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Waste chicken feathers integrated with phase change materials as new inner insulation envelope for buildings

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ABSTRACT

Recycling wastes, especially feathers in the construction sector, is considered a free source to reduce environmental pollution. Integration of waste chicken feathers (WCF) in certain ratios with phase change materials (PCM) contributes to enhancing the thermal properties of the PCM as a new insulation material in the construction sector. This paper aimed to elaborate on a new bio-composite material based on PCM with different mass fractions (25 %, 50 %, and 75 %) of WCF within polyvinyl chloride (PVC) panels as building inner envelopes. The tests were conducted under the methodological conditions of Baghdad city using five identical rooms with dimensions of 0.8 m × 0.8 m × 0.8 m. These were built based on the specifications of construction in Iraq. Compared to PVC panels that are filled with PCM only, the results indicated that the integration of WCF at a ratio of 75 % with PCM within PVC panels improved the acoustic insulation by 9 % and reduced the cooling load by 20.3 %, in which 22.5 % of the electricity cost saving for the testing room were achieved. The new insulation material can fulfill thermal comfort requirements, reduce energy consumption, and ensure a sustainable environment through waste recycling.

1. Introduction

In recent years, high energy consumption rates have resulted in an increase in pollution rates due to the emission of CO_2 and the generation of residues, and the building sector is one of the most energy-consuming in heating and cooling loads. Furthermore, buildings in the European Union are responsible for energy consumption reaching 40 % and leading to 36 % of the total CO_2 emissions [1]. A good thermally insulated building envelope can achieve a reduction in energy consumption by reducing heating and cooling load, which will contribute to reducing the level of environmental pollution. In this situation, the need to develop new materials for thermal insulation in the building sector arises, and it's preferred to be at a low cost.

In the construction industry, waste from agriculture, industry, and animal waste such as wool or feathers is one cheap solution that will contribute to reducing the energy demand, and reducing CO_2 emissions if it is utilized in the right way in the manufacturing of construction materials. These wastes are available and reusing it will contribute to the reduction in the total cost of the composite materials, and reduce the environmental pollution which is caused by the traditional methods of this waste destruction. Poultry consumption, in general, is growing globally, thanks to its low operating cost and rapid growth of the chickens, where in Europe alone, people consume about 14,013,000 tons of poultry per year [2]. The high consumption of poultry leads to high production of feather waste, reaching to 3.1 million tons of the waste per year in the EU. The traditional methods of waste feather destruction are burial in landfills or incineration. This process contributes to the pollution of air, soil, groundwater, and surface water. Its degradation process is highly toxic for humans [3].

Utilizing waste feather in construction materials is considered a great free source and ensures a healthy environment through waste recycling. Where, feathers are one of the most effective thermal insulation materials, with thermal conductivities ranging from 0.024 to 0.034 W/(mK) depending on the type of feathers [4]. The low thermal conductivity of the feathers depends on their chemical composition and microstructure,

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Nomenclature

A	Area (m^2)
CL	Cooling load (W)
CLR	Cooling load reduction (%)
CLTD	Cooling load temperature difference (°C)
DR	Daily range temperature (°C)
E	Sound energy absorbed by a material (W/m^2)
ECS	Electricity cost saving (USD)
1/F	Walls film resistance ((m^2 K)/W)
FU	Functional unit (kg/m^2)
k	Thermal conductivity of wall (W/(mK))
L	Sound level (dB)
PCM	Phase change material
PVC	Polyvinyl chloride
R	Conduction resistance(K/W)
S	Sound speed (m/s)
T	Temperature (°C)
t	Wall thickness (m)
U	Heat transfer coefficient (W/(mK))
V	Room volume (m^3)
WCF	Waste chicken feathers
ρ	density (kg/m^3)
σ	Absorption coefficient
Γ	Wall correction factor of Latitude and month

Subscripts

1	First layer
c	Correction
f	Ventilation factor
i	Inside
m	Outdoor design
n	Last layer
o	Outside
r	Room
T	Overall/total
w	Wall

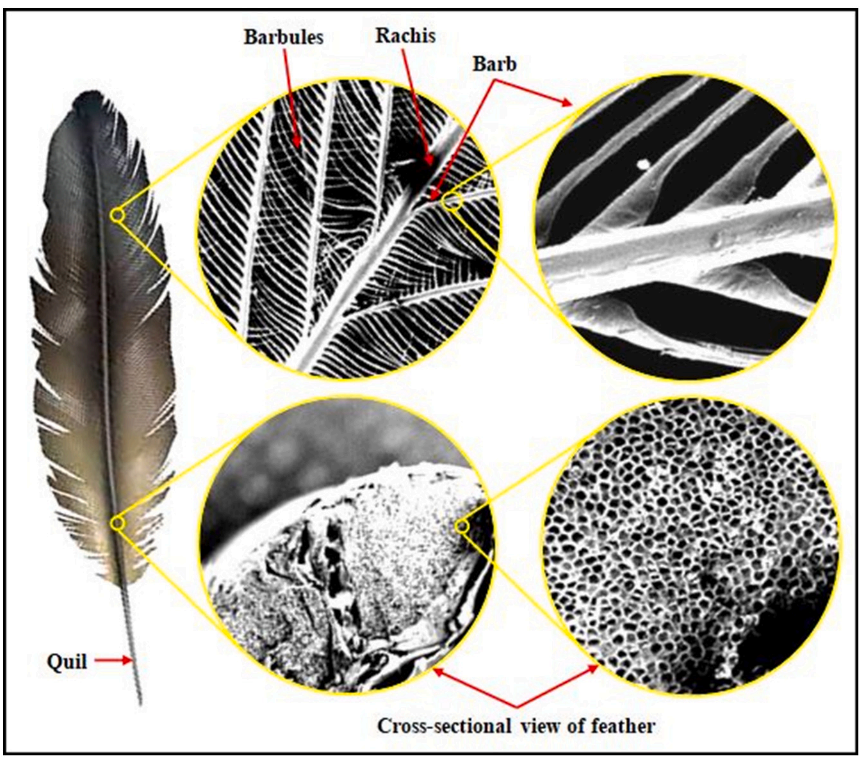

Fig. 1. Microstructures of feather.

which effectively traps air and produces a highly effective thermal barrier as shown in Fig. 1.

