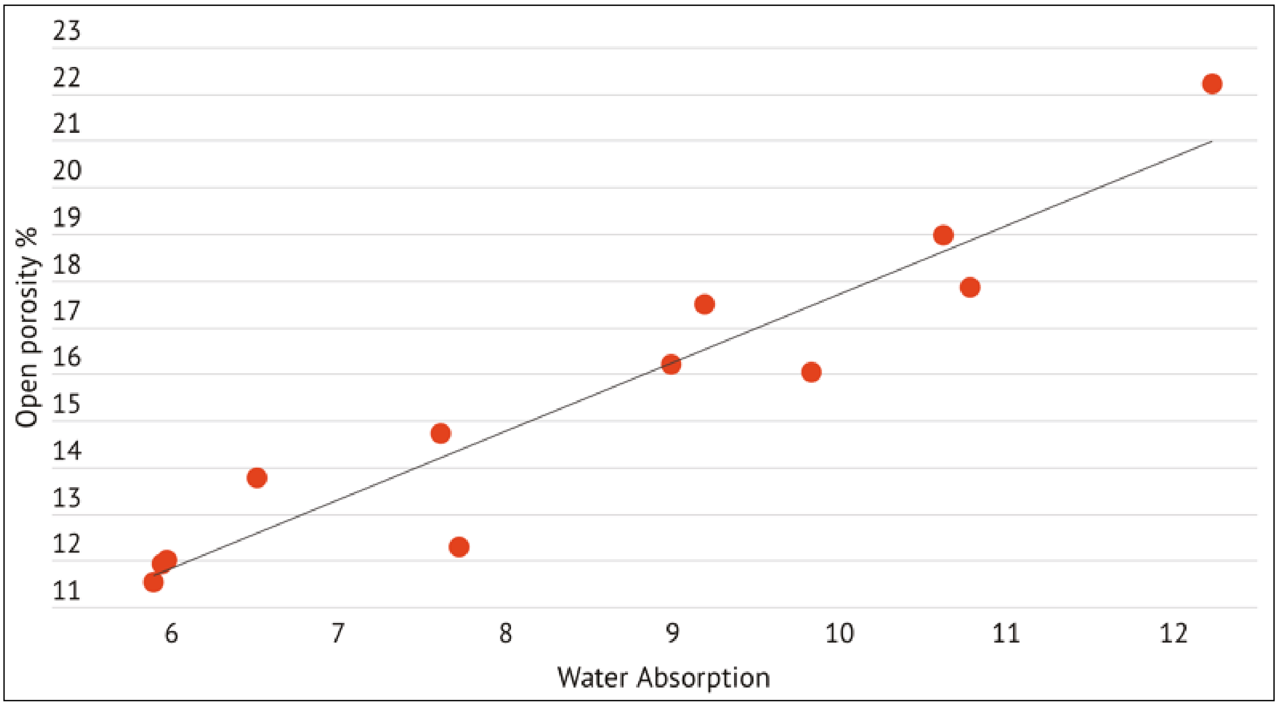

Figure 6 The correlation between the porosity of concrete and its water absorbability.

As shown in Figure 7, the samples with shredded plastic mix (PL.SH.Mix 10 and 20) exhibited strength resistance better than samples with melted plastic or plastic waste as a layer in the middle of the concrete panel. The 28-day period exhibits a delayed increase in compressive strength compared to the early age period. The diminished durability seen at a later stage (28 days) may be related to the low density of recycled waste particles and the reduction in mass of the solidified concrete specimen throughout the hydration process. Therefore, a decrease in density had an impact on the increase in strength.

4. RESULTS AND DISCUSSION

4.1. THERMAL PROPERTIES

The Heat Flow Meter (HFM-100) was used to measure the test samples' thermal conductivity and thermal resistance with an accuracy of ±1 to 2%. The results were then checked against standards such as ASTM C518, C1784, ISO 8301, JIS A1412, EN 12667, and EN 12664. Those measurements are critical in defining energy efficiency and the enhancement of materials' thermal performance. HFM sensors are thermopile sensors with equally spaced thermocouple connections. Each thermocouple junction creates a voltage proportionate to the temperature differential between its hot and cold junctions. Each HFM testing plate has a flux sensor with three surface thermocouples for heat flux measurements. Then, the heat flux sensor is included in each plate and is utilized to measure the heat flux (Q/A) created by the temperature differential (T) between the top and bottom plates at regular intervals until steady-state heat flux is recorded. Fourier's Law is then used to compute thermal conductivity (TC) and thermal resistance (R) based on the composite heat flow.

