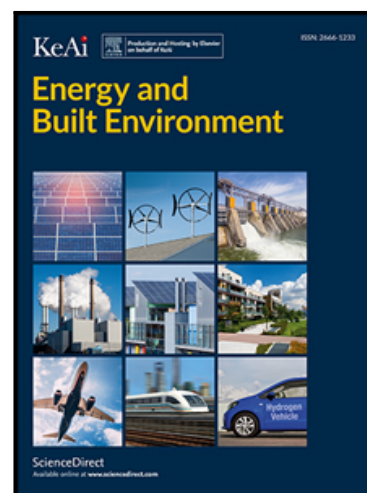


## Journal Pre-proof

Empirical investigation to explore potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings

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**Highlights:**

- Panels containing PCM, Wood-shaving and PCM/wood-shavings amalgams are created.
- Panels are subjected to heat profiles and their thermal performances were compared.
- Heat peak reduction, heat peak shift and fluctuation of temperatures are examined.
- Amalgamation of wood-shavings did not improve the PCM's thermal performance.
- The overall weight of the panels was reduced due to amalgamating wood-shavings.

Journal Pre-proof

# Empirical investigation to explore potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings

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## Abstract

The reduction of gained heat, heat peak shifting and the mitigation of air temperature fluctuations are some desirable properties that are sought after in any thermal insulation system. It cannot be overstated that these factors, in addition to others, govern the performance of such systems thus their effect on indoor ambient conditions. The effect of such systems extends also to Heating, Ventilation and Air-conditioning (HVAC) systems that are set up to operate optimally in certain conditions. Where literature shows that PCMs and natural materials such as wood-shavings can provide efficient passive insulation for buildings, it is evident that such approaches utilise methods that are of a degree of intricacy which requires specialist knowledge and complex techniques, such as micro-encapsulation for instance. With technical and economic aspects in mind, an amalgam of PCM and wood-shavings has been created for the purpose of being utilised as a feasible thermal insulation. The amalgamation was performed in the simplest of methods, through submerging the wood shavings in PCM. An experimental procedure was devised to test the thermal performance of the amalgam and compare this to the performance of the same un-amalgamated materials. Comparative analysis revealed that no significant thermal gains would be expected from such amalgamation. However, significant reduction in the total weight of the insulation system would be achieved that, in this case, shown to be up to 20.94%. Thus, further reducing possible strains on structural elements due to the application of insulation on buildings. This can be especially beneficial in vernacular architectural approaches where considerably large amounts and thicknesses of insulations are used. In addition, cost reduction could be attained as wood shavings are significantly cheaper compared to the cost of PCMs.

**Keywords:** PCMs; Heat peak; Heat peak shift; Thermal performance; Wood shavings; By-products.

## 1. Introduction

To achieve higher comfort levels of occupants, traditional architecture incorporated varied aspects such as natural ventilation, shading, thermal mass and passive cooling techniques as some of the most important passive design features of traditional architecture [1,2]. In hot-arid climate regions, 70-80% of total energy consumption is used to operate active cooling systems [3], and consequently, reducing the reliance on those will have a drastic impact on energy consumption. An optimized envelope design can improve the thermal performance through passive solar techniques [4–7]. Some of the other variables that influence indoor thermal comfort includes: thermos-physical properties of the building's envelope material [8]; the roof optical properties, namely the albedo, thermal emissivity and building insulation [5,9–11] that play an important role in the energy balance of buildings. Indoor air temperature is one of the important factors that contributes to achieving thermal comfort of occupants inside buildings [12,13] [14–16]. It is evident that the outdoor heat loads that a building is exposed to may affect the indoor air temperatures as heat is conducted through the building's envelope. Many passive attempts to limit the effect of exterior heat on interior temperatures have been, to a good extent, successful [17–20]. This results in a lowered indoor temperature which increases thermal comfort in hot climates and reduces strain on HVAC systems caused due to heat overload on these devices [13,21–24].

In last couple of years, PCMs have been extensively researched as a possible part of passive thermal control methods. Many researchers have attempted to utilize them in different ways [25–31], which have shown good potential. The innovative manner in which PCMs have been utilised has been miscellaneous. Methods such as using a layer of paraffin wax on brick walls and inside building envelopes which has shown to be successful in reducing indoor air temperatures and related cooling electricity consumption of up to 75% [32–41]. Other studies have attempted utilise "PCM immersion" of building elements such as PCMs infused wallboards [42–45,39], PCM-mortar [46–51], PCM infused bricks [52–54], PCM-concrete [55–66] and PCM-enhanced plaster [67–69]. Such methods have reported the ability to reduce indoor temperatures by up to 5 °C. Similarly, the combination of PCMs and other materials such as Silica, Graphene and Gypsum has also been investigated with promising results as to the thermal performance [70–78]. Also, the incipient field of Nano-technology has allowed for much progress in this regard by adding certain types Nano-particles to enhance PCM mixtures [31,79–83]. In terms of methods of utilising PCMs, encapsulation of PCMs seems to provide a good potential as a passive thermal control technique [84–92]. The encapsulated PCM is used also in various manners. Macro-encapsulated PCMs can be used to fill void in brick walls which show a possible reduction in temperature of up to 6.31°C or 25% of peak temperatures [29,93–95]. Similarly, macro-encapsulated PCMs can be placed in bags which also show a decrease in peak indoor temperatures, reported to be around 12.04 to 17.26% [96–98].

Traditional methods have also shown good thermal performance, in many cases comparable to modern passive thermal control methods [99–102]. Such methods involve using copious natural materials such as stone, mud, fabrics, plant segments and wood, utilised in various ways [101]. With the abundance of suitable natural materials, wood shavings have been the focus of investigation as it has shown good thermal behaviour. In addition, wood shavings are commonly found as a by-product in wood workshops and through industrial process. In many cases, it is disposed of with no significant use [103], which consequently results in it being of low cost, thus, further expanding the feasibility of usage. Furthermore, wood shavings are low in density compared to materials such as PCMs, resulting in lower weights. Also, utilization of wood-waste in particular is seen to be of desirable environmental impacts [102,104], which includes many forms such as cork, wood fibre and hemp. It is further explained that the advantageous thermal properties are a result of certain