Several studies have been carried out on utilizing waste chicken feathers (WCF), in construction materials to get rid of this waste. Srivatsav et al. [5] studied the additives of chicken feather fibers as reinforcement materials on the mechanical properties of composites made of epoxy prepared using the hand layup process. Also, Subramani et al. [6] studied the additives of chicken feather fibers as reinforcement materials on the mechanical properties of composites made of polyester, and phenyl ester, the bi-directional chicken feather fibers reinforced composites were produced with phenyl ester and polyester resins with fiber reinforced composites. Acda [7] demonstrated the similarity in strength and stiffness of composite boards reinforced by (5–10 %) of the waste feather mixed by cement and sand, with composite boards consisting of cement reinforced with wood fibers in the same density and thickness. El-Hawary and Hamoush [8] found that the new mixes feather fiber with cement have give a lower values in compressive and tensile strengths than those of plain concrete. But, Staron et al. [9] found that a high concentration of pH in cementations of composite materials can result in the degradation of the fibers of the chicken feathers. In addition, Zhang et al. [10] compared different mass fractions additives of chicken feathers varying from 1 % to 5 % in two types of mortars magnesium silicate hydrate cement mortars (pH = 10) and portland cement mortars (pH = 12.6), and observed that magnesium silicate hydrate cement mortars excellently adhere with fibers of the chicken feather. Ouakarrouch, et al. [11] showed that adding WCF to the plaster building material leads to a remarkable reduction in apparent density and thermal conductivity. Safaric et al. [12] studied the addition of WCF into the fiberboard's structure to determine the thermal insulation properties. They found that they improved the thermal insulation properties and the biodegradability of fiberboard, but decreased their bending strength. Aranberri et al. [13] developed biodegradable polymeric material based on WCF with selected biopolymers as flooring or buildings panel components instead of bio-plastics. The high concentration ratio of WCF gave a good thermal-insulating and led to light weightness compared with the bio-plastics. Odusote et al. [14] found that ceiling board consist of 10 % waste carton, 80 % portland cement, and 10 % of WCF, can compete favorably with most ceiling boards available in the market in terms of good density, compressive strength, modulus of elasticity, modulus of rupture and thermal conductivity. In methods of delivering chilled and frozen foods(susceptible to degradation by high temperatures during delivery), Dieckmann et al. [15] said that the air-laid nonwoven feather fiber liners have the potential to displace expanded polystyrene used for delivering chilled and frozen foods.

The study of phase change materials (PCM) as heat-sink in many applications is gaining attention [16] due it has a good latent heat of fusion and low thermal conductivity (about 0.2), which gives them advantages to use as thermal insulation material. In the construction materials sector, Koschenz and Lehmann [17] developed the ceiling panel using PCM. The new ceiling panel was able to abate and regulate the excessive heat emanating from the ceiling of an office building. Kuznik et al. [18] investigated the thermal performances of a PCM copolymer composite wallboard in a full-scale test room. They found that the new copolymer composite wallboard contributed to decreasing in the air temperature inside the room. Errebai et al. [19] used microencapsulated PCM by perforating the panel with several small holes yielding a greater contact surface area with the surrounding air. This technical solution improved the thermal behavior of plasterboards, which produced an augmentation in heat absorption and release. Kuznik et al. [20] investigated new lightweight wallboard using PCM to enhance the thermal behavior of building internal partition walls for a full-scale test room. They found that using PCM reduces room air temperature fluctuations, particularly when outside overheating occurs.

The thermal insulation of buildings' inner envelopes is one of the effective techniques adopted to ensure thermal comfort and reduce the energy demand for cooling and heating, which will contribute to reducing greenhouse gas emissions. It can conclude from the previous literature the advantages of using PCMs in building components; can improve thermal inertia by storing the excess heat in the building during the daytime, and later releasing the stored heat at night to the indoor environment when there is a drop in temperatures below the melting point of the PCM. Furthermore, utilizing waste feather in construction materials is considered a great free source and ensures a healthy environment through waste recycling. Where, feathers are one of the most effective thermal insulation materials.

Based on previous research, this work aimed to elaborate on a new bio-composite material based on phase change materials (PCM) integrated with different mass fractions of WCF (25 %, 50 %, and 75 %). This new bio-composite material can achieve thermal comfort requirements and reduce energy consumption simultaneously. Moreover, ensuring a sustainable environment through waste recycling.

2. Materials used

2.1. Phase change materials

PCM is a very interesting material used recently in buildings as an insulating material due to its low thermal conductivity, It also has the ability to save energy during the phase change from solid to liquid phase [21–23]. In this work, paraffin wax type Heptacosane ($CH_3(CH_2)25CH_3$) was used as a PCM to be integrated with WCF in this work.

2.2. Waste chicken feathers

Broiler chicken meat production worldwide in 2018 amounted to about 92.7 million metric tons, and it reached 102.060 million metric tons in 2021 [24]. The WCF represents about 5–10 % of the chicken's total weight, and it is considered the poultry waste industry product [25]. This waste product is related to the excessive consumption of white meat. Furthermore, if recycled properly, this waste is regarded as an essentially free source in the industry, hence WCF was used in this study as recycled waste combined with PCM.

2.3. PVC panels

Commercial hollow PVC plastic panels with a thickness of 7 mm were offered as an inner wall packing material in this study. Work specimens were made using PVC plastic panels that were filled with PCM and WCF in certain ratios (25 %, 50 %, and 75 %). Due to the fixed hollow of the used PVC panels as buildings' inner envelopes, which directly influences their thermal performance as buildings insulation materials, the variation in the PCM mass is related to the WCF addition quantity to the PCM. The integrated insulating panels with PCM and WCF are installed directly on the inside of the testing rooms' walls and ceilings.

3. Experiments preparation

3.1. Samples preparation

The discarded chicken feathers were washed in a professional washing machine with a mesh bag at 60 °C before being applied. In this technique, Caely CG88169N nonionic detergent was employed. Water makes up 75 % of the weight of the cleaned feathers. The drying has to be done extremely carefully at an appropriate temperature to avoid polluting the feathers with fungus spores from the air and to preserve the chemical and physical structure of the feathers. The drying process was divided into two stages, the first of which was completed using a commercial washing machine. The second process was completed in a Tornado TEO-48DG oven at 60 °C for 36 h, stirring every 4 h to ensure proper temperature distribution and to eliminate the moisture. The grinder type Silver Crest SC-66B was used to give minced waste chicken feathers in small proportions to ensure good mixing of waste chicken feathers in particular ratios with PCM.

By melting the PCM, the combined PVC panels with PCM and WCF at various weight ratios were created, and then adding minced WCF in various weight ratios (25 %, 50 %, and 75 %). At temperatures ranging from 55 to 60 °C, a hand mixer type Cx-6625 was utilized to combine melted PCM with minced WCF. The PCM and WCF mixes are then retained at around 50 °C to fill the hollow PVC panels with the blends, avoiding the deformation of the used PVC panels due to high temperatures.

3.2. Thermal, mechanical and acoustic tests

A differential scanning calorimeter (DSC) type Mettler Toledo Star DSC1 was used to analyze the thermo-physical parameters of the used PCM (the latent heat of fusion and melting temperature). The specific heat capacity and thermal conductivity of the combined PVC panels (PVC only, and PVC filled by 25 %, 50 %, and 75 % of WCF and PCM, respectively) were measured using a TPS-500 thermal constants analyzer.

The capacity of the PVC panels with the effects of the additive materials (PCM with WCF) to withstand external variables such as overloads, shocks, and tension or compression was assessed using a WDW-100 computer-controlled electronic universal testing machine and an XJU-22 pendulum impact tester.

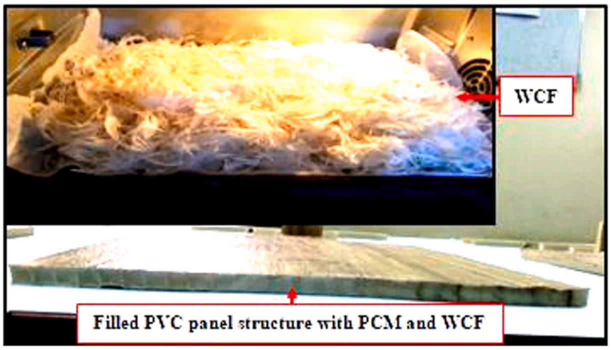

Fig. 2. PVC structure filled with PCM and WCF.