4.1.1 Thermal conductivity

For all specimens, TC was measured in two temperature ranges (10–30°C and 30–50°C) by the Heat Flow Meter (HFM-100) instrument, as shown in Figure 8 and Table 5.

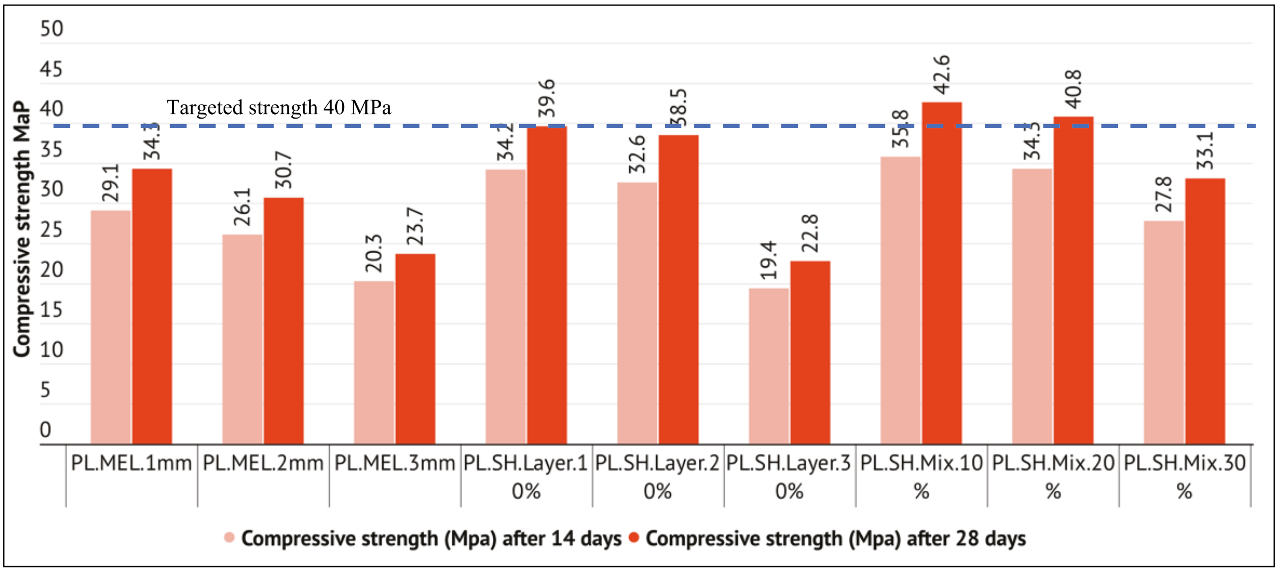

Figure 7 Compressive strength and load results.

