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Metal fibers-enhanced PCM thermal energy storage unit: An experimental approach on a composite roof application

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ABSTRACT

Integrating phase change materials (PCMs) into building elements considerably reduces energy demand and improves indoor thermal comfort. However, PCM's low thermal conductivity limits thermal cycles and slows the melting/solidification rate. Literature studies reported various solutions to enhance PCM performance, including nanoparticle dispersion, fins, shape and form stabilizing, metallic foams, and porous mediums, showing noteworthy advancements. Nevertheless, researchers highlighted some limitations in these enhancers, such as instability and agglomeration of nanoparticles, complex configuration of fins, design concerns, and limited shapes of foams. Therefore, presenting a novel thermal enhancer that could tackle the above limitations and benefit from recycled metals is essential. This research investigates the thermal advancements of immersing galvanized steel metal fibers with 0.1 % by weight into PCM units and shows their influence on a compact composite roof arrangement. To this aim, four experimental roofs are fabricated; one set for referencing, the second equipped with pristine PCM (PPCM), and two roofs equipped with PCM-enhanced metal fibres of different thicknesses (MFPCM1 and MFPCM2). The roof's thermal performance is analyzed in view of maximum inner surface temperature reduction, attenuation coefficient, and time delay for two hot days. Study outcomes showed that immersing thin metal fibers into PCM (i.e., MFPCM1) has improved the roof's thermal performance noticeably, wherein the maximum inner surface temperature reduction, attenuation coefficient, and time delay reached a maximum mark of ~17 %, 77.8 %, and 170 % over the reference roof. Comparatively, MFPCM2 showed lower advancements than MFPCM1, achieving 16.5 %, 75.6 %, and 150 %, respectively.

1. Introduction

Phase change materials (PCMs) have undoubtedly shown remarkable advancements during recent years in various thermal applications, especially in the building sector [1–3]. Consequently, numerous studies have been conducted on energy saving and improving building performance in terms of improving heat exchange of HVAC systems [4], optimizing heat storage capacity [5], and increasing building construction inertia [6,7]. In the field of building thermal applications, PCMs have the potential to lower energy needs and enhance building thermal comfort [8]. In this regard, PCMs were applied to building materials and elements as a separate layer [9], immersed into bricks as capsules [10], integrated with plasters [11], and many other different methods [12]. Nevertheless, suitable techniques for introducing PCMs into building envelopes either walls or roofs are crucial and restricted by various parameters such as the PCM melting temperature, position, thickness, etc. [13]. Besides, some limitations are common in such applications, including incorporation difficulties into building construction materials without leakage and poor thermal conductivity which influence the time of heat charging and discharging [14].

Various enhancers have been employed to advance the characteristics of PCMs in thermal applications, such as the immersion of nanoparticles, fins, metallic foams, shape and form-stabilized carriers, and porous mediums [15–17]. For instance, Pandey et al. [18] experimentally developed organic PCMs-based silver nanoparticles with five different concentrations (from 0.2 % to 1 %, with 0.2 % increment), to improve PCM's energy storage capacity. The outcomes showed that mixing silver nanoparticles at 0.8 % with organic PCM has increased the thermal conductivity of pristine PCM from 0.218 to 0.44 W/m·K.

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Nomenclature

Abbreviations

MFPCM1	Phase change material enhanced by thin metal fibers
MFPCM2	Phase change material enhanced by thick metal fibers
PCM	Phase change material
PPCM	Pristine phase change material

Symbols

$T_{in,max}$	Maximum inner surface temperature of roof [°C]
$T_{in,min}$	Minimum inner surface temperature of roof [°C]
$T_{in,REF\ roof}$	Inner surface temperature of reference roof [°C]
$T_{in,PCM\ roof}$	Inner surface temperature of PCM roof [°C]
$T_{out,max}$	Maximum outer surface temperature of roof [°C]
$T_{out,min}$	Minimum outer surface temperature of roof [°C]
$\tau_{Tin,max}$	Time at the maximum inner surface temperature of roof [min]
$\tau_{Tout,max}$	Time at the maximum outer surface temperature of roof [min]