The ASTM E-336 instrument was used to evaluate the acoustical insulation performance of the PVC panels with the effects of additive materials (PCM with WCF). It is made up of an insulated chamber, a speaker, an AV 298 sound amplifier, a UNIT 092812 sound wave generator, and a sound meter with a 30–130 dB range. The frequency range of 0 to 4000 Hz is a commonly used range for assessing acoustic performance in construction sectors, and it was used in these experiments. Fig. 2 depicts a PVC panel structure filled with PCM and WCF. Fig. 3 depicts the shapes of the work specimens as well as the experimental test setups in this work.

3.3. Testing rooms

As testing room prototypes, five identical rooms with dimensions of 0.8 m 0.8 m 0.8 m were built. Fig. 4 depicts the use of familiar construction materials in the room's construction models based on Iraqi construction specifications [26,27]. These rooms are made of bricks with thermal conductivity of 0.46 W/(mK) and a thickness of 12 cm, while the ceiling is made of 5 cm thick concrete. To coat the bricks and ceiling from the outside, a layer of cement and sand with a thickness of 1 cm and a thermal conductivity of 0.721 W/(mK) was applied. A 1 cm thick plaster layer with thermal conductivity of 0.81 W/(mK) is applied to the inner side of the bricks and ceiling. The prepared envelopes are directly attached to this wall type.

The first room is a standard room with no insulation (no inner envelopes), and the second room has inner envelopes filled with PCM only

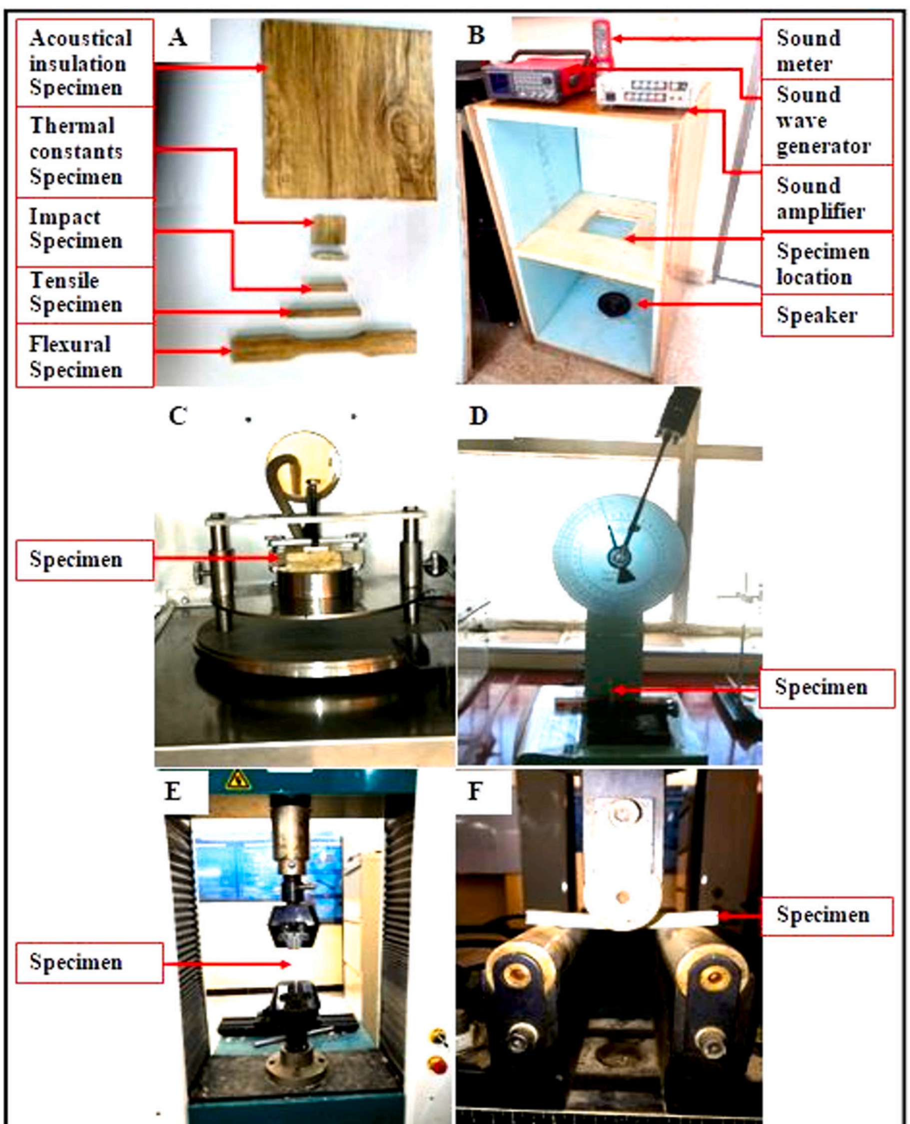

Fig. 3. Work specimens with experimental tests setups; A) Work specimens, B) Acoustical insulation device, C) Thermal constant analyzer, D) Tensile test device, E) Flexural test device, F) Impact test device.

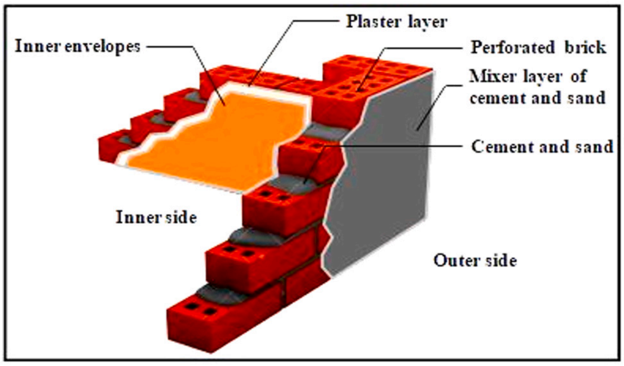

Fig. 4. Walls model.

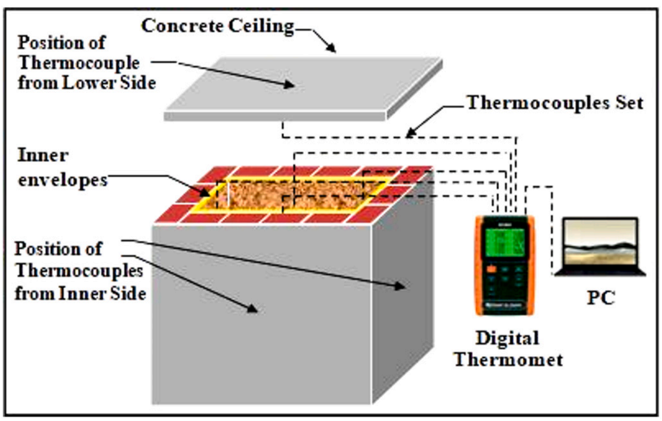

Fig. 5. Schematic diagram of the test room.

(44.02 °C melting temperature). The remaining three rooms with inner envelopes were filled by 25 %, 50 %, and 75 % of WCF and PCM, respectively. The experiments were carried out in testing rooms under Baghdad-Iraq city's methodological conditions (latitude 33.310° N, longitude 44.450° E).