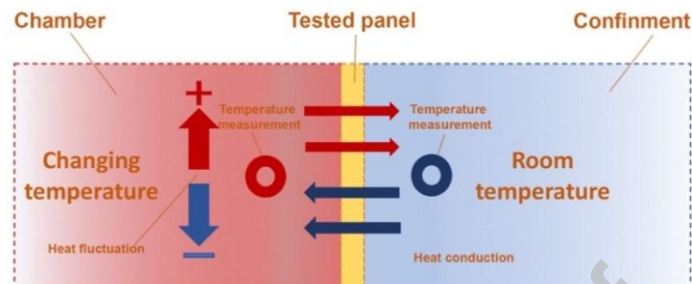
characteristics such as lower embodied energy, moisture buffering capacity compared to other inorganic materials [104]. In addition to its low thermal conductivity that ranges from 0.048 to 0.055 W/mK, which is comparable to other commercial insulation materials [102,104–106]. Furthermore, waste wood can be formed into panel-like shape that can act as effective thermal insulation with a density of around 315 kg/m<sup>3</sup> and a thermal conductivity of around 0.08 W/m/K [106,107]. It is worthy to note that many segments of various types of plants are considered to be composed of wood-fibres, especially plants stalks and stems. Under certain conditions, these segments can be utilized to act as actual wood-fibres, which that have been found to provide good thermal behaviour, be cost-effective and have less environmental impact [15,99,103,107–112][103,111,112]. Such plant segments can include cotton-stalk [113–117], date palm branches [118], tomato-stalks [119], sun flower [120], corn cob [121], straw-bale [122–125], bamboo [41] and poppy husk [126]. Such materials have been utilised in various ways, which has shown thermal conductivities ranging between 0.051 and 0.053 W/(m K) [122] and as low as 0.040 W/mK [125,127,128] in some cases, with heat dampening of 93.6% and a heat time lag of 9.12 h [123]. Combined wood particles of different sizes, in to boards, are also a viable approach that has shown efficient performance with thermal conductivities of between 0.1078 W/mK and 0.0742 W/mK [129,130]. It is evident from the previously discussed literature that using wood-related materials as a form of natural insulation is advantageous, with thermal performances similar to this of commercial synthetic materials, in addition to having better environmental impacts.

The mentioned earlier refers to successful attempts to utilise both wood-base materials and PCMs. However, most of these attempts were made through mechanisms that require substantial technical effort such as impregnation of PCMs into the micro-structure of fibrous materials, including wood, through the use of vacuum pressure [131–133]. In the present study, wood shavings were amalgamated with PCMs through submerging. This particular method was utilised as it requires little intricacies thus eliminating cost, effort and technical issues. Hence, the novelty of the present study lays in the experimental investigation of the effectiveness of a simplified amalgamation approach as an alternative to common complex PCM utilisation methods that require intricate technologies to conduct, such as these mentioned earlier. Furthermore, the experimental approach carried out in this case differs from similar studies in terms of the purpose of using wood-shaving. Where most studies perceive such material as an encapsulation medium for the PCM particles as a macro encapsulation [134–138], the present study uses wood-shavings as supplement to PCM, with the goal to enhance its thermal performance as thermal insulation. The aim of the mentioned earlier is to explore possible advantageous gains the may be achieved from such simple method, weather gain of a thermal nature or otherwise. To achieve this, the amalgamated mixture is investigated for many features. Aspects such as heat peak reduction is important and heat peak shift are investigated as they describe the potential of a thermal insulator to impede conduction of heat through facades and the influence of the latent heat storage of such materials [40,41,54,66,97,139–142]. Also, the ability to reduce fluctuations in indoor air temperature has been investigated in this article. This is of significance as outdoor air temperature may fluctuate un-uniformly [20,143,144] causing analogous fluctuations in indoor air temperatures [145,146], which can cause thermal discomfort to inhabitants and affect the performance of HVAC systems exposed to this.

## 2. Thermal performance of PCM panels

As determined, the tested panel is placed between two controlled environments. To apply the required heat variations on one of the sides of the panel, a climatic chamber was used. To control the initial temperature of the other side, a confinement holding the panel was

created. As the temperature would vary on the side of the panel that is exposed to the chamber, the other side would gradually be thermally influenced by this variation. Through measuring the air temperature on both sides and comparing them, the effect of the PCM/PCM-wood shavings could be assessed. The same process was repeated for the control panel (panel with 1 sheet of Plexi-glass) and the 1 cm air gap panel (panel with 2 sheets of Plexi-glass). Figure 1 shows a schematic representation describing the position of the tested panel in relation to the controlled environments applied.



**Figure 1:** Schematic representation of the experimental procedures carried out on the tested panels (Authors' own).

To choose an appropriate type of PCM for this study several factors were considered. It was considered that the chosen type of PCM is applicable in building applications, thus, having a melting/freezing temperature that is within range of the prevailing temperatures found in some hot climates. It is important to note that literature has pointed out that applications relying on PCMs can fail due to inappropriate melting/solidification temperatures [147]. In addition to being durable and having congruent melting to ensure that it retains original structure throughout numerous cycles of phase change [148,149]. In addition, aspects such as 1) chemical stability; 2) complete reversible freeze/melt cycle; 3) limited degradation; 4) non-toxicity, 5) non-flammability and 6) non-explosiveness and non-corrosiveness where taken in to account [150]. Paraffin waxes are able to provide most of the required criteria described earlier [151]. The PCM initially chosen to be used is Paraffin wax 43/46 obtained from a UK based chemical company (Scientific laboratory supplies SLS) product No. CHE2750, shown in Figure 2 (A&B). Table 1 shows some of physical and chemical properties of the PCM as provided by the supplier.



(A)



(B)

**Figure 2:** (A) Packaging of Paraffin wax as provided by supplier. (B) Appearance of paraffin wax in the solid phase.

**Table 1:** physical and chemical properties of the paraffin wax as provided by the supplier.

<b>Appearance</b>	White waxy solid
<b>Odour</b>	Nectareous.
<b>pH</b>	Not applicable
<b>Boiling Point</b>	350°C
<b>Melting Point</b>	43°C
<b>Flash Point</b>	300°C (Closed cup)
<b>Upper Flammable Limit</b>	Not applicable
<b>Lower Flammable Limit</b>	Not applicable
<b>Auto Ignition</b>	Not applicable
<b>Explosive Properties</b>	No.
<b>Oxidising Properties</b>	No.
<b>Vapour Pressure</b>	Not applicable
<b>Relative Density</b>	0.9550
<b>Water Solubility</b>	Insoluble in water.