However, the latent heat of the modified PCM was better than that of the base PCM by 1 % only, which was thermally stable up to 220 °C. Wang et al. [19] developed a simplified numerical PCM unit integrated various-style fins (x and z style) with 0.5, 0.75, 1, and 1.5 ratios inclined at 45° and 90° angles to study the PCM melting process. Study outcomes indicated a direct relationship between the fin length and PCM melting rate in which longer fins caused a faster melting rate with uniform temperature change during the melting phase. Moreover, the PCM unit with z style, 1.5 ratio, and 90° inclination angle displayed the best melting rate and maximum energy storage as compared with the other cases. Nassar et al. [20] impregnated hybrid nanoparticles with copper foam into PCM to improve its thermal conductivity considering the effect of weight percentage and the average specific surface of copper foams on PCM thermal properties. The study designated that increasing hybrid nanoparticles and copper foam weight has improved thermal conductivity by 37.7 % compared to pure PCM. Besides, the average specific surface at 1600 m^2/m^3 exhibited desirable thermal properties than other studied cases. Bouzennada et al. [21] explored the effect of dendrite fins on heat melting rate of a nano-enhanced PCM included in rectangular capsules for various cases, including no fins, fin branches length decreased downward (type 1), and fin branches length increased downward (type 2). The study further studied the effect of nanoparticle immersion at 0 %, 3 %, and 6 % volume concentrations on PCM performance. The results showed that increasing nanoparticle concentration together with fins has improved the base PCM characteristics remarkably. Among other cases, fin (type 2) nanoparticle concentration showed the highest PCM utilization at 6 % in which the melting rate was increased by 33 % as compared to the container without fins. Qasem et al. [22] employed a tree-like fin and copper nanoparticles to improve the PCM thermal conductivity and accelerate the charging phase of a PCM-integrated shell-and-tube heat exchanger considering the effect of nanoparticle concentration and sub-fins distribution. The study results revealed that lengthening sub-fins inside the PCM element has reduced the PCM melting time by about 75.7 %. Besides, immersing 6 % nanomaterials into PCM has reduced the melting phase further by 15 % more than pure PCM. Du et al. [23] developed a 3D model with square-shaped latent heat storage units to explore the melting phase progress for pure paraffin, metal foam, fin, and metal foam/fin. The study reported that using metal foam and fins has helped to regulate the overall temperature of the device and improved the PCM melting process but adversely influenced the total heat storage capacity. Compared to pure paraffin, the melting time of PCM using fin, metal foam, and metal foam/fin was minimized by 47.48 %, 79.53 %, and 83.68 %, respectively. These improvements have correspondingly increased the unit temperature by 28.97 %, 79.37 %, and 91.12 %, while decreasing the overall heat storage capacity by 6.0 %, 4.6 %, and 11.64 %, respectively.

Some researchers have discussed the above-mentioned enhancers considering building applications. For example, Kumar et al. [24] explored the appropriate porous material to develop a form stable Capric acid PCM with cement composite. The study findings confirmed that silica aerogel granules have high porosity to prepare stable encapsulated Capric acid PCM with about 80 wt%, while the recycled expanded glass absorbed 25 % only. Besides, the Capric acid-silica aerogel granule showed poor thermal conductivity of about 0.39 W/m.K, compressive strength of about 3.66 MPa, high thermal inertia and energy storage of about 1.32 °C, and 690 kJ/m^3, respectively. The findings also showed that the Capric acid/recycled expanded glass had the highest thermal conductivity of 1.0 W/mK, and a high compressive strength of 13 MPa, while thermal inertia and storage have lower values of about 0.62 °C, and 542 kJ/m^3, respectively. Another study conducted by Canım and Kalfa [25] employed pumice as an economical, lightweight envelope material and good PCM carrier. In their study, three pumice block samples were loaded with paraffinic at 5 %, 10 %, and 15 % ratios by weight while a fourth pumice sample was left without PCM as a reference. The thermophysical characteristics of samples, such as specific heat capacity, thermal conductivity, and latent heat, were measured under controlled laboratory conditions. Later, the Design-Builder software was adopted as a simulation tool to prolong the time of experimental data and demonstrate the influence of PCM/pumice samples concerning the time delay and indoor temperature fluctuations. Results observed that the PCM/pumice thermal characteristics were enhanced notably in which the thermal conductivity was advanced by up to 6 % and specific heat capacity by about 75 %. Simulation findings showed that the developed PCM/pumice could lessen the peak temperature, increase the wall time delay, and dampen the temperature fluctuations averagely by 1.5 °C, 30%, and 25%, respectively. Gupta et al. [26] experimentally examined the influence of PCM-macro encapsulated different-shaped capsules (tubular, square, and rectangular) loaded into constructive clay bricks with and without immersing nanoparticles. The nano PCM was dispersed with 20 wt% graphite to advance thermal storage capacity and investigate the effect of capsules on brick thermal performance in terms of peak temperature and cooling load reduction. Findings showed that the peak temperature of the PCM brick was reduced by up to 81.66 % as compared with the reference brick. The highest thermal amplitude reduction of about 33.33 % and 27.43 % was attained without nano graphite for the brick-enhanced tubular and square capsules, respectively. Furthermore, a maximum cooling load reduction of 23.66 % was achieved for the PCM-enhanced tubular capsules without nano graphite, though the PCM bricks-enhanced rectangular capsules without nano graphite reported a minimum cooling load of about 3.31%. Some other literature studies investigated the advancements of PCM roofs using various metal enhancers are presented in Table 1.

The objective of the current work is to explore novel galvanized steel metal fibers as a potential thermal enhancer for PCM units benefiting from waste and recycled metals. Unlike conventional enhancers (fins, nanoparticles, and foams) which require complex design and costly preparation methods, the proposed enhancer is a flexible technique to be integrated into different PCM unit sizes with cost-effectiveness and sustainability. Besides, the research analyzes the thermal contribution of the proposed PCM unit when incorporating real composite roof arrangement in terms of surface temperature shaving and shifting. To the best authors' knowledge, the proposed technique has not been discussed in previous studies and is worthy to be explored considering its availability, recyclability, and thermal advancements to the built environment.

Table 1
Summary of literature studies carried out to improve PCM roof thermal performance using different enhancement techniques.