The solar irradiance was measured using a TES-1333 solar power meter while the walls and room air temperature for each constructed room were measured using six K-type thermocouples that were directly connected to the BTM-4208SD digital thermometer. Five thermocouples were installed on each of the inner envelopes for the walls and ceiling, with a sixth thermocouple installed in the center of the room. Figs. 5 and 6 show the schematic diagram and construction of the test room, respectively.

4. Mathematical formulations

4.1. *Sound-absorbing coefficient (α)*

The sound-absorbing coefficient (σ) can be expressed mathematically as [28]:

$$\sigma = \frac{E}{E_o} \quad (1)$$

It is the evaluating index for the sound-absorbing performances of materials, where it is the ratio of the sound energy absorbed by a material (E) to the overall sound energy reaching the material's surface (E_o).

The amount of sound energy absorbed by a material (E) is as follows:

$$E = \frac{0.921 * V * L}{S} \quad (2)$$

V is the room volume, L is the sound level, and S is the sound speed.

4.2. *Cooling load reduction (CLR)*

The conduction resistance (R) can be expressed by [26]:

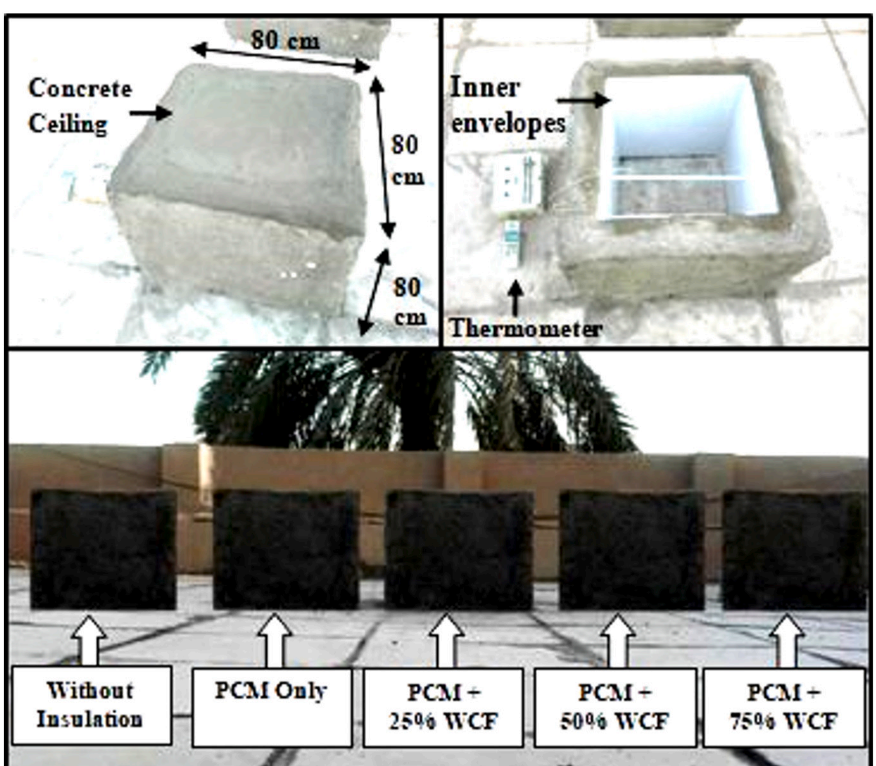

Fig. 6. Constructed test rooms.

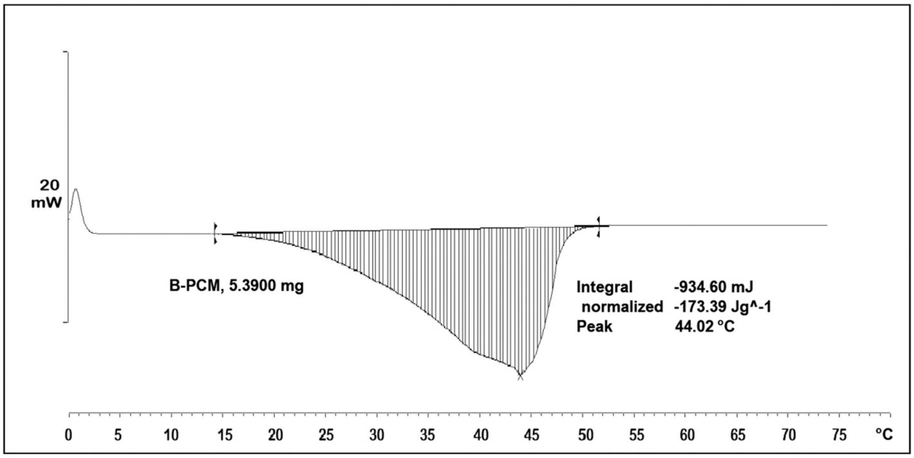

Fig. 7. DSC test results for the used PCM.

$$R = \frac{t_w}{k.A} \quad (3)$$

t_w is the wall thickness and k is the thermal conductivity of the wall. The total thermal resistance (R_T) can be expressed as the following [26]:

$$R_T = \frac{1}{F_i} + R_1 + R_2 + \ldots + R_n + \frac{1}{F_o} \quad (4)$$

1/F is the wall's film resistance (for internal wall $1/F_i = 9.26$ (m^2K)/W, for external wall $1/F_o = 22.7$ (m^2K)/W).

The overall heat transfer coefficient (UT) was calculated using the following equation [26]:

$$U_T = \frac{1}{R_T} \quad (5)$$

The structural design of the building is the primary source of heat transfer to the building (i.e., heat gain) during a specific period, where the heat gain equals the cooling load. The cooling load temperature difference (CLTD) method can be applied to walls and roofs to obtain the cooling load (CL) through a building's exterior structure [26].

$$CL = U_T{*}A{*}CLTD_C \quad (6)$$

The $CLTD_C$ for walls:

$$CLTD_C = [(CLTD + \Gamma){*}\acute{\Gamma} + (25.5 - T_r) + (T_m - 29.4)] \quad (7)$$

The CLTDc for ceilings:

$$CLTD_C = [(CLTD + \Gamma){*}\acute{\Gamma} + (25.5 - T_r) + (T_m - 29.4)]{*}f \quad (8)$$

Where U_T is the overall heat transfer coefficient, A is the surface area of the ceiling or walls, and CLTD is the cooling load temperature difference for walls and roofs, which can be obtained from the special tables provided by [26], based on the location's latitude and testing month. $CLTD_C$ is the corrected cooling load temperature difference for walls and roofs, Γ is the correction factor of the wall for latitude (44.4) and month (July), and $\acute{\Gamma}$ is the color correction factor (1.00 for dark color, 0.83 for medium color, and 0.65 for light color). While the value 29.4 is the mean outdoor temperature, and the value 25.5 is the design inside temperature. Furthermore, T_r is the room temperature, f is the ventilation factor between the italics and second ceilings (f = 0.75 for fan ventilation and f = 1 for no fan ventilation), and T_m is the outdoor design temperature. Based on the provided previous information, the values of $CLTD_C$ can be obtained [26].