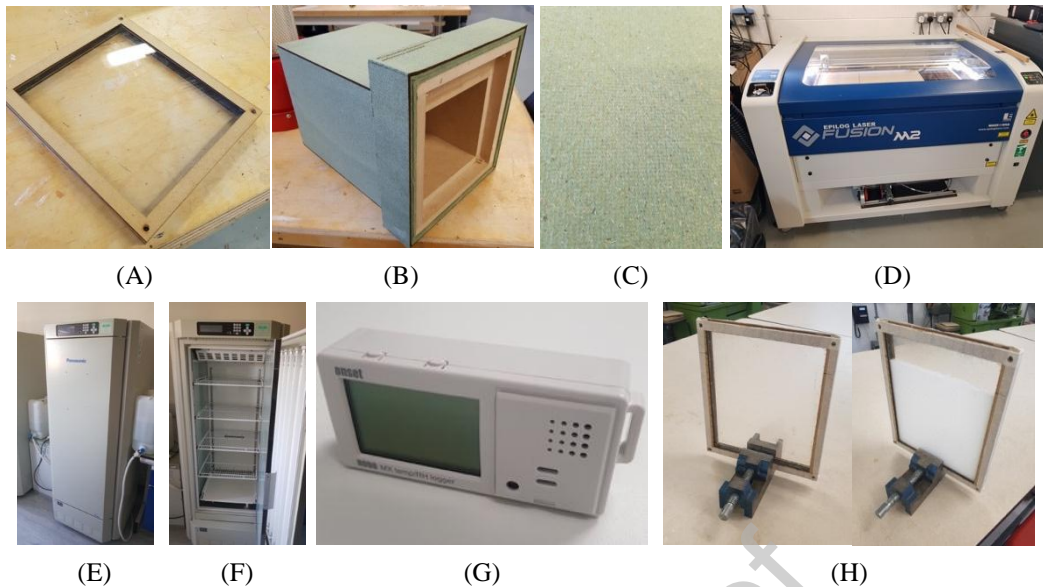
## 2.1. Experimental rig

To conduct the experimental condition described earlier, a rig consisting of several elements was designed. An appropriate container was required to encapsulate the tested material without affecting test results. Factors such as leakage, chemical compatibility and expansion properties of the PCM were taken into account as literature shows that they may be of importance in PCM testing [148,152]. The container used for this experiment was created using sheets of MDF wood that were cut using an Epilog Fusion M2™ Laser cutter and engraver for precise cutting. The container is constructed of a frame of MDF wood with a thickness of 10 mm, with a width of 18 mm. The inner dimensions were 20 \* 24 cm so as to accommodate the PCM panel (20 \* 20 cm) and provide a 20 percent of the PCM volume as void for expansion (4 cm). Four layers of water-sealing varnish coating are applied to ensure that no absorption of the PCM would occur when it is in the liquid phase. The top side of the frame was removable to allow for the materials to be inserted into the container. Both sides of the frame were covered with sheets of Plexi-glass of 2mm thickness using glue. The container after assembly is shown in Figure 3 (A). For comparison purposes, two more panels were created. One of them, a panel that consisted of a single 2 mm layer of Plexi-glass and a wooden frame with the same dimensions as the PCM encapsulation panel, was used as a reference control panel. The other panel was identical to the previously mentioned, however, no materials were placed inside. The purpose of this panel is to test the thermal performance of the two layers of Plexi-glass with an intermediate air gap of 1 cm width.

As mentioned earlier, a five-sided box-like confinement was constructed of isolating materials. The 6<sup>th</sup> side remained as a void to accommodate the panel under investigation. This allowed the side of the panel that is facing the inner part of the confinement to be exposed (initially) to room temperature while the other side is exposed to the pre-set temperatures. Figure 3 (B) shows the confinement after final assembly, including fibre-wood insulation. The box-like confinement was made of 18 mm thick sheets of medium density fibre wood (MDF) that were cut and assembled with inner dimensions of 20cm\*20cm\*35cm. To hold the PCM encapsulation panel at the front of the confinement as required, a platform with the same inner dimensions as the panel was created from the same materials. Insulation was made by covering all sides with four layers of wood-fibre sheets (Diall™ Fibre wood underlay) with total thickness of 20mm, shown in Figure 3 (C). An Epilog Fusion M2™ Laser cutter and engraver, shown in Figure 3 (D), was used to ensure accuracy of the cut parts. To subject the PCM panel that are under investigation to environment-like conditions, the panels and the insulated confinement were placed inside an environmental chamber during the testing process. The environmental chamber used was a Panasonic™ versatile environmental test chamber model MLR-352 as shown in Figure 3 (E&F). The chamber has the ability to be programmed to manipulate the temperature of the inner environment to change from 0°C to 60°C. To monitor the change in air temperature of both side of the encapsulation panel throughout the duration of the experiment in which heat was applied, two HOBO® MX Temp/RH Data Loggers model-(MX1101) shown in Figure 3 (G) below are used. The data loggers had built in thermal sensors with a range of -20° to 70°C with an accuracy of ±0.21°C in addition to humidity sensors. The loggers are capable of logging up to one reading per second. Control and setup of the data loggers can be done through an iOS or Android™ device through a Bluetooth® connection. Logged data is also downloaded through the wireless connection mentioned earlier through HOBO mobile® app.

## 2.2. Experimental procedures

The following depicts details regarding the creation of the three panels in addition to a control panel and an empty panel created for further comparison purposes. A description of the heat profiles applied to the panels with various details is also provided.



**Figure 3:** (A) Material container after assembly. (B) The Box-like confinement, with the platform end. (C) Diall™ Fibre wood underlay sheets. (D) Epilog Fusion M2™ Laser cutter and engraver. (E) Exterior of environmental chamber. (F) Interior of chamber, (G) HOBO® MX Temp/RH Data Logger model-(MX1101). (H) Encapsulation panel secured upright using a holder, PCM had been poured in and left to cool, photographed after 10 minutes approximately.