Reference	Study location	Enhancement method/ mechanism	Main outcomes
Rahi et al. [27]	Bengaluru, India	PCM concrete roof with immersed two-coin cylinders macro capsules (Polyethylene terephthalate as an encapsulation material)	Peak and average temperature reduction of the roof by 3.2 °C and 1.2 °C, respectively.
Kim et al. [28]	Anseong, Korea	PCM roof-enhanced carbonized rice husks encapsulated inside polyethylene bags	Roof surface temperature minimized by 11 °C.
Kosny [29]	USA	PCM roof-impregnated Polyurethane foams, fabrics, and aluminum foil	Peak heat flow reduction by 70 %.
Baskar and Chellapandian [30]	Delhi, India	Form-stable PCM roof (mixture of lauric acid, palmitic acid, and nano-silica)	Indoor temperature decrement and time delay increment by 8 °C- 10 °C and 60 min, respectively.
Huang et al. [31]	Lab conditions	Form-stabilized composite PCM roof (sodium acetate trihydrate-formamide mixture combined with expanded perlite)	Indoor temperature fluctuations were declined from 32.9 °C to 31.4 °C.
Kumar et al. [32]	Lab conditions	Shape-stabilized composite PCM roof (Gypsum/Lauric acid/ Zeolite loaded into Graphite)	Peak indoor surface temperature reduction by 13.86 % and an average time delay of about 3.46 h were attained.
Rathore and Shukla [33]	Varanasi, India	Shape-stabilized composite PCM roof (Expanded Graphite and Expanded Vermiculite as a PCM carrier)	Maximum indoor peak temperature reduction by 3.8 °C.
Yu et al. [34]	Guangzhou, China	Shape-stabilized PCM roof (paraffin mixed with high-density polyethylene)	The roof's inner surface temperature was minimized by 3.7 °C along with decrement factor reduction by 85 %.
Kumar [35]	Sultanate of Oman	PCM roof with a double-skin aluminum radiation reflector	Internal roof surface temperature and heat gain were reduced by 30.1 % and 18 W/m^2, respectively.
Nguyen et al. [36]	Controlled conditions by simulation	Ferro-PCM enhanced with Al_2O_3 nanoparticles	Roof thermal resistance improvement by 45 %.
Nguyen et al. [37]	Lab conditions	PCM roof-based fumed silica	Room indoor temperature reduction by 9 °C −10 °C.
Meng et al. [38]	Suzhou, China	Foamed cement PCM roof	Internal surface temperature and heat gain were reduced by 2.9 °C and 59 %, respectively.

2. Materials and methods

2.1. Experimental cases

Four roof arrangements were fabricated and tested experimentally in this study; one roof was equipped with pristine PCM (PPCM), two were equipped with PCM-enhanced metal fibers of different thicknesses (thin fibers of 1 mm termed as MFPCM1, and thick fibers of 2 mm termed as MFPCM2), while the fourth roof represented the reference case (REF) which was left without PCM. The schematic representation of prepared roof arrangements is indicated in Fig. 1. The MFPCM units were tested and compared against the PCM and REF cases under harsh conditions of Al Amarah City (located at Latitude: 31.84° & Longitude: 47.14°), Iraq. The PCM was charged into galvanized steel containers and involved in a simple roof arrangement placed within thermally-insulated expanded polystyrene boxes. Tested units were placed in a wide-open air area in which the sunlight hit the units all day. Each unit consisted of an exterior black roofing Isogam (without a reflecting layer) to absorb as much solar