T_m is calculated using the following equation in terms of outside temperature (T_o) and outdoor daily range ($DR_o = 11.6$ C) [26]:

$$T_m = T_o - \frac{DR_o}{2} \quad (9)$$

The percentage reduction in cooling load (CLR) due to the use of the proposed insulation materials can be calculated as follows: [26]:

$$CLR = \frac{CL_{\text{with Insulation}} - CL_{\text{without Insulation}}}{CL_{\text{without Insulation}}} \times 100\% \quad (10)$$

4.3. Electricity cost saving (ECS)

The electricity cost savings at peak hours can be calculated for all cases of using the proposed insulation materials. The electricity cost savings are calculated using the default price in Iraq, which is 35 Iraqi dinars (IQD) (0.024 USD) per kWh (The price of electrical energy consumption is based on the Iraqi Ministry of Electricity's official pricing) [29]. The following equation was used to calculate the savings in electricity costs for the built rooms using the new proposed insulation material [30].

$$ECS\left(\frac{IQD}{day}\right) = CLR\ (kW){*}35\left(\frac{IQD}{kW.h}\right){*}24\left(\frac{hour}{day}\right) \quad (11)$$

4.4. Functional unit (FU)

A functional unit (FU) is considered a reference unit in a life cycle assessment [31,32] based on the ISO 14040 standard to obtain information about the amount of insulation material required to perform thermal resistance during the insulation lifetime. According to a proposal by the Council for European Producers of Building Materials [33,34], FU can be defined as the mass (kg) of insulating material with a thermal resistance R equal to 1 (m^2K)/W.

$$FU = R{*}k{*}\rho{*}A\ (kg) \quad (12)$$

R is the thermal resistance of the insulation material, k is the thermal conductivity of the insulation material (W/(mK)), ρ is the density of the insulation material in kg/m^3, and A is the surface area of the insulation material (1 m^2).

5. Results and discussions

5.1. Thermo physical properties

The thermophysical properties of the PCM were obtained using the DSC instrument as illustrated in Fig. 7. The experimental results indicated that the melting temperature of the used PCM was 44.02 °C at the peak point of the melting process which represented the phase change

Table 1
Thermo-physical properties results for the used materials.

Used materials	Thermal conductivity K (W/(mK))	Specific heat C_p (J/(kg K))	Density ρ(kg/m^3)	Melting Temperature (°C)	Latent heat of fusion (J/g)
WCF	0.033	75.84	59	232.8	21.8
PCM	0.224	2951	870	44.02	173.39
PCM + 25 % WCF	0.189	2661	859	51.62	170.23
PCM + 50 % WCF	0.159	2361	843	63.83	165.07
PCM + 75 % WCF	0.140	2011	838	77.58	156.56
PVC with PCM	0.397	4101	880	–	–
PVC with PCM + 25 % WCF	0.362	3811	869	–	–
PVC with PCM + 50 % WCF	0.332	3511	853	–	–
PVC with PCM + 75 % WCF	0.313	3161	838	–	–

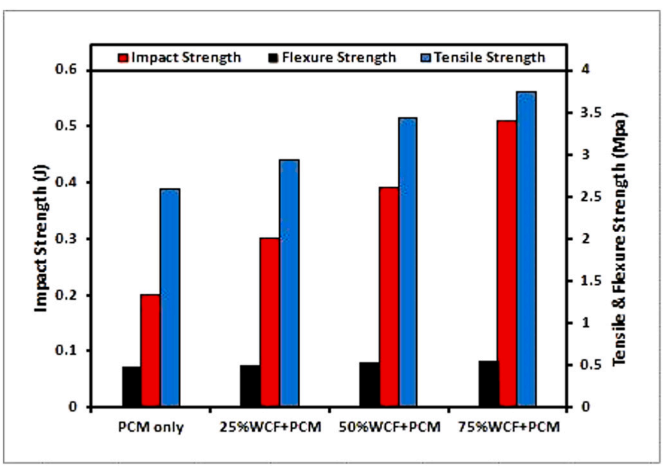

Fig. 8. Mechanical properties test results.

from solid to liquid of the used PCM. Moreover, the PCM's latent heat of fusion was 173.39 J/g. The changes in the melting temperatures and latent heat of fusion of the used PCM with different additives ratios of WCF obtained by DSC were illustrated in Table 1. Where the increase in the WCF additives within PCM leads to an increase in the melting temperature and slightly decreases in latent heat of fusion of the compound PCM and WCF. These changes in the melting temperature, and latent heat of fusion of the compound it is due to the change in the structure of the compound with increasing in the WCF ratios within PCM. Furthermore, Table 1 illustrates the results of the thermo-physical properties obtained by the hot disk for PVC panels with PCM and WCF additives. The results showed that increasing the weight percentage ratios of WCF in the PCM resulted in a decrease in the thermal conductivity and specific heat capacity of the compound PCM with WCF (i.e. improving insulation and reducing heat storage), which will support the study's goal of improving thermal insulation for the building's inner envelope.

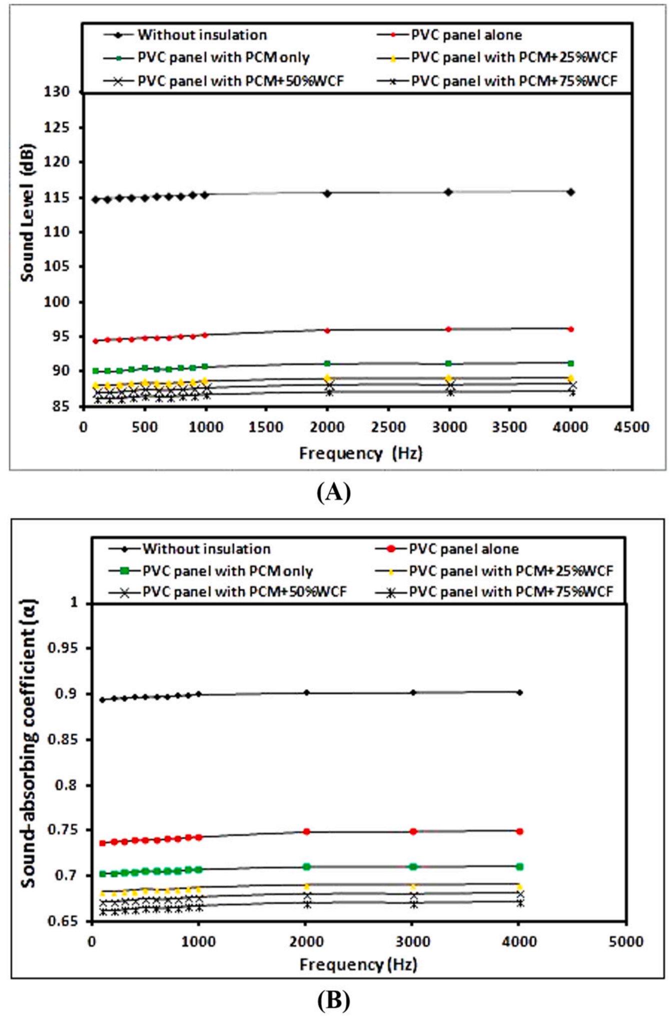

Fig. 9. Acoustic insulation properties; A) Sound level readings, B) Sound absorption coefficient (σ).