### 2.2.1. PCM panel testing

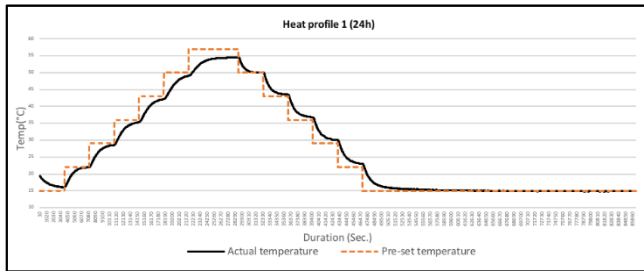
To create a PCM panel, 382 grams of the PCM were weighed (the PCM had a density of 0.9550, and the required panel was with dimensions of 20\*20\*1 cm). This was the amount required to create a panel with the desired dimensions. The PCM was then placed in a steel container then liquefied using an electric hotplate to temperature of 65°C approximately. The liquefied PCM was poured in the encapsulation panel. The encapsulation panel was held upright using a holder shown in in Figure 3 (H) above as the liquefied PCM was poured-in till 200 mm were filled in order to leave 40 mm for expansion as mentioned earlier. The PCM was poured slowly so that to ensure that no air pockets (air-bubbles) had been formed. The panel was left over-night in a relatively cool environment so as to allow for the PCM to solidify. Both the encapsulation and the confinement were then placed inside the environmental chamber, which was then sealed. A series of tests were performed on the panel. In each test, a different heat profile was used. The aim of this is to monitor the performance of the tested materials under different modes of heat loads. It is important to note that two of the heat profiles are used to simulate natural day/night cycles were as the rest was used to simulate different fluctuation in temperatures that may occur in certain environmental conditions. Table 2 depicts the temperatures and durations that the chamber was pre-set to. A difference is identified between the pre-set and actual measured temperatures, due to capabilities. Measurements were set to be logged every 10 seconds.

In heat profile 1, a gradually increasing/decreasing profile was used. The profile was an attempt to simulate the natural gradual increase of temperature that would occur in a hot environment during day time and the decrease of temperature during night. The heat profile ranged from 15°C to 57°C in a duration of 24 hours. Figure 4 (A) shows the temperature inside the chamber during test. In order to achieve a gradually changing temperatures as required, twelve steps of temperatures had to be set. Each step was for the duration of 1 hour and increased in temperature by 7°C. Likewise, Profiles 2-6 were conducted with varying cycles of heat and different durations. Figure 4 (B, C, D, E & F) show the change in temperature according to the setting of each profile.

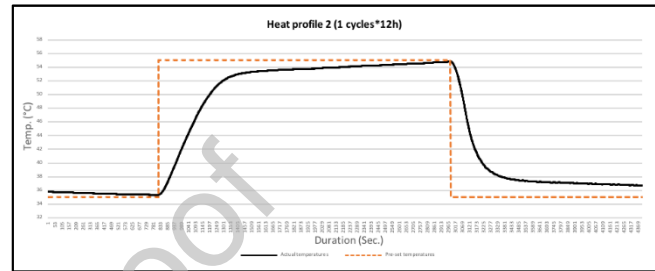


**Table 2:** Pre-set heat profiles

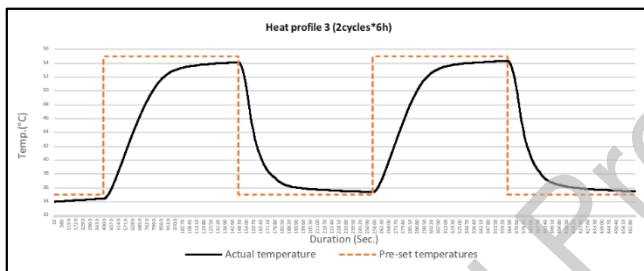
Heat profile	Minimum temp. °C	Maximum temp. °C	Cycles	Cycle duration (hours)	Total duration (hours)
1	15	57	1	24	24
2	15	55	1	12	12
3	35	55	2	6	12
4	35	55	3	4	8
5	35	55	3	2	6
6	35	55	3	1	3



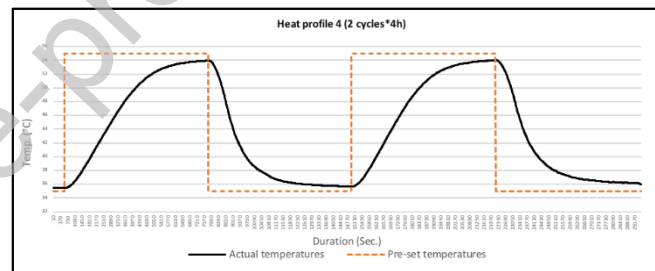
(A)



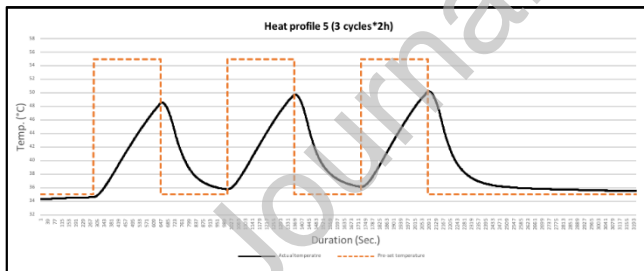
(B)



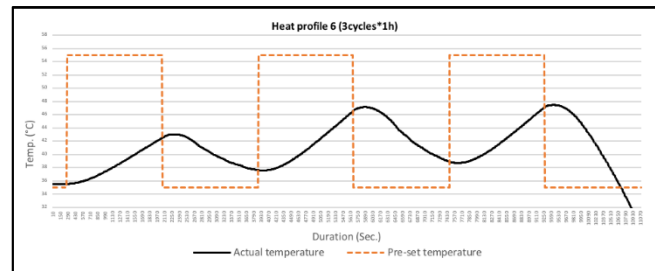
(C)



(D)



(E)



(F)

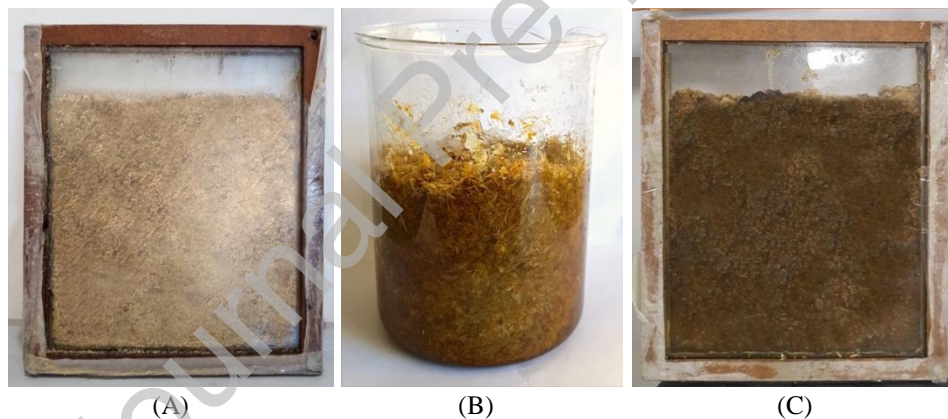
**Figure 4:** Pre-set and actual temperature inside the environmental chamber for: (A) Heat profile 1, (B) Heat profile 2, (C) Heat profile 3, (D) Heat profile 4, (E) Heat profile 5, (f) Heat profile 6.