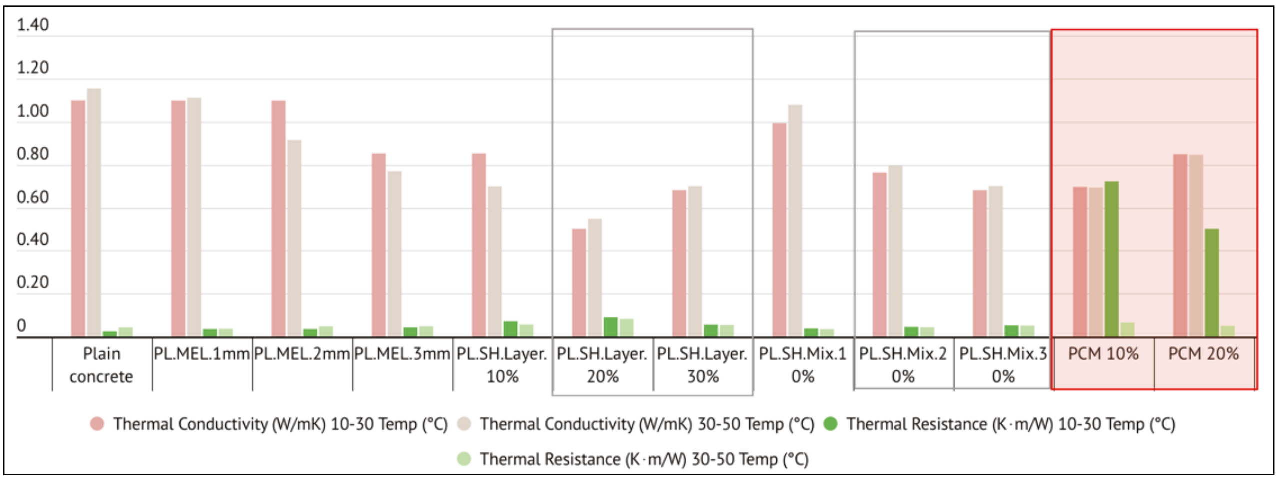

Figure 8 Thermal conductivity in two temperature range (10–30 C, 30–50 C).

SAMPLE	THERMAL CONDUCTIVITY (W/mK) 10–30 Temp (°C)	THERMAL CONDUCTIVITY (W/mK) 30–50 TEMP (°C)	THERMAL RESISTANCE (K·m/W)	THERMAL RESISTANCE (K·m/W)
			10–30 Temp (°C)	30–50 Temp (°C)
Plain concrete	1.1002	1.1558	0.0245	0.0429
PL.MEL.1 mm	1.0995	1.1130	0.0352	0.0360
PL.MEL.2 mm	1.0995	0.9154	0.0352	0.0479
PL.MEL.3 mm	0.8532	0.7699	0.0433	0.0482
PL.SH.Layer.10%	0.8532	0.7001	0.0716	0.0563
PL.SH.Layer.20%	0.5020	0.5490	0.0903	0.0825
PL.SH.Layer.30%	0.6823	0.7010	0.0559	0.0544
PL.SH.Mix.10%	0.9941	1.0793	0.0378	0.0348
PL.SH.Mix.20%	0.7640	0.7958	0.0455	0.0437
PL.SH.Mix.30%	0.6821	0.7013	0.0528	0.0513
PCM 10%	0.6972	0.6942	0.723	0.0657
PCM 20%	0.8493	0.8474	0.502	0.0504

Table 5 Thermal conductivity and thermal resistance measured at each sample in two temperature range.

The first three specimens with a melted plastic layer (PLMEL.1 mm, PLMEL.2 mm, and PLMEL.3 mm) gave a slight thermal enhancement with PLMEL.30 that reached 0.85 in the range of 10–30°C and 0.77 in the range of 30–50°C as shown in Figure 8, compared to the plain concrete. The other three specimens with shredded plastic (PL.SH.layer.10%, PL.SH.layer.20%, and PL.SH.layer.30%) have the best improvement, with 0.85, 0.85 and 0.50 in the range of 10–30°C and 0.70, 0.55 and 0.70 in the range of temperature 30–50°C. However, it was noticed that sample with mixed shredded plastic with a percentage of 10% (PL.SH.Mix.10%) has achieved a slight reduction in thermal conductivity, while sample with percentage 20% (PL.SH.Mix.20%) has achieved better results. By comparing these results with the PCM samples, PL.SH.layer.10%, PL.SH.layer.20% and PL.SH.layer.30% have achieved results more than the PCM samples values. And for the melted plastic, PLMEL.3 mm has a thermal performance of 0.85 in range of 10–30°C and 0.77 in range of temperature 30–50°C which is close to the PCM thermal performance.

The structures of the materials change as PW is added to them. Lower densities and greater porosity of the material are caused by the existence of voids (Kumar et al., 2023). Overall, the findings are in line with prior studies that have shown that porosity is directly correlated with water absorption and inversely correlated with bulk density.

4.1.2 Energy performance and economic evaluation

Thermal resistance, or thermal resistance, refers to the ability of materials to resist heat flow and is used to compare the insulation qualities of various materials. Theoretically, a higher R-value signifies more insulation capacity, which is calculated by dividing the heat transfer rate by the temperature difference across the structure. Therefore, enhancing the thermal conductivity will present better thermal performance which will reflect accordingly to the energy consumption (Telicko and Jakovics, 2023).