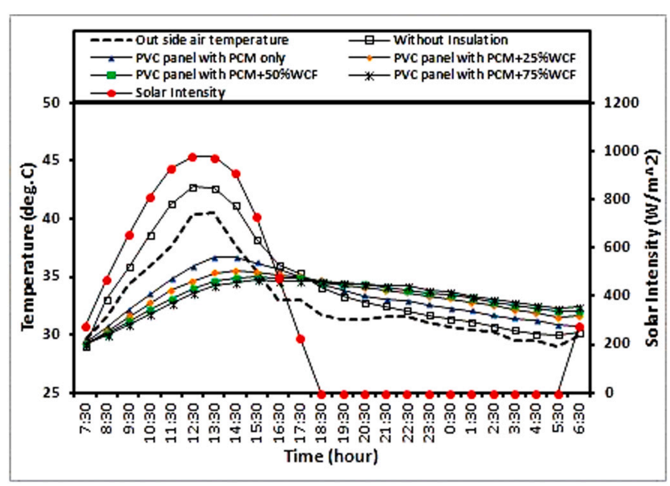

Fig. 10. Five rooms' air temperature with solar irradiance.

5.2. Mechanical properties

Mechanical properties for materials are flexure, tensile, and impact. These properties indicated the materials' strength and their ability to withstand external conditions. Fig. 8 depicts the mechanical properties

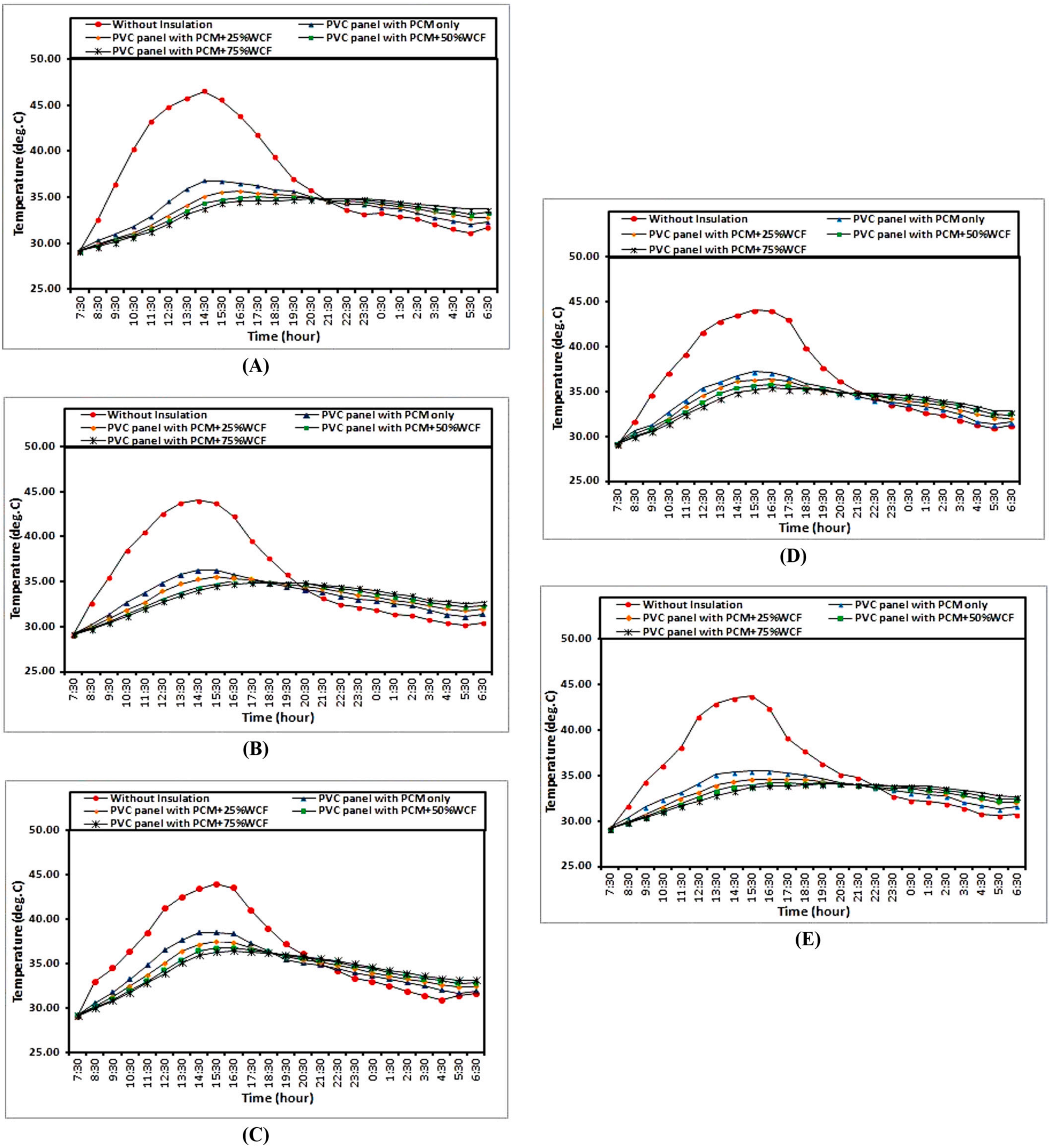

Fig. 11. Inner envelopes surface temperature; A) Ceiling, B) North wall, C) South wall, D) East wall, and E) West wall.

of the PVC panels with PCM additives and specific WCF ratios used in this study. It can be seen that all combined PVC panels with PCM and specific WCF ratios provided excellent flexure, tensile, and impact properties when compared to PVC panels filled with PCM only. The physical rationale for these improvements in mechanical properties is that the addition of WCF fibers to PCM increased the cohesiveness between the PCM layers, resulting in an upswing in mechanical characteristics [5–8]. Additionally, the combined PVC panel with a WCF content of 75 % had a maximum tensile strength of 3.75 MPa, a flexure strength of 0.55 MPa, and an impact strength of 0.51 J.

5.3. Acoustic insulation properties

Acoustic insulation for any material is determined by its ability to absorb sound, which varies from one material to the next. Furthermore, sound incidence, frequency, and direction are important in determining the sound absorption coefficient, where the absorbed sound frequency should be explicit, and it uses the mean value of absorbing sound from

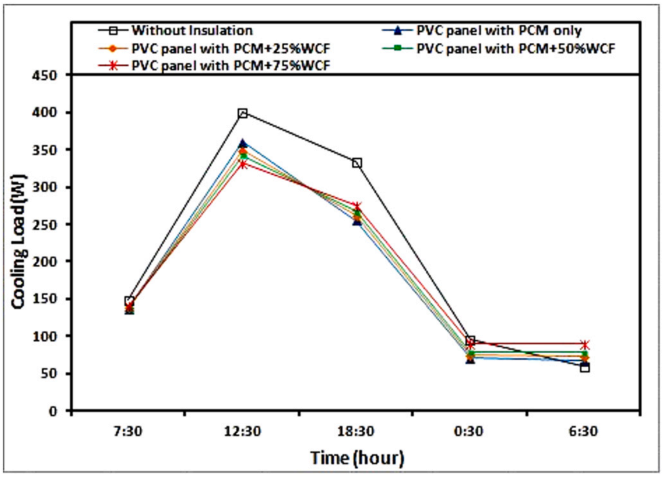

Fig. 12. Cooling load of the test rooms.