### 2.2.2. Wood shavings filled panel (Ws):

Wood shavings obtained from a local provider were used. The utilized wood shavings were chipping of plywood obtained as a by-product of wood manufacturing processes. The approximate calculated bulk density of the shaving in their loose form was  $0.1 \text{ g/cm}^3$ . An amount of 40g of wood shavings was placed inside the panel (with dimensions of  $20 \times 20 \times 1 \text{ cm}$ ). This mount was sufficient for the panel to be filled with wood shavings without any form of compression. Figure 5(A) shows the panel filled with the amount of wood shavings.

### 2.2.3. PCM/Wood-shavings (PCM/Ws) panel testing

Wood-shavings were obtained from a local provider. To create the mixture of wood-shavings and Paraffin wax, 40g of wood-shavings were weighed on a scale (as 14% of the total weight of the mixture). An amount of 260g of Paraffin wax (86% of the total weight of the mixture) was melted on a magnetic stirrer (set to 60°C) which was used to stir the wood-shavings in the mixture. The wood-shavings were added gradually to the wax while being stirred. This is to ensure that all particles of the wood-shavings have been engulfed with the wax. Once the entire amount of wood-shavings was added to the wax, it was important to manually stir the mixture as it had created a paste-like substance which demanded manual stirring to ensure that the mixture is completely homogenous. It should be noted that the stirring was performed at a constant temperature of 60°C so that to ensure that the wax would remain in a liquefied form throughout the entire process. After being stirred, the mixture left to slightly cool (to around 43°C) to facilitate placing it into the panel for testing. Figure 5(B) shows the slightly cooled mixture. Initial trials have shown that it may be hard to place the mixture in the panel in a liquefied form as it is of high density which makes it difficult to manage placement in a relatively small opening such as this of the panel. Similar to previous tests performed on the PCM panel (described in section 2.2.1), the panel was filled with the created mixture, as shown in Figure 5(C). The panel was cooled to room temperature prior to any testing to ensure that no latent heat would affect testing, which was repeated prior to all tests. Then, the filled panel was placed in its analogues section in the testing confinement which is then placed inside the environmental chamber in the same manner as described earlier in the previously mentioned thermal tests.



**Figure 5:** (A) Panel filled with 40g of wood shavings. (B) Mixture of 20% wood-shavings and 80%paraffin wax cooled to a temperature of around 43°C. (C) Panel filled with mixture ready to be placed inside environmental chamber.

### 2.2.4. Control panel and air gap panel test

As explained earlier, the same tests using the mentioned heat profiles were carried out on the control panel and the air gap panel for comparison purposes.

### 2.2.5. Verification of measurements

It should be noted that to verify the accuracy of the measurements obtained, several steps were taken. In addition to the measurements mentioned earlier, for profile 2 and profile 6, the measurements were repeated once with the same data logger mentioned earlier and twice with another data logger of the same type. In total, the mentioned tests were carried out four times using two different loggers. These profiles were specifically selected for the verification process as they represent both a short and long-term duration cycle of heat. The results showed that all of the verification tests were in alignment and the deviations in

temperature readings were less than ( $0.05^{\circ}\text{C}$ ) thus suggesting the validity of measurements. In addition to this, all of the profiles were also repeated with an alternate logger (in total two repetitions for each profile). The results of this also showed an alignment with a deviation in measurements less than ( $0.03^{\circ}\text{C}$ ). Hence, it can be verified that measurements are accurate.

### 2.3. Results and Analysis

Table 3 shows the results for all the tested panels under the influence of various heat profiles. In the mentioned table, a comparison is presented between results of the panel created with a single sheet of Plexi-glass which simulates a single-panel window referred to as the control panel in this study. Results for the panel consisting of two panels of plexiglass is referred to as the “1 cm” air gap panel, the PCM filled panel is referred to as “PCM panel” and the panel filled with the PCM/wood-shavings mixture is referred to as “PCM/Ws panel”. In Table 3, the column named "Chamber temperature ranges" presents the actual temperatures measured inside the chamber during each heat profile. Also, for each panel, the table presents the actual measured temperature ranges (maximum and minimum temperatures) that have occurred inside the confinement (shown in the column named “Temperature range”). The maximum temperature inside the confinement compared to the actual maximum applied heat shows the potential in reduction of heat gain in the event of using a certain panel (referred to in the table as “Peak temperature reduction”). The reduction in peak temperatures is calculated as (the Max temp. of chamber – Max. temp. inside the confinement). The table also shows the variation in temperature fluctuation which was calculated as a percentage based on the difference of temperatures measured inside and outside the confinement (“Max. temp. inside the confinement – Min temp. inside the confinement” / “Max. temp. in chamber - Min. Temp. in chamber” \* 100 %), thus, showing the potential of using such panels to mitigate heat fluctuations. This also shows the influence of the duration of exposure to heat has on the ability to mitigate fluctuations. The results additionally show the shift in the peak temperature time due to the presence of each panel, which is a property that could be utilised in many applications such as heat storage devices.