In addition to improving the dependability of interior climate forecasts inside a structure, it is suggested that temperature swings and variations in the TC be taken into account.

For indoor Ta 25°C, the energy savings for cooling during summer days and heating during winter nights were computed for the study's senarios. Due to this, various equations were utilised in the study.

To determine the required energy, use equations (1) through (5).

$$Q(KJ) = m \times Cp \times (T\ average\ room\ temp. - T25) \quad (1)$$

$$m = r \times V \quad (2)$$

The variables are as follows: V represents the volume of the test room (0.7 m^3), Cp signifies the specific heat of dry air (1.005 J/g K), T average room temperature signifies the mean temperature, and T25 indicates the required cool indoor temperature.

$$P\ (Watt) = Q\ (KJ) \times 1000\ K\ /\ Time\ (second). \quad (3)$$

where P is the power needed to cool or heat indoor Ta to 25°C.

$$P(Kw/h) = Pwatt\ 3.6 \quad (4)$$

$$P\ (Ac)\ (KW/h) = P\ (KW/h)\ 4\ C.O.P. \quad (5)$$

where P (Ac) represents the required power for the air conditioner and C.O.P. denotes the intended coefficient of the air conditioner, which is eq.5.

For estimating the energy consumption and thermal performance, the energy needed for heating and cooling to reach the thermal comfort for all the study scenarios for concrete specimens mixed with plastic waste in the summer and winter, respectively. These results will demonstrate the effects of adding plastic trash as a thermal resistant material and the variations in each scenario proposed by the study byapplying the measured TC for each scenario in the previously stated equations.

In comparison to plain concrete, the maximum indoor reduction throughout the day in the summer for various scenarios is close to 3°C to 13°C. As mentioned in Table 5 and Figure 7, the thermal conductivity of the PL.SH.Layer 10% sample was reduced to 0.853 (W/mK compared to a plain concrete sample with 1.1002 (W/mK) for thermal conductivity. Implementing shredded plastic as a layer in PL.SH.Layer.30% further decreased the conductivity to 0.682 (W/mK), for example. These reductions in TC represent 22.4% and 38%, respectively, and these reductions are commensurate with the decreases in heat gain and cooling energy consumption compared to plain