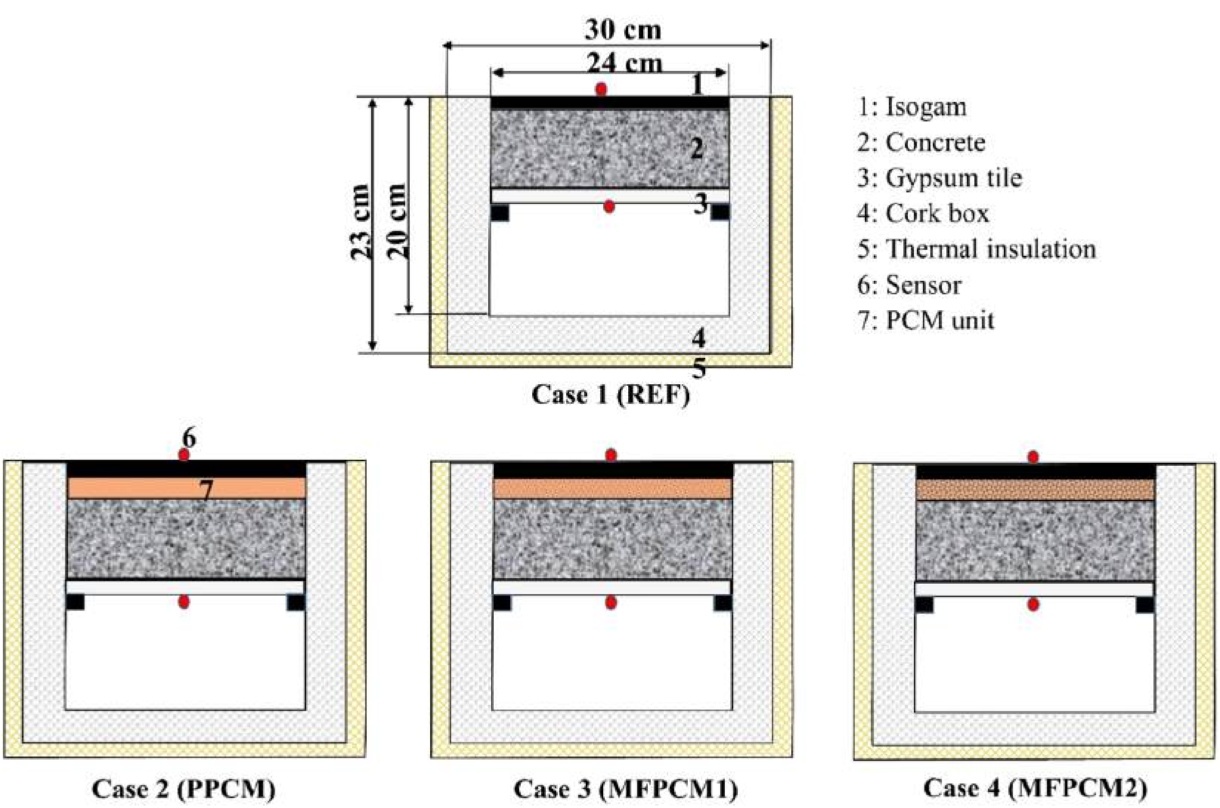

Fig. 1. Representation of tested cases.

radiation as possible and examine the PCM under high outer surface temperatures. A concrete tile of 5 cm was placed next to the Isogam layer. These tiles were made up following the procedure recommended in the Iraqi thermal blog and commonly applied in constructions [39], using locally available raw materials such as Portland cement, sand, and fine gravel with a mixing ratio of 1:2:4, respectively (Fig. 2-d) [Anon., 40,41]. The PCM and MFPCM layers were positioned between the Isogam and concrete layers in the PPCM, MFPCM1, and MFPCM2. The roof arrangement ended with a gypsum mortar title placed beneath the concrete layer to increase the roof's thermal resistance. More detail about the preparation procedure and thermophysical properties of layers could be found in our earlier work [42].

The PCM employed in this experimental work is a bulky Iraqi organic paraffin wax with a high melting temperature of about 40 °C - 44 °C, thermal conductivity of 0.21 W/m.K during melting and solidification, fusion heat of 190 kJ/kg, specific heat of 2.1 kJ/kg and density of 930/830 kg/m^3 for the solid/liquid phases. The paraffin was contained inside three galvanized steel panels establishing the PPCM, MFPCM1, and MFPCM2 (Case 2, Case 3 and Case 4, respectively).

The PCM loaded inside each panel with a quantity of 500 g, as displayed in Fig. 2-a, which was liquefied using a gas boiler (Fig. 2- b), poured, and solidified before being installed in the test boxes.

The metallic fibers included in Case 3 (MFPCM1) and Case 4 (MFPCM2) were made of galvanized steel (1 and 2 mm thicknesses), originally collected from local turning workshops, and used as a novel thermal enhancer of PCM thermal cycles. These fibers could tackle the main limitations of existing enhancement solutions, such as nanoparticle dispersion (instability and agglomeration) [43], complex configuration of extended surfaces (fins) [44], costly process of shape and form-stabilized carriers [45], and limited shapes of metal foams and porous mediums which limits the PCM thermal applications [46,47]. Accordingly, the flexible structure of fibers could provide ease of inclusion at any shape and size of PCM units with no agglomeration issues. Besides, the availability and simple design of fibers could positively affect application feasibility and encourage the use of recycled metals which support the world's efforts towards sustainability [48]. The two types of metal fibers were weighted to be 50 g, included in 500 g of PCM in the MFPCM1 and MFPCM2 (Fig. 2-c). This weight ratio was adopted to appropriately fill PCM units following the recommendations of some literature studies that reported decent thermal advancements for 10 % by weight of metal enhancers/PCM [43,49–52]. The final appearance of experimental boxes is shown in Fig. 2-e.

This experimental study was applied for two days during September, a hot summer month in the study location. Twelve T-type thermocouples (TEMPSENS brand) were employed to record the surface temperature every 10 min with ± 0.5 °C accuracy. A thermocouple was positioned on the outer Isogam layer of each box to measure the outer surface temperatures, while two thermocouples were fixed on the inner gypsum tile of each roof arrangement for inner surface temperature measurement.

