High thermal performance phase-change material integrated bamboo wall

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Abstract
Previous studies showed that phase change material (PCM) can have high thermal performance in tropical regions. However, the inclusion of bamboo in PCM walls and the influence of wall orientation have not yet been studied. To analyze the impact of PCM position and thickness, wall composition, and orientation on the building's thermal performance, the thermal performance of 12 variants was simulated using EnergyPlus. The study found that the PCM position was the determinant factor, with orientation being more significant than thickness. Bamboo should be placed on the interior side to achieve high thermal performance and low carbon emissions.

Highlights
- Placing the PCM as the exterior layer provides the best thermal performance
- Bamboo is added on the interior side to enhance the ecological value
- Orienting the wall towards sunlight radiation improves its thermal performance

Introduction
The building sector's high energy demand and CO₂ emissions are major contributors to global warming, with building materials accounting for 9% of energy-related carbon emissions. Therefore, reducing energy consumption for mechanically ventilated buildings and utilizing local organic materials are crucial to reducing carbon emissions. One potential solution is using phase change materials (PCMs) to absorb massive heat during a phase transition to reduce cooling loads. A review of PCM application studies revealed that the majority focused on regions located in nine different climate regions, mainly between 25° to 60° north and 25° to 40° south latitude. Paraffin has been the most commonly used PCM, achieving the best air temperature reduction of 4.2°C (Cui et al., 2017). By developing building envelope materials incorporating PCMs, the building sector can significantly reduce its carbon footprint and contribute to the fight against global warming.

Despite the slight diurnal temperature variation, several studies (Al-Obaidi et al., 2022; Bimaganbetova et al., 2020; Carlucci et al., 2021; Guichard et al., 2014; Hwang et al., 2021; Lei et al., 2016; Nematchoua et al., 2020) demonstrate the effectiveness of building envelope-integrated PCM in the tropics in reducing cooling loads or indoor air temperature. Studies conducted in Singapore (Lei et al., 2016) and Malaysia (Al-Obaidi et al., 2022) indicate significant benefits of PCM applications, mainly when applied to exterior surfaces of walls. Increasing the thickness of PCM improves thermal stability, but the effects are insignificant compared to cost benefits. In Malaysia, the highest heat storage capacity was achieved by integrating 18-mm PCM into building walls (Al-Abi et al., 2020).

Building envelopes integrated with phase change materials (PCM) comprise multiple layers, with the PCM being held inside or attached to the building envelope panel. For instance, Guichard et al. (2014) installed a composite PCM roof consisting of a corrugated galvanized steel sheet, an air layer, a PCM, and a plasterboard on Reunion Island. On the other hand, building envelopes integrated with PCM in Singapore are composed of concrete and PCM (Lei et al., 2016). Nematchoua et al. (2020) used PCM walls made of mortar, concrete, EPS, and bio PCM to improve indoor thermal comfort and reduce cooling energy demand in coastal regions of Madagascar. In Malaysia, Al-Obaidi et al. (2022) investigated the thermal effectiveness of two types of PCM-integrated building envelopes comprising a brick wall and PCM for the wall type and a steel roof and PCM for the roof type.

An ideal PCM should possess high heat of fusion, specific heat, thermal conductivity, and density. It should also be chemically stable, have a low corrosion rate, be nontoxic during a fire, and exhibit a small volume change during solidification (Beltrán and Martínez-Gómez, 2019). Organic PCMs are non-corrosive and have high heat of fusion. Some organic PCMs, such as paraffin, have stable thermal cycling and high latent heat. On the other hand, inorganic PCMs tend to be flammable but possess high thermal conductivity.

Microencapsulation or macro encapsulation is used to maintain the PCM in a solid form to prevent chemical reactions with other materials. Microencapsulation involves holding micro PCMs in a microsphere to keep the material solid when the PCM core melts. Micro encapsulation, on the other hand, usually involves enclosing PCMs in a panel, pouch, or tube (Al-Obaidi et al., 2022).