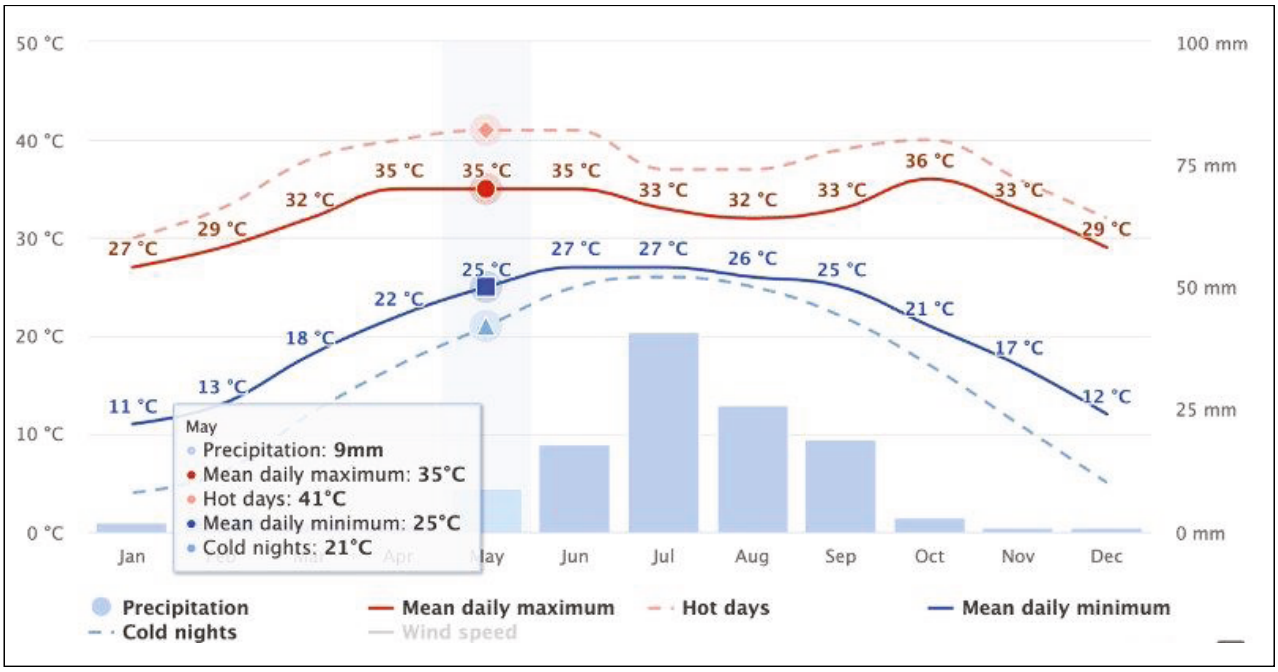

Figure 9 Annual mean of the highest and lowest Ta (out) values in the NBAC ("Meteoblue, Weather Data for Cairo" 2022).

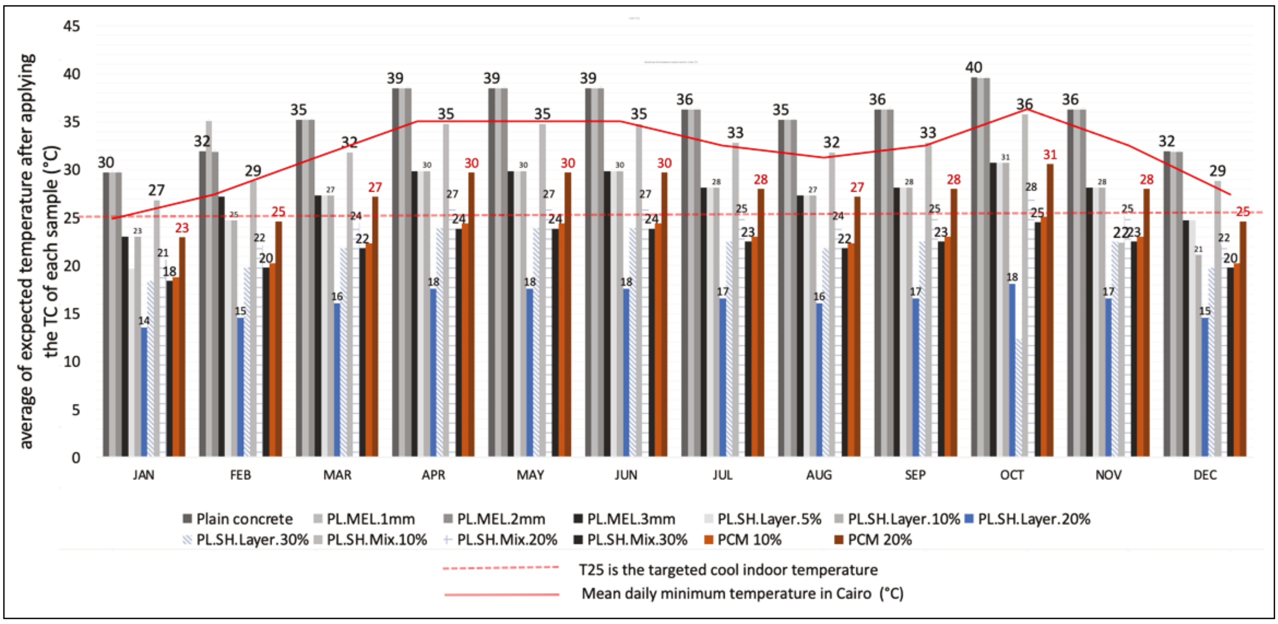

Figure 10 Average of expected temperature after applying the TC of each sample within the year comparing to the mean daily maximum in Cairo.