**Table 3:** Thermal measurement of panels under heat profiles.

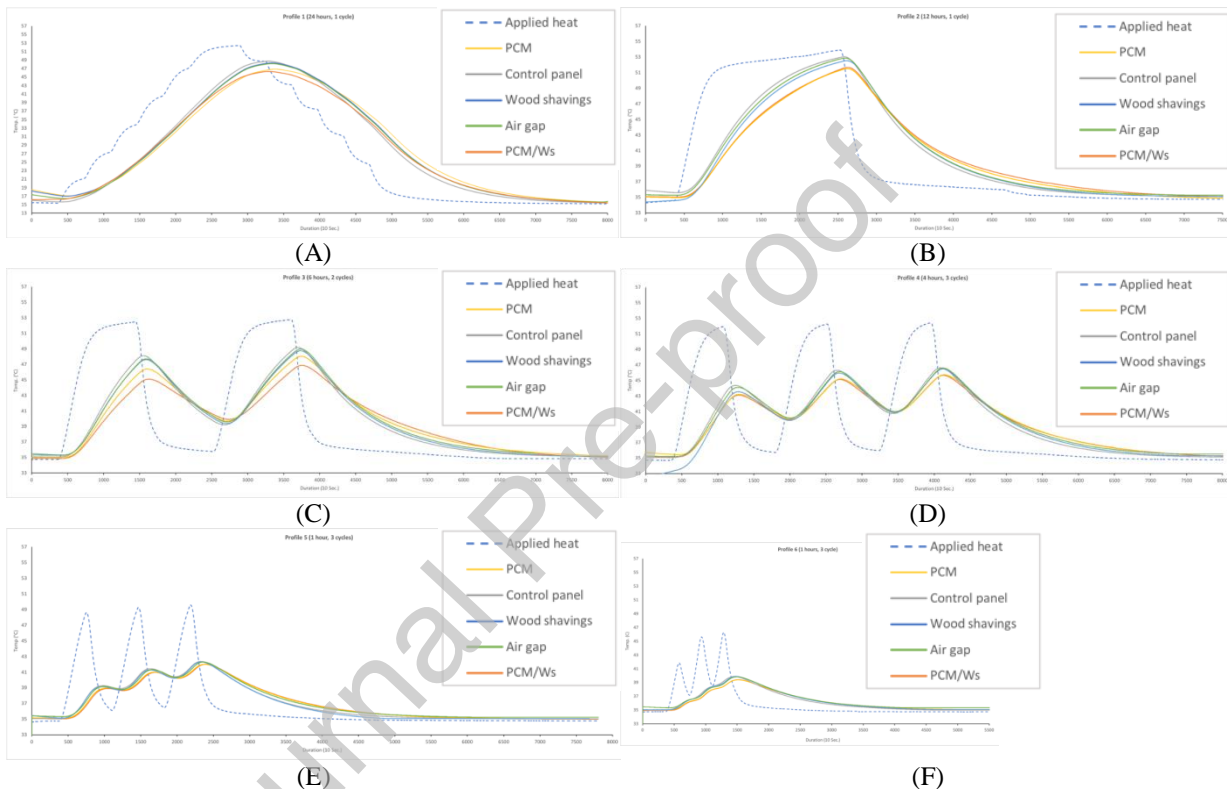
Heat profile No.	Chamber temp. ranges ( $^{\circ}\text{C}$ )	Control panel				1 cm Air gap panel				Wood shavings			
		Temp. range ( $^{\circ}\text{C}$ )	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction ( $^{\circ}\text{C}$ )	Temp. range ( $^{\circ}\text{C}$ )	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction ( $^{\circ}\text{C}$ )	Temp. range ( $^{\circ}\text{C}$ )	Fluctuation (%)	Peak temp. shift (Min.)	Peak temp. reduction ( $^{\circ}\text{C}$ )
1	15 - 52.5	15 - 49.8	92.8	60.3	2.7	15 - 48.1	88.2	66.7	4.4	15 - 48.4	89.1	78.8	4.1
2	35 - 53.8	35 - 53.04	96	9.83	0.76	35 - 52.5	93	19.7	1.3	35 - 52.9	95.2	23.3	0.9
3	35 - 52.6	35 - 49.1	80.1	11.5	3.5	40.8 - 48.7	44.9	23.7	3.9	38.7 - 49	58.5	25.8	3.6
4	35 - 52.3	35 - 46.6	67	9.6	5.7	37.2 - 46.5	53.6	15.7	5.8	40.1 - 46.6	37.6	30	5.7
5	35 - 49.6	35 - 42.4	50.7	18.5	7.2	35 - 42.7	52.7	30.7	6.9	35 - 42.2	49.3	39	7.4
6	35 - 46	35 - 39.9	44.5	7	6.1	35 - 39.9	44.5	18	6.1	35 - 39.8	43.6	44.8	6.2
		PCM				PCM/Ws							
1	15 - 52.5	15 - 46.9	85	74.8	5.6	15 - 46.7	84.5	72.2	5.8				
2	35 - 53.8	35 - 51.6	88	24.8	2.2	35 - 52.5	93	23.7	1.3				
3	35 - 52.6	38.7 - 46.9	46.6	27.1	5.7	39.7 - 48.8	51.7	28.3	3.8				
4	35 - 52.3	37.2 - 45.6	48.5	32.5	6.7	40 - 45.7	32.9	34	6.6				
5	35 - 49.6	35 - 42.0	47.9	36.1	7.6	38.8 - 42	21.9	41.1	7.6				
6	35 - 46	35 - 39.3	39	21.7	6.7	35 - 39.4	40	40.5	6.6				

In heat profile 1, shown in Figure 6(A), there was a reduction in the peak air temperature and a shift in the peak temperature time for all panels. As expected, the control panel has shown the least influence on the temperatures as it only consists of a 2 mm Plexi-glass panel. The “1 cm” air gap panel showed more influence as it resulted in decreased temperatures in comparison with the control panel. This is due to the effect of the air gap which acts as thermal insulation to an extent [153–157]. The Ws panel has shown reduction in temperature close to this of the “1 cm” air gap panel. The most thermal influence was observed in both the PCM and the PCM/Ws panel. A negligible difference in temperature reduction was present between both mentioned panels. As for temperature fluctuation, similar results can be observed in all panels. The PCM and the PCM/Ws panel have shown the least fluctuation percentage in comparison with the other panels. This is also true for the peak heat shift durations. It is noted also that heat profile 1 showed the largest heat peak time shift in comparison with other heat profiles. Although the increase of temperatures was almost identical in all panels, the pace at which temperatures dropped inside the confinement is not as identical. The control panel was the fastest to cool down. The “1 cm” air gap panel was slower to cool. The PCM and the PCM/Ws however, were the last to cool. This is possibly due to the latent heat effect of the PCM [158–160].

In heat profile 2, shown in Figure 6(B), similar results as heat profile 1 can be seen. However, it is noted that the peak temperatures of panels were higher than those of heat profile 1. This is possibly due to the applied heat increasing rapidly to 54°C within 1.5 hours of the test then stabilizing for the rest of the duration of the test. This implies that the fluctuation of temperatures may be less reduced if the temperature change is slow as this would allow for the heat to be further conducted through the panels thus causing further increasing and decreasing in the temperature inside the confinement. Similar results are shown in the rest of the heat profiles in regards to the performance of the panels shown in Figure 6(C, D, E & F). It is evident that there is a strong correlation between the duration of the cycle and the performance of the panels. In cycles with longer durations such as in heat profile 3 and 4, the temperatures inside the confinement were found to be fluctuating relatively higher. Whereas in heat profiles with shorter cycles such as heat profile 5 and 6, the fluctuations were found to be lower. It is important to note that this is the case for all the tested panels although the PCM/Ws was seen to have the least fluctuation in all heat profiles regardless of the duration of the cycle. Figure 7(A) shows the relation between cycle duration and the percentage of fluctuation in the tested panels based on the logged measurements of this investigation.