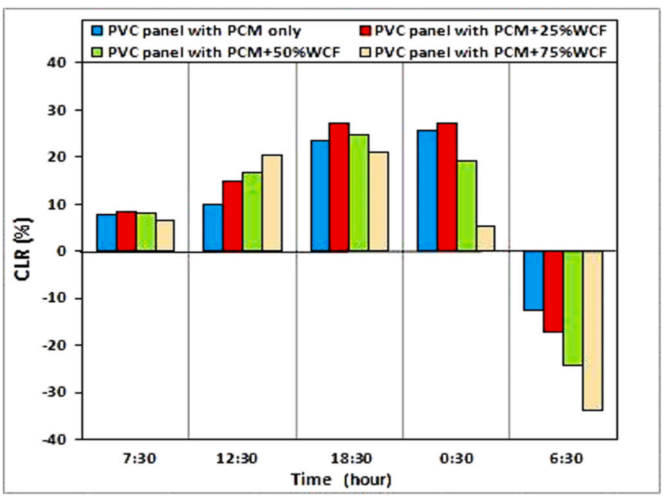

Fig. 13. Cooling load reduction of the test rooms.

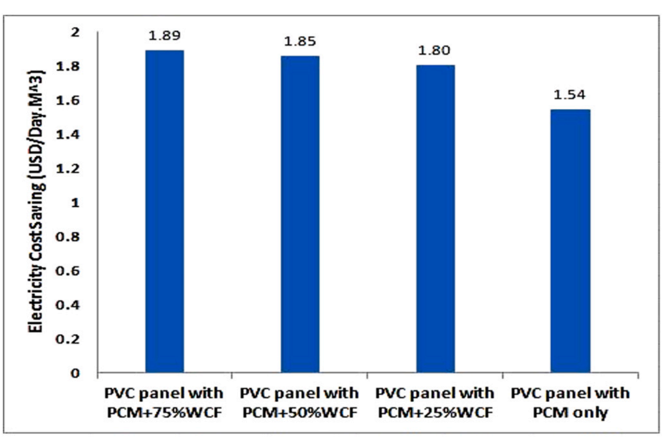

Fig. 14. Electricity cost saving of the test rooms.

all incidence directions. Six frequencies were used to evaluate the acoustic insulation of the proposed insulating materials: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, and these frequencies were normally used in the acoustic insulation tests. Fig. 9 (a) and (b) show the acoustic insulation performance of the proposed combined PVC panels with PCM and 25 %, 50 %, and 75 % WCF compared to the PVC panel alone (b). It is clear that using WCF at different ratios (25 %, 50 %, and 75 %) of WCF reduced noise levels by about 6.8 %, 8 %, and 9 %, respectively when compared to PVC panels filled with PCM. These improvements in the acoustic insulation of combined PVC panels can be attributed to the presence of WCF fibers with adequate acoustic insulation. As a result, increasing the proportion of WCF in PCM reduces the noise level of the combined PVC panel [35,36].

5.4. Thermal comfort

5.4.1. Rooms' air temperature

Fig. 10 depicted the variation in the air temperature of the five test rooms with the incident solar irradiance on the test day, where the tests were done on all rooms were walls packaged internally by PVC panels without PCM, PVC panels filled with PCM only, and PVC panels filled PCM with different ratios of WCF (25 %, 50 %, and 75 %), where the tests were performed on 22 July 2021. The air temperature in the room with the PVC panel filled with PCM only is lower than the air temperature in the room with the PVC panel alone from 7:30 AM to 5:30 PM. This is due to the effect of the PCM insulation material, which reduced heat gain in the room by absorbing heat energy and keeping the room's air temperature at minimum values [20]. During the night, the air temperature in the room with the PVC panel filled by PCM only is higher than the air temperature in the room with the PVC panel alone, because PCM began discharging the heat energy stored into the room's space [18]. At peak charging (12:30 PM), the percentage of drooping in the room's air temperature using a PVC panel filled with only PCM was only 20 %. Furthermore, increasing the WCF additive within PCM resulted in a significant improvement in thermal insulation of the PCM over the same time period (7:30 AM to 5:30 PM) [13,15]. Whereas, at peak charging time (12:30 PM), the percentage of drooping in the air temperature of the other rooms (PVC panels filled with 25 %, 50 %, and 75 % WCF and PCM) was 4.5 %, 7 %, and 9.2 %, respectively when compared to the room with PVC filled with PCM only.

5.4.2. Inner envelopes temperatures

Fig. 11 depicts the variations in surface temperature of the inner envelopes for the ceiling and walls of all five rooms (A - E). The surface temperatures of inner envelopes for all walls enveloped by PVC panels filled with only PCM decreased more than in the room with PVC panels alone between 7:30 AM and 5:30 PM. This is due to the effect of the PCM as an insulation material, which resulted in less heat entering the inner surface of the wall envelopes [20]. As a result, less heat enters the room space, keeping the room's air temperature at a minimum. Furthermore, increasing the WCF additive within PCM for other rooms results in a significant reduction in the inner surface temperature of inner envelopes for the same time period (7:30 AM to 5:30 PM), when compared to the room with PVC filled with PCM only. This is due to an increase in the WCF additive within PCM, which reduced the transferred heat through the inner envelopes of the walls, and improved the thermal insulation of the combined PVC panels [13,15].

5.5. Cooling load

The variation in cooling load and its percentage reduction in cooling load for the five-room cases were investigated and illustrated in Figs. 12 and 13. The cooling load is reduced during the day in the case of the room with PVC panels filled by PCM only compared to the room with PVC panels alone; additionally, an increase in the WCF within PCM of the PVC panels (i.e., 25 %, 50 %, and 75 % of WCF within PCM) resulted in a greater reduction in the required cooling load. In this study, using PCM only in the PVC panels that served as the test room's inner envelopes resulted in a 9.6 % reduction in cooling load. Furthermore, using WCF at 25 %, 50 %, and 75 % within PCM in PVC panels reduced cooling load by 14.7 %, 16.6 %, and 20.3 %, respectively. It is most notable that

Table 2
Calculation details of CLR and ECS along the test day.