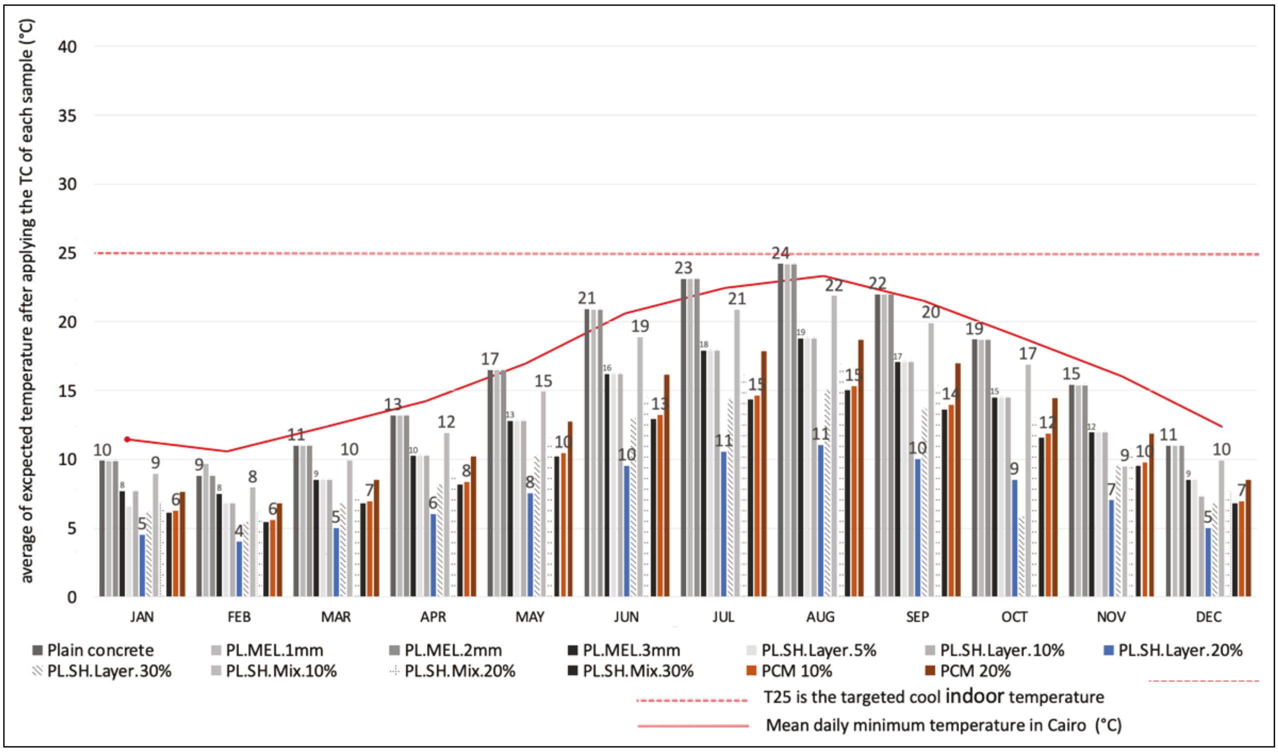

Figure 11 Average of expected temperature after applying the TC of each sample within the year comparing to the mean daily minimum in Cairo.

concrete. A brief numerical calculation was performed using equations 1 through 5, which were discussed in the preceding section, in order to approximate the energy savings that would result from incorporating the study's samples into the curriculum.

Furthermore, as illustrated in Figures 10 and 11, the summertime temperature would be approximately 36°C as shown in Figure 9, If plain concrete were utilized; however, the addition of 10 percent shredded waste plastic (PL.SH.Layer.10%) would reduce it to 28 and 16°C from 36°C. In PCM samples, it could reduce it to 23 and 28°C in samples PCM10% and 20%. Comparing those results with previous studies (Abd El Raheim et al. 2022), found that adding PCM with 20 mm, the room temperature can be decreased by as much as 9 degrees Celsius. An additional investigation (Kocher and Kamil. M. Yousif, 2022; Tayeh et al., 2021) examines the impacts of incorporating plastic particles into concrete on its mechanical, acoustical, and thermal characteristics. The study incorporated plastic waste in varying proportions (0–25 percent). The results indicate that the compressive strength of the concrete is reduced by around 40–51% when compared to normal concrete. In addition, the thermal conductivity was reduced by approximately 50% compared to standard concrete. Comparing the findings with the current study, the PL.SH.layer.20% decreased the TC from 1.1002 W/mK to 0.502 W/mK. Reduction than ordinary concrete, which is equivalent to a decrease of around fifty percent. For physical properties, in another study (Mustafa et al. 2019a; 2019b), the dry density values went down from 2210 kg/m^3 for mixtures that didn't have any plastic aggregates to 1960 kg/m^3 for mixtures that did have 20% plastic particles. This reduction is about 10% lower than normal concrete. It was observed that the compressive strength of plastic concrete generally dropped as the plastic component increased. With a 20 percent volume replacement, the average compressive stress decreases by 24 percent when plastic waste replaces sand. Those results are consistent with the findings of the present investigation, as the density fell from 2036. 7 Kg/m^3 to 1891.9 Kg/m^3 in PL.SH.Mix.20%, which represents 7%.