As for the heat peak time shift which represents the duration elapsed from the point that the maximum air temperature occurs inside the chamber and the point that the maximum air temperature is reached inside the confinement, it is evident that there is a minor correlation between the duration of heat application and shift in peak temperature, as seen in Figure 7(B). To elucidate, despite several inconsistencies, the shift seems to increase as the duration of exposure to heat is decreased. An exception to this is profile 1, in which, the largest shifts have been observed despite exerting the most duration of exposure to heat. This may be explained as a result of the highly gradual mode of increase and decrease of heat. The gradual increase in heat allows for the PCM to reach its melting point after a longer duration without being affected by the heat prior to this point. It is worthy to note that the Ws, PCM and PCM/Ws panels have shown the most shift duration, with the PCM and PCM/Ws performing most efficiently in this regard in most of the heat profiles. It is important to point out that the type of PCM will influence its latent heat capacity thus affecting its capability to shift the heat peak [161], other types of PCMs are able to cause an extended heat peak shift as observed in the work of Chung and Park [96], Piselli et al. [97] and Principi and Fioretti [162] discussed earlier. This is true also for the reduction in the peak temperature. All panels

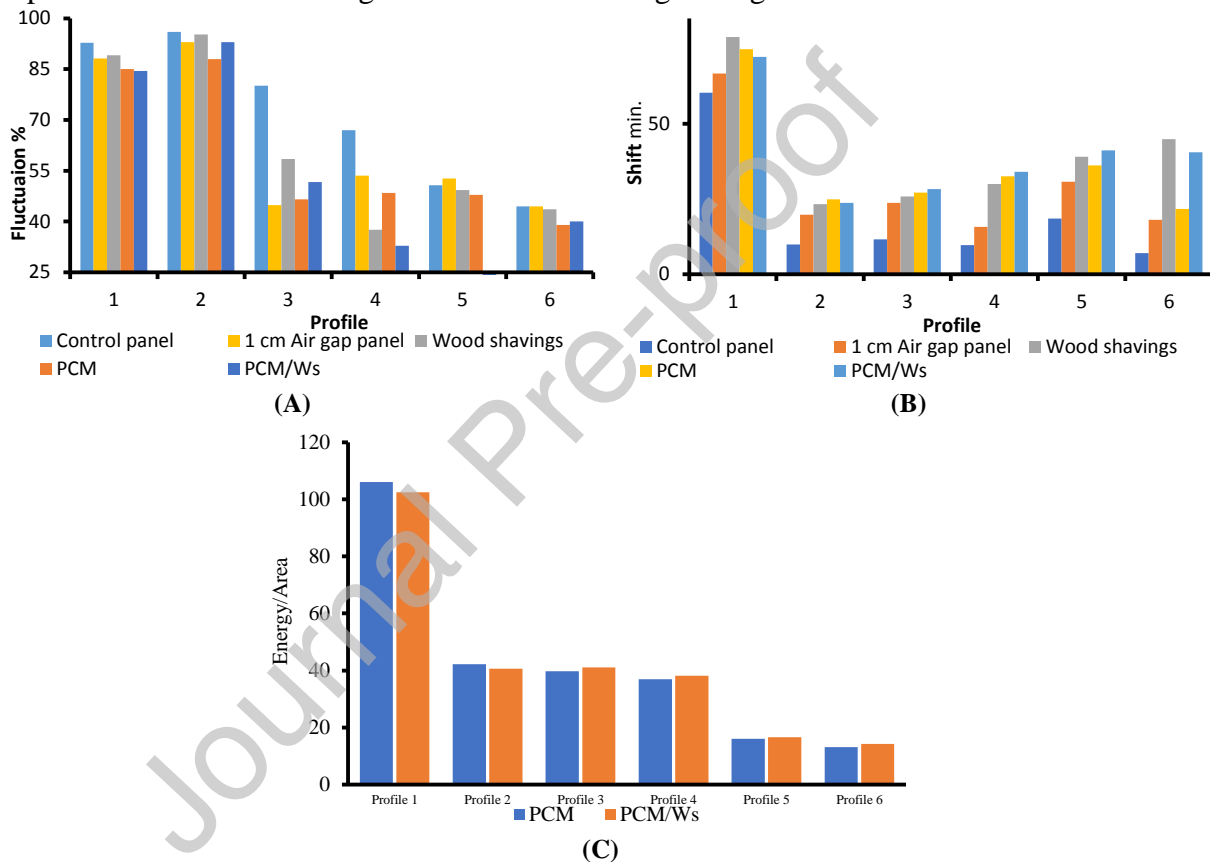
have resulted in a reduction that ranged from an insignificant reduction (such as  $0.76^{\circ}\text{C}$  in the control panel) to very significant reductions (such as  $7.6^{\circ}\text{C}$  in the PCM panel). It is evident that both the PCM and PCM/WS panel have resulted in the most reduction in all heat profile due to the melting properties of the PCM as discussed earlier in literature. However, it can be seen also that the reduction is at its greatest the shorter the heat cycle is. This can be elucidated as due to the lack of sufficient duration that allows the tested panel to gain heat so as to raise its temperature. Hence, it can be inferred that heat profile 1 and profile 2 represent a more accurate assessment of the temperature reduction capabilities of the tested panels as they have longer cycle durations (24 hours and 12 hours). Whereas, heat profile 3,4,5 and 6 may represent temperature reduction of these panel in conditions where rapid changes in temperature are occurring.



**Figure 6:** Temperatures of all panels during testing. (A) Profile 1. (B) Profile 2. (C) Profile 3. (D) Profile 4. (E) Profile 5. (F) Profile 6.