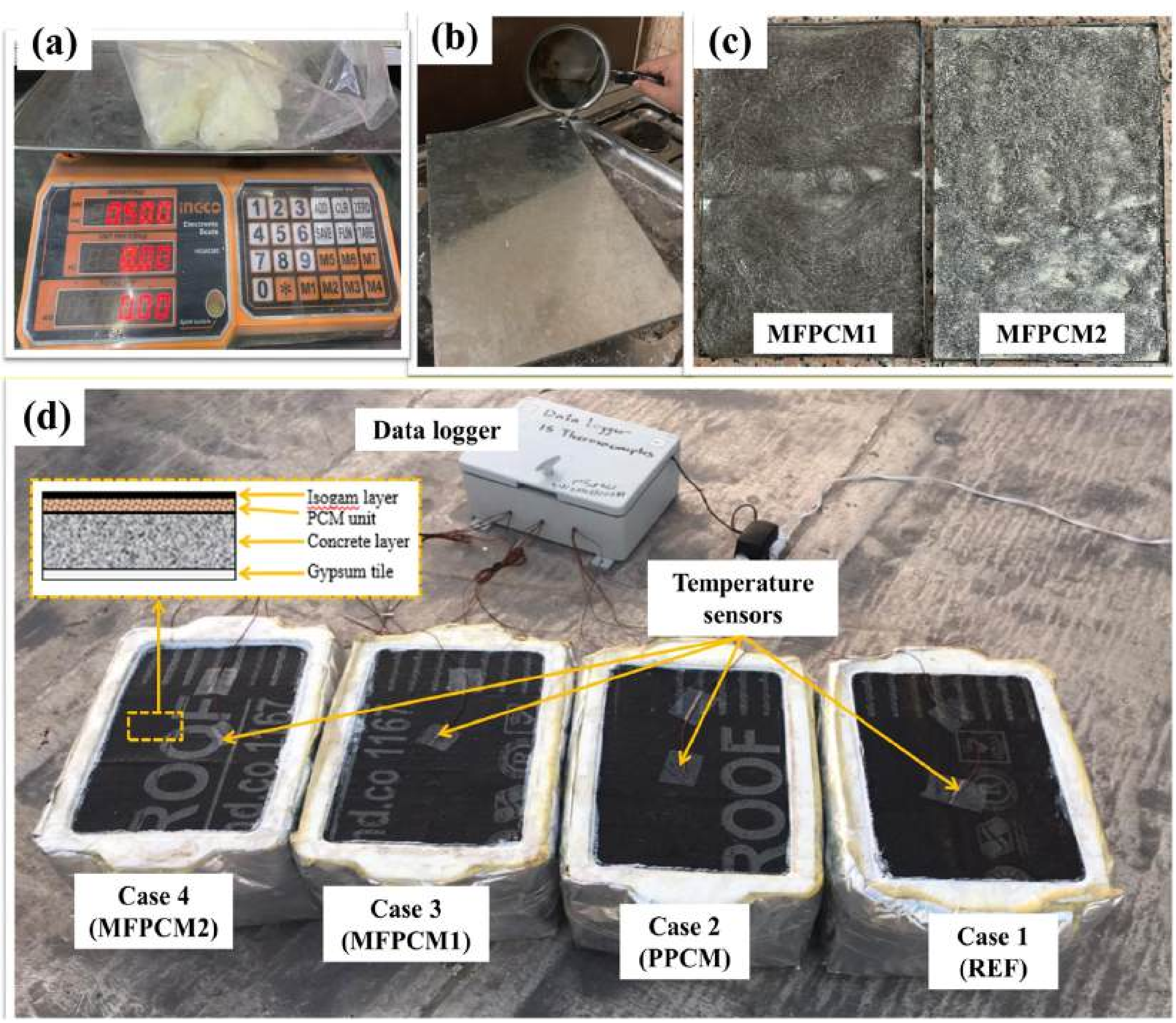

Fig. 2. (a) Weight of PCM (b) PCM charging (c) MFPCM1 and MFPCM2 units (d) final experimental arrangement.

2.2. Evaluation of thermal performance

The thermal performance of experimental roofs was examined using three thermal indicators, dealing with the surface temperature variations throughout the thermal cycle. These indicators include the maximum inner surface temperature reduction, attenuation coefficient, and temperature time delay.

The maximum temperature reduction indicates the highest reduction in the inner surface temperature of the PCM roofs as compared to the reference one. Mathematically, the maximum temperature reduction was calculated using Eq. (1).

$$\textit{Maximum temperature reduction} = \frac{T_{in,REF\ roof} - T_{in,PCM\ roof}}{T_{in,REF\ roof}} \times 100\% \tag{1}$$

where $T_{in,REFroof}$and $T_{in,PCMroof}$ refer to the maximum inner surface temperature in the reference roof and roofs equipped with PCM (i.e., PPCM, MFPCM1, and MFPCM2).

The second indicator, the attenuation coefficient, denotes the temperature decrease across the roof elements in terms of the maximum and minimum inner and outer surface temperatures (i.e., the roof's thermal resistance). Consequently, the lower attenuation coefficient designates lower temperature fluctuations within the roof, indicating improved thermal behavior of the roof. Mathematically, the attenuation coefficient was calculated by Eq. (2) [53], as follows:

$$\textit{Attenuation coefficient} = \frac{T_{in,max} - T_{in,min}}{T_{out,max} - T_{out,min}} \tag{2}$$

The time delay is introduced as the period between peak temperatures of the outer and inner surfaces of the roof. This calculated parameter is significant to present the roof's ability to resist heat transfer. Mathematically, the time delay was calculated according to Eq. (3) [5], as follows:

$$\textit{Time delay} = \tau_{\,T_{in,max}} - \tau_{T_{out,max}} \tag{3}$$

3. Results and discussion

Fig. 3 displays the variation of the outer and inner surface temperatures of examined roofs. It could be observed that the inner surface temperature of roofs equipped with PCM is remarkably lower than that of the reference roof during the day. However, the temperature behavior is reversed at 18:00 onwards and the inner surface temperature of the reference roof became lower than that of the PCM roofs until the end of the cycle.

Considering peak inner surface temperature, the reference roof showed a high temperature of about 66.5 °C in the first cycle, against 58 °C, 55.25 °C and 55.5 °C for the PPCM, MFPCM1 and MFPCM2 roof, respectively. Same like, the reference roof showed 67.5 °C in the second cycle, while the PPCM, MFPCM1, and MFPCM2 roofs showed 59 °C, 56.25 °C, and 56.5, respectively. Reversely, the reference roof designated the lowest inner surface temperatures in the early morning, showing 31.5 °C in the first and second cycles, while it ranged between 35.25 °C – 36.25 °C in the PCM-based roofs.