Generally, the substitution of plastic results in a negative impact on its mechanical properties. Nevertheless, when PET was utilised at a particular replacement ratio and in a specific plastic phase, the mechanical properties experienced an acceptable decrease. This suggests that PET could potentially serve as a substantial substitute for sand in the future of concrete. At various ages, the compressive strength of concrete diminishes as the proportion of plastic in the mixture increases. It was found that the compressive strengths of 10% and 20% PET after 28 days of curing were 3% and 15.42% lower than the reference sample (Tayeh et al., 2021). In the current study, samples of shredded plastic waste mixed with concrete with percentages of 10%, 20%, and 30% resulted in a reduction in compressive strength of 6% and 15%, respectively.

As shown from the previous comparable studies with the current study, the improvements derived from the integration of waste plastic material into concrete panels were found to be comparable in scope to those identified in the findings of this study (Tayeh et al. 2021; Kocher and Kamil. M. Yousif, 2022; Abd El-Raheim et al. 2022), which found that the maximum increase of plastic shredded waste of 20% is accepted in the physical characteristics, this also achieved accepted thermal enhancement. An additional characteristic of the study's results is the comparison between the performance of various states of plastic and PCM.

5. CONCLUSION

Because of their low thermal conductivity, plastics are a good choice for increasing the thermal resistance of building materials in the construction industry. In addition to offering a cost-effective substitute for phase change materials (PCM), recycled plastic integrated into concrete panels may improve the structures' sustainability and circular economy. The purpose of this research is to determine whether or not recycled plastic with cement panels can be used effectively as thermal insulation. Eleven samples were examined for their thermal and physical qualities and thicknesses. Some of the samples also included pieces of shredded waste plastic, some combined with melted plastic waste, and others with shredded plastic laid inside the concrete panels. Each design's potential energy savings were estimated by measuring the thermal conductivity.

This research shows that recycled plastic may be a great alternative to cost-effective PCM as thermal insulation. The outcomes achieved by PL.SH.layer.10% and PL.SH.layer.20% are similar in thermal performance as an insulation compared to the PCM samples, and these alternatives are seen as more cost-effective. Almost all the samples, except the ones with melted plastic waste, have achieved enhanced thermal performance in insulating heat.

The workability values of all plastic waste used in concrete were expected to decline as the plastic content increased, mostly owing to the formation of a complex network structure. However, in the case of 20% shredded plastic mixed with the concrete mixture, the opposite effect was seen, which may be attributed to fibre aggregating. PL.SH.Mix at 20% achieved 40.8 MPa in compressive strength, achieving similar performance as PCM at 20%. In addition, the incorporation of waste materials into concrete may lead to a rise in porosity and a drop in bulk density. This is due to the hydrophobic properties of plastics, which can create air voids inside the concrete. It can increase the thermal comfort of buildings, save energy, and make building envelopes more insulating. This study's results may help guide efforts to create more sustainable construction materials in the future and speed up the shift to a circular economy.

DATA ACCESSIBILITY STATEMENT

The authors declare that the data supporting the findings of this study (Grasshopper script and Results tables) are available within the manuscript besides the attached supplementary file (Appendices). However, if any data files are needed in another format, they are available from the corresponding author upon request.

ETHICS AND CONSENT

This study does not contain any studies with human or animal subjects performed by any of the authors.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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