It can be seen that the thermal performance of the PCM and the PCM/WS amalgam are similar to a large extent. For further comparison, the area encompassed under the curves of the mentioned earlier panels, represented earlier, are compared. Such areas can be indicative of the energy exerted inside the confinement during testing the mentioned panels. Trapezoidal approximation is used to calculate the mentioned areas. Figure 7(C) shows a comparison between the mentioned panels for all heat profiles. It can be seen that the performance of the panels in terms of energy is similar to a large extent. It may be worthy to note that the area under profile 1 curves are clearly much larger, which is consistent with the duration of applied heat for that profile. The areas for Profiles 5 and 6, however, are seen to be particularly small as a result of the applied heat fluctuating. This is to imply that the effect of heat fluctuation on the applied heat is similar to the effect of reducing the maximum applied temperature in terms of exerted energy. Most importantly, it can be observed from the measurements discussed earlier that although both PCMs and wood shavings have significant thermal performance, the amalgamation of both materials has not resulted in a significant

thermal enhancement in the thermal performance of the panels. The measured data shows that the performance of the PCM panel and the PCM/Ws panel is almost identical. Thus, it can be inferred that adding wood shavings to PCMs would not result in enhancing the thermal performance. The values of thermal conductivities of PCM and wood-shaving can explain this fact. Studies show that the thermal conductivity of paraffin waxes, as PCM, of similar melting points to this used in the present study to be around 0.20 to 0.22 W/(m·K) [163–170]. Whereas, the thermal conductivity of MDF/plywood wood-shavings can be as low as 0.11 to 0.17 W/(m·K) [171–177] and in some cases as low as 0.03 W/(m·K) [178,179]. The inherent low thermal conductivity of wood-shavings, compared to this of PCM, can explain the fact that replacing an amount of PCM with a similar volume of wood-shavings will not negatively impact the overall thermal insulation performance. Meaning that, within the amalgam panels, a portion of the denser PCM content is replaced with a material of a lower thermal conductivity, wood-shavings, which increases its overall insulation capabilities and reduces weight due to its relative light weight.



**Figure 7:** (A) Relation between observed temperature fluctuations in all panels and duration of heat profile cycles. (B) Relation between shift in peak temperatures in all panels and duration of heat profile cycles. (C) Comparison of area under curves for panels.

From a constructional perspective, the amalgamation of these two materials can be of good use. As thermal insulation is applied to the exterior of buildings, this presents a structural load that is taken into consideration during the construction process. Heavier loads would result in more strain on structural elements which require further structural support thus increasing cost. However, having a density of 0.1 g/cm<sup>3</sup>, the addition of wood shavings to PCM would result in a significantly lower weight with the same, if not improved, thermal performance. For example, the PCM panel mentioned earlier was filled with 380 g of PCMs (with the density of 9.95 g/cm<sup>3</sup>). The thermal performance of the mentioned panel was matched and improved in some cases with the usage of the PCM/Ws which contained 260g

of PCMs and 40g of wood shavings with a total weight of 300g. This constitutes for a weight reduction of 80g (20.94 % of total weight). It is important to note that such reduction in weight can be of significant influence in certain area in the world where traditional architecture prevails. In such buildings, considerably thick insulation may be applied to counter extreme weather conditions, such as rural egyptian architecture built in hot-arid desert climates for instance [180], where insulations can reach a thickness of over 50cm. In fact, many countries around the world still utilise such vernacular building approaches to the present day, such as India [181,182], Yamen [183], Macedonia [184], Myanmar [185], Nepal [186], Spain [187], Romania [188] and Japan [189]. Such buildings carry a large potential to benefit from insulation solutions such as this presented in the present study, where a saving in weight can be highly advantageous.

### 3. Conclusions

The appraisal of literature presented in this work identified that the use of PCMs, wood shavings and other natural materials as an innovative approach for passive thermal control is highly promising at low cost. However, attempts to combine these materials to gain enhanced thermal performance, although promising, has been performed using complex techniques that may be unsuitable where high-tech is not widely available. Little or no attempts have been carried out to investigate possible gains through simple amalgamation of PCMs and wood shavings. In the context of this article, this was investigated with regards to not only thermal aspect but possible other gains. Comparison of the tested materials shows the following:

- PCMs and PCMs submerged in wood shaving have shown to have better thermal performance compared to wood shavings (in the Ws panel). However, measurements have shown that both PCMs and PCMs/wood shavings have very similar thermal performance, with PCM/wood shavings demonstrating a slightly better performance. This implies that adding amounts of wood shavings to PCMs would not result in any significant enhancement in the thermal performance.
- Although no or little thermal gain can be achieved from submerging wood shavings in PCM, from a construction perspective, advantageous gains may be achieved. Namely, a reduction in weight of 22.94% may be achieved when using mixture of PCMs and wood shavings rather than using PCMs, with almost identical thermal performance. This is also economically advantageous as wood shavings are typically of low cost as a by-product of industrial processes. Hence, replacing amounts of PCM, in PCM related applications, with wood-shavings will certainly reduce thermal insulation costs.
- PCMs and wood shavings submerged in PCMs are able to mitigate heat gain significantly. In cases of long heat cycles, the peak temperature was reduced by up to 5.8°C. In cycles that have shorter durations, the heat peak reduction was up to 7.6°C. It should be noted that this reduction was achieved using 1 cm thick panels. Similar panels with larger thicknesses can have significantly better reduction in temperatures. This highlights the advantageous attribute of weight reduction through using wood-shavings.
- The experimental study shows that PCMs and wood shavings submerged in PCMs have a good potential to reduce air temperature fluctuations. For example, the PCM/Ws panel has shown a notable reduction in air temperature fluctuations (by 15.5% to 60%) compared to the thermal performance of the control panel (reduced fluctuations by 7.2% to 55.5%) and the 1 cm air gap panel (reduced fluctuations by 11.8% to 55.5%). This is true for all of the tested heat profiles which have different

cycles of high/low temperatures with various cycle durations. The reduction in fluctuations is evidently affected by its duration and intensity.

- A shift in the peak temperature can be achieved using thermal insulation systems, depending on the system's latent heat properties and the durations of the applied heat cycles. However, it is clear that adding wood shavings to PCM in an insulation system will not have a significant effect in the duration of the heat peak shift.

The results of this investigation have shown that, in addition to PCMs having the capability to reduce heat conduction through building walls, they are able to play a good role in mitigating air temperature fluctuations and cause a shift in the heat peak which may in certain cases be beneficial. More importantly, the data has shown that adding wood shaving to PCMs on a thermal insulation system in a simple submerged manner would not negatively affect the performance of this system, and, would result in a reduction of weight and cost. This reduction is of high significance in terms of construction requirements and cost. Other materials have such qualities which is a good area for future research. It is evident that further studies are needed to comprehend possible gains of amalgamating PCMs with natural low-cost substances to further improve thermal, technical and economic aspects of thermal insulation systems.

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CRediT statements

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#### Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the article entitled " Potential gains from the amalgamation of Phase Changing Materials (PCMs) and wood shavings".



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