Referring to Fig. 4, MFPCM-based roofs showed noticeable maximum temperature reduction over the PPCM-based roof in both cycles. Thin metallic fibers (in MFPCM1) have minimized the maximum temperature of the roof by about 4.1 % and 3.7 % over the PPCM unite in the first and second cycles, while thick fibers (in MFPCM2) have minimized the temperature by 3.7 % and 3.3 %, respectively.

Overall, the MFPCM1-based roof showed better temperature reduction than the MFPCM2-based roof, which means that the thin metal fibers enhanced the PCM more than the thick fibers during peak time (around noon). Here it could be said that thin metal fibers have accelerated the melting phase of PCM during the hours before noon more than thick fibers since the surface area of heat transfer of thin metal fibers is larger than that of thick fibers.

The temperature reduction of the MFPCM1-based roof and the MFPCM2-based roof during the whole thermal cycle gives a better indication of the thermal advancements of metal fibers against the PPCM-based roof and reference roof. Referring to the time-by-time temperature reduction (every 10 min) presented in Fig. 5, it could be observed that the temperature reduction of the MFPCM1-enhanced roof is higher than that of roof-based MFPCM2 during peak time. This means that the PCM was melted in the MFPCM1 much better than in the MFPCM2 resulting from the fast heat charging process, although the difference was insignificant. Considering the time after sunset (18:00 onwards), it could be realized that the MFPCM1-based roof indicated lower temperature reduction as compared to the MFPCM and PPCM-

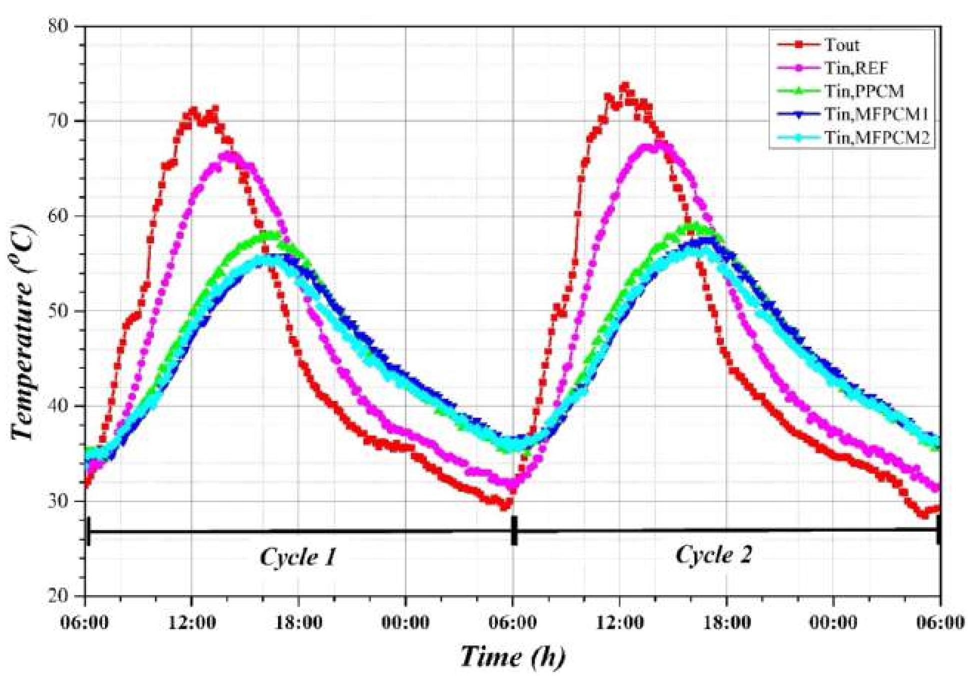

Fig. 3. Temperature variation of examined cases (T_{out} represents the average outer surface temperature of all roofs).