Time	75%RWP + PCM		50%RWP + PCM		25%RWP + PCM		PCM only	
	CLR (W)	ECS (USD/ h.m^3)	CLR (W)	ECS (USD/ h.m^3)	CLR (W)	ECS (USD/ h.m^3)	CLR (W)	ECS (USD/ h.m^3)
7:30	84.004	0.0483	80.405	0.0463	76.283	0.0439	55.338	0.0318
8:30	131.976	0.0760	126.037	0.0725	120.979	0.0696	95.726	0.0551
9:30	187.972	0.1082	181.618	0.1046	172.519	0.0993	144.787	0.0833
10:30	227.005	0.1307	219.539	0.1264	208.812	0.1202	179.196	0.1032
11:30	263.654	0.1518	255.699	0.1472	242.695	0.1397	210.834	0.1214
12:30	307.342	0.1770	300.188	0.1729	288.781	0.1663	252.988	0.1457
13:30	326.393	0.1880	318.050	0.1831	306.774	0.1767	269.836	0.1554
14:30	302.956	0.1745	294.523	0.1696	284.345	0.1637	249.725	0.1438
15:30	284.033	0.1636	278.050	0.1601	270.295	0.1556	240.832	0.1387
16:30	253.716	0.1461	248.249	0.1429	240.909	0.1387	217.352	0.1251
17:30	245.512	0.1414	240.643	0.1386	235.156	0.1354	218.257	0.1257
18:30	208.735	0.1202	206.879	0.1191	202.412	0.1165	188.494	0.1085
19:30	159.219	0.0917	158.434	0.0912	156.792	0.0903	144.900	0.0834
20:30	118.923	0.0685	117.351	0.0675	117.950	0.0679	108.592	0.0625
21:30	98.966	0.0570	98.580	0.0567	99.040	0.0570	91.255	0.0525
22:30	45.453	0.0261	46.756	0.0269	46.836	0.0269	36.694	0.0211
23:30	30.336	0.0174	30.948	0.0178	32.183	0.0185	21.147	0.0121
0:30	16.681	0.0096	17.241	0.0099	17.739	0.0102	8.364	0.0048
1:30	8.894	0.0051	8.792	0.0050	9.864	0.0056	−0.313	−0.0001
2:30	0.478	0.0002	1.603	0.0009	1.987	0.0011	−7.492	−0.0043
3:30	−9.186	−0.0052	−8.726	−0.0050	−7.784	−0.0044	−18.906	−0.0108
4:30	−7.958	−0.0045	−6.862	−0.0039	−5.272	−0.0030	−17.233	−0.0099
5:30	−12.381	−0.0071	−11.936	−0.0068	−8.472	−0.0048	−20.786	−0.0119
6:30	13.545	0.0078	14.966	0.0086	17.355	0.0099	8.620	0.0049
ECS (USD/Day.m^3)		1.892898		1.853012		1.801837		1.5426

Table 3
Comparison between the different insulation materials and the investigated insulation panels in this study.

Materials	Density ρ (kg/m^3)	Thermal conductivity k (W/(mK))	Thickness (cm)	FU (kg/m^2)	Absorption coefficient σ at 500 Hz
Glass wool [37]	160	0.050	5.0	8.00	1.0
Cellulose flocks (panels) [37]	60	0.039	6.0	2.34	1.0
Kenaf fibers [37]	50	0.038	5.0	1.90	0.740
Rock wool [37]	30	0.040	5.0	1.20	0.900
Expanded polyurethane [37]	30	0.030	5.0	0.90	0.610
Expanded polystyrene [37]	20	0.040	4.0	0.80	0.50
Cork (panels) [37]	100	0.050	4.0	5.00	0.390
PVC panel with PCM	880	0.397	0.7	349	0.705
PVC panel with PCM + 25 % WCF	869	0.362	0.7	290	0.685
PVC panel with PCM + 50 % WCF	853	0.332	0.7	271	0.675
PVC panel with PCM + 75 % WCF	838	0.313	0.7	253	0.665

the cooling load at night increased due to rejected heat from the PCM inside the room space during the discharging heat process.

5.6. *Electricity cost saving*

Based on the calculations of the CLR and ECS were described in detail in Sections 4.2, and 4.3 of this study, Fig. 14 depicts the total electricity cost savings per day per cubic meter achieved by this study in US dollars. This figure shows that increasing the percentage of WCF within PCM in PVC panels leads to an increase in total electricity cost savings due to a decrease in the required total cooling load, as discussed previously in Fig. 12. Thus, the increase in electricity cost savings per day per cubic meter for the investigated room cases (rooms with PVC panels filled with PCM and 25 %, 50 %, and 75 % of WCF) was 16.9 %, 20.1 %, and 22.5 %, respectively, when compared to the room internally enveloped by PVC panels filled with PCM only. Furthermore, Table 2 illustrates the calculation details of the CLR versus ECS conducted for each hour along the test day (from 7:30 AM on 22 July 2021 to 6:30 AM on 23 July 2021).

5.7. *Performance comparison between traditional solutions and the proposed insulation panels in this study*

Many studies have used natural fibers and mineral synthetics like glass wool, rock wool, kenaf fibers, expanded polystyrene, expanded polyurethane, cellulose flocks (panels), and cork (panels) as traditional solutions in building insulation. Table 3 illustrates the comparison between the proposed insulation materials used in this study and the traditional solutions, where the weight and thickness of each material used for this purpose have been evaluated. Furthermore, the density, thermal conductivity, functional unit, and absorption coefficient of these materials were reported and considered in this analysis (at 500 Hz) [37].

Based on the previous results the effect of using WCF additives within PCM on the thermo-physical, mechanical, and acoustic properties can be summarized as follow:

1- Thermo-physical properties; the increases in the WCF at ratios 25 %, 50 %, and 75 % within PCM leads to an increase in the melting temperature of the compound by 17 %, 45 %, and 76 %, and slightly decreases in latent heat of fusion by 1 %, 4 %, and 9 %, respectively. These changes in the melting temperature, and latent heat of fusion of the compound it is due to the change in the structure of the compound with increasing in the WCF ratios within PCM. While it resulted in a decrease in the thermal conductivity by 15 %, 29 %, 37 % and specific heat capacity by 9 %, 19 %, and 31 %, respectively of the compound PCM with WCF (i.e. improving insulation and reducing heat storage), which will support the study's goal of improving thermal insulation for the building's inner envelope.

2- Mechanical properties; all combined PVC panels with PCM and specific WCF ratios provided excellent flexure, tensile, and impact properties when compared to PVC panels filled with PCM only. Additionally, the combined PVC panel with a WCF content of 75 % had a maximum tensile strength of 3.75 MPa, flexure strength of 0.55 MPa, and impact strength of 0.51 J.

3- Acoustic insulation properties; using WCF at different ratios (25 %, 50 %, and 75 %) reduced noise levels by about 6.8 %, 8 %, and 9 %, respectively when compared to PVC panels filled with PCM only.

6. Conclusions

Based on the experimental results, the feasibility of using recycled waste chicken feathers integrated with phase change materials as a new thermal insulation material for the inner envelope of buildings can be concluded as follows:

1. Using phase change materials with polyvinyl chloride panels as inner wall packaging in the building resulted in a decrease in air room temperature, which reduced the required cooling load of the room by 9.6 %.
2. The incorporation of waste chicken feathers at a weight ratio of 75 % within phase change materials improved compound properties as thermal insulation materials. Where lead to an increase in the melting temperature by 76 % and a decrease in the latent heat of fusion by 9 %. Additionally, the combined PVC panel with a WCF content of 75 % had a maximum tensile strength of 3.75 MPa, flexure strength of 0.55 MPa, and impact strength of 0.51 J. Moreover, reduced noise levels by 9 %, respectively when compared to PVC panels filled with PCM only.
3. Finally, for electricity cost savings, integrating waste chicken feathers at a 75 % ratio with phase change materials results in a 22.5 % reduction in required electricity cost when compared to polyvinyl chloride panels filled with phase change materials only.

CRediT authorship contribution statment

Abdulmunem R. Abdulmunem: Conceptualization, Investigation, Writing-Original draft.
Pakharuddin Mohd Samin: Project administration, Preparation.
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Davide Astiaso Garcia: Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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