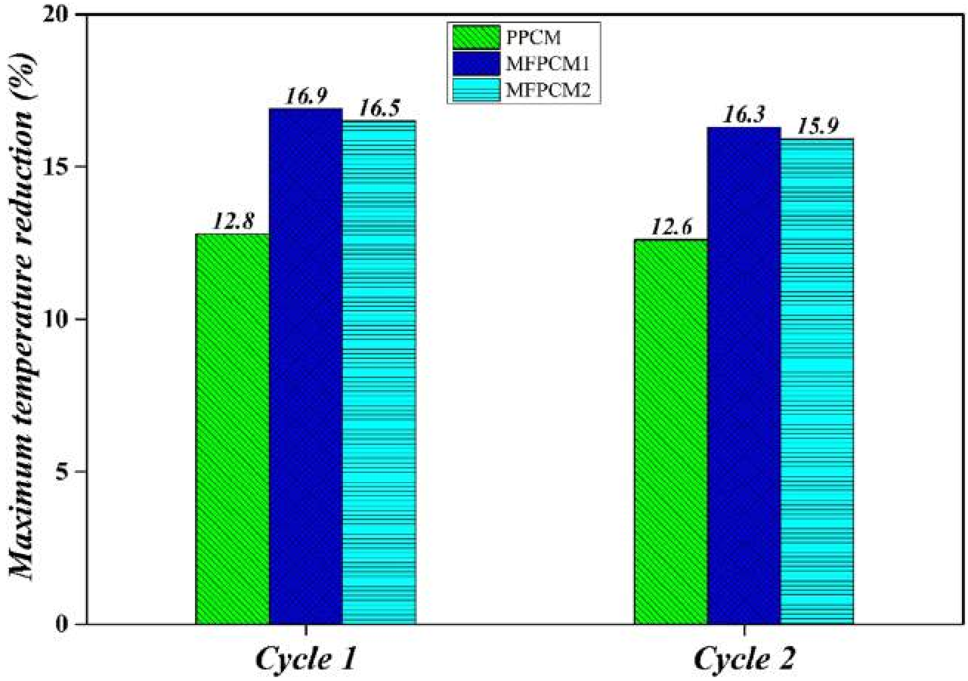

Fig. 4. Maximum temperature reduction of PCM roofs as compared to reference roof.

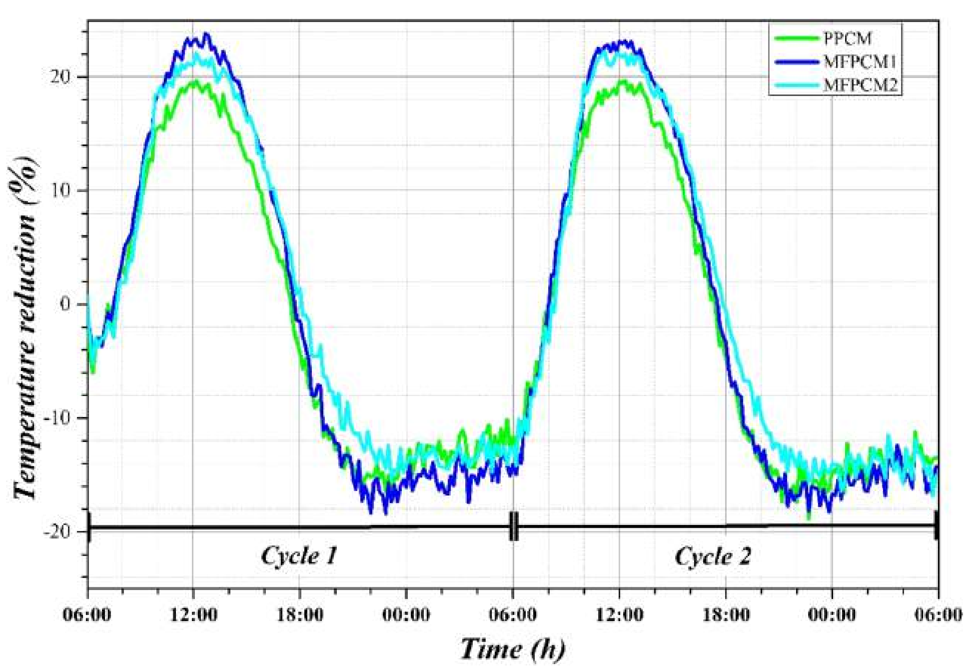

Fig. 5. Temperature difference of PCM roofs compared to reference roof.

based roofs. This could be attributed to the high amount of heat stored during the day inside the MFPCM1 unit which needs more time to be released during low-temperature hours at night.

Fig. 6 presents the attenuation coefficient of experimental roofs. As expected, PCM roofs showed a remarkably lower attenuation coefficient than the reference roof. The attenuation coefficient of the PPCM, MFPCM1, and MFPCM2-based roofs was about 56 %, 75 %, and 73 % lower than that of the reference roof in the first cycle, while it was respectively about 55 %, 78 %, and 76 %, in the second cycle. These results revealed that the metal fibers have noticeably narrowed the temperature fluctuation in the MFPCM1 and MFPCM2-based roofs compared with the PPCM and reference roofs.

The calculation results of a temperature-time delay of experimental roofs are shown in Fig. 7, which obviously displays that PCM-based roofs had a high time delay compared to the reference roof. The PPCM, MFPCM1, and MFPCM2-based roofs showed extended time delay over the reference roof by 120 min, 150 min, and 140 min in the first thermal cycle, and about 120 min, 170 min, and 150 min in the second cycle, respectively. These results are equivalent to 109 %, 136 %, and 127 % in the first cycle, and about 120 %, 170 %, and 150 % in the following thermal cycle. The results indicate significant thermal benefits of PCM inclusion into the roof regardless of the presence of metal fibers, which

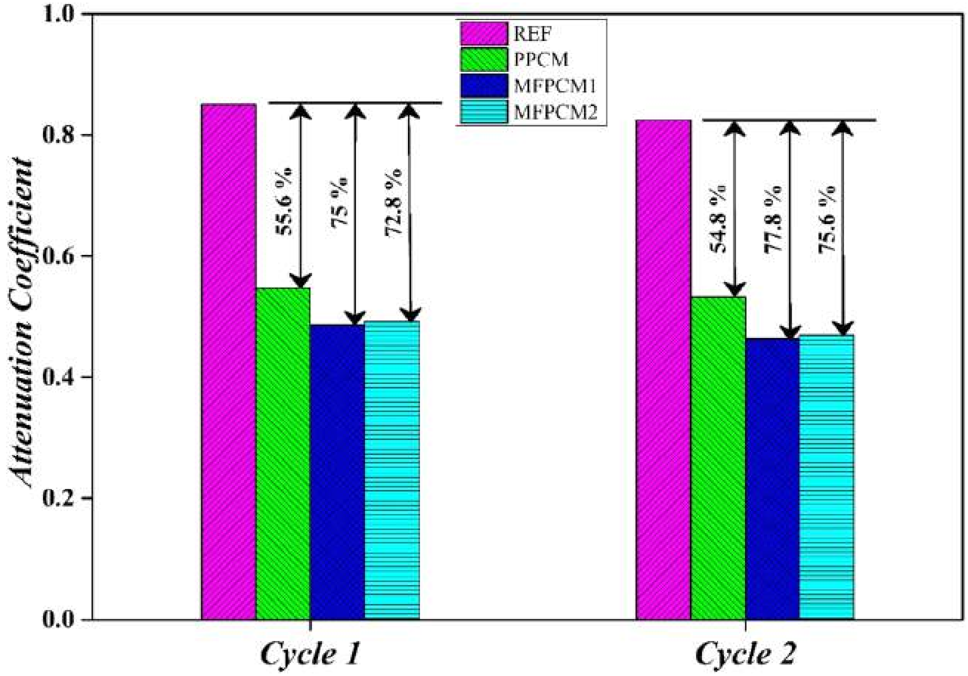

Fig. 6. Attenuation coefficient of examined roofs.

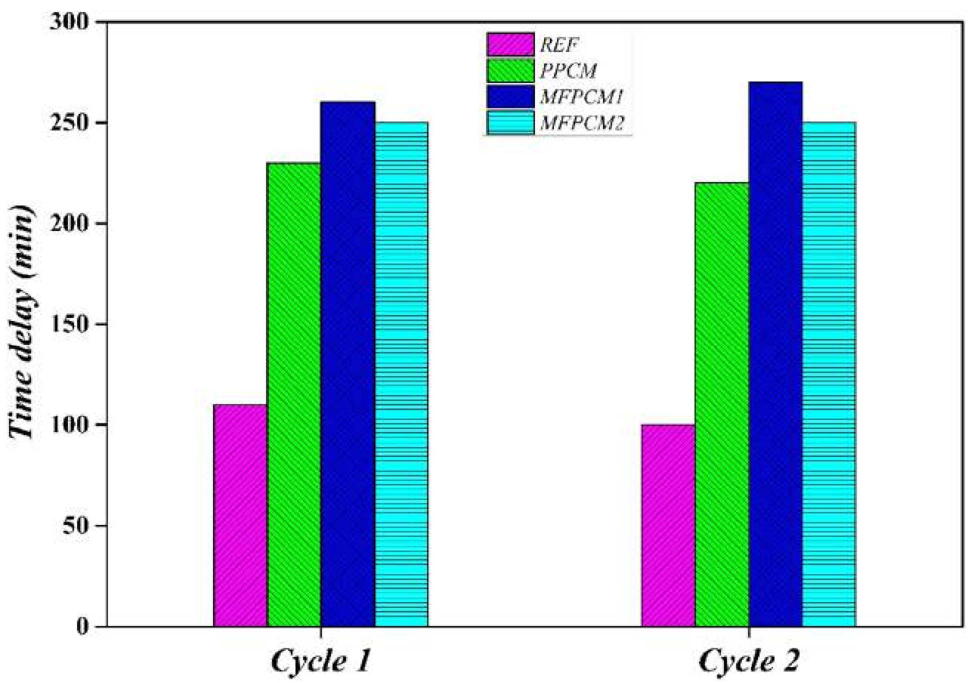

Fig. 7. Time delay of examined roofs.

further enhanced the PCM thermal performance. Besides, heat shifting by at least two hours is a significant gain in the building industry and significantly proves the worthy implementation of PCMs under harsh weather conditions.

4. Conclusion

The present work experimentally examines the influence of immersing metal fibers into phase change material (PCM) units for a composite roof application. Four composite roofs were examined for two thermal cycles under two harsh summer days in Al Amarah City, Iraq. A pristine PCM (PPCM) was involved in one roof, while thin and thick metal fibers with 50 g were immersed into 500 g paraffin wax equipped into two other roofs (i.e., MFPCM1 and MFPCM2-based roofs), while the fourth roof was left without PCM for referencing. Overall, the MFPCM1, followed by MFPCM2 roofs showed better thermal behavior than the PPCM and reference roofs. Concerning the inner surface temperature, the MFPCM1 indicated lower temperatures than other roofs thanks to the effective enhancement of thin fibers for the PCM melting and solidification phases. The MFPCM1-based roof showed better temperature difference than the MFPCM2-based roof during the daytime (between 6:00 and 18:00), while the latter showed better behavior after 18:00.

The MFPCM1-based roof also displayed better attenuation coefficient and time delay over the MFPCM2 and PPCM-based roofs as compared to the reference one.

Further analysis could be conducted considering other metal fiber types with lower weight per PCM quantity to investigate the techno-economic aspects of this enhancer. Besides, long-term numerical simulations could be conducted to compare various thermal enhancers, including fins, foams, and metal porous mediums, to show the contribution of each enhancer to the built environment in comparison to the enhancement method presented in this research.

CRediT authorship contribution statement

Qudama Al-Yasiri: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization. **Mohammed Alktranee:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Márta Szabó:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis.

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

Data will be made available on request.

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