Using bamboo as a replacement for one layer of the PCM composite wall aims to increase the ecological value of the building. Bamboo is a lightweight and low-carbon material proven to reduce carbon emissions and create...
relatively lightweight PCM-integrated bamboo walls, which can help reduce construction costs and environmental burdens, as noted by previous studies (Borowski et al., 2022; Yu et al., 2011).

This study examines the factors determining its thermal performance to achieve a high-performance bamboo integrated PCM wall. Previous studies have established that the position and thickness of the PCM layer significantly affect the thermal performance of buildings in the tropics. In addition, the composition of the wall layers and orientation are also being investigated for their influence on thermal performance. The study employed parametric simulations for thermal performance analysis. The study seeks to find the optimal combination of these factors to create a highly efficient and sustainable bamboo integrated PCM wall.

Materials and methods

Location and Climate profiles

The PCM-integrated bamboo walls (PCM-I BWs) were installed in Kuching, Malaysia (1.550° N, 110.333° E), which has a tropical rainforest climate (Af), according to Koppen and Geiger. The air temperature ranges from 23.3°C to 30.4°C, with a yearly variation of 1.4°C. High precipitation and humidity occur year-round, with the driest month being July (humidity at 85%) and the wettest months reaching 90% humidity. The average wind speed is between 1.073 m/s and 1.699 m/s, varying with local topography. See Figure 1 for the average daily incident shortwave solar radiation.

Figure 1: Kuching’s average daily incident shortwave solar radiation

Material selection

Effective selection of PCM is crucial for reducing indoor surface temperatures in buildings. Previous studies have highlighted the importance of selecting the correct PCM with appropriate melting points (Lei et al., 2016). For hot and humid climates like Kolkata, India, the melting temperature of PCM is the most crucial factor, followed by its thermal conductivity (Bhamare et al., 2020). A study in Malaysia found that PCM with lower melting temperatures was more effective in reducing the temperature, particularly when combined with night ventilation (Al-Absi et al., 2020).

Two studies have examined the use of PCM to reduce indoor surface temperatures in buildings in Malaysia. In one study (Al-Obaidi et al., 2022), an inorganic PCM with a melting temperature of 29°C was applied to building walls, resulting in a reduction of 2°C in indoor surface temperatures during normal days. In another study (Al-Absi et al., 2020), mineral-based raw materials with a melting temperature of 29°C were inserted between wall layers, reducing up to 4.87°C in indoor surface temperatures. PCM transition temperatures should be within the acceptable comfort range of 25-31°C, as suggested by previous studies (Akeiber et al., 2016; Al-Absi et al., 2020; Al-Obaidi et al., 2022), to ensure relatively comfortable indoor conditions in Malaysia. Thus, the present study used mineral-based raw materials encapsulated in macro containers with a melting temperature range of 26-27°C for the PCM-integrated bamboo wall.

In our study, the PCM-integrated bamboo wall was composed of macro-encapsulated organic PCM, bamboo, and concrete (the same material used for regular walls). Table 1 presents the thermophysical properties of these materials, which were carefully selected to achieve the desired thermal performance. Using a combination of appropriate materials and PCM melting temperatures, we aimed to create an efficient and sustainable PCM-I BW that can effectively reduce indoor surface temperatures. The thermophysical properties of the PCM can be described in a temperature curve (Table 2).

Table 1: Thermophysical properties of PCM-IBW’s materials

<table>
<thead>
<tr>
<th>Thermophysical property</th>
<th>PCM</th>
<th>bamboo</th>
<th>concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m3)</td>
<td>1540</td>
<td>960</td>
<td>2000</td>
</tr>
<tr>
<td>Thermal conductivity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solid (W/m.K)</td>
<td>1.04</td>
<td>0.35</td>
<td>1.13</td>
</tr>
<tr>
<td>- Liquid (W/m.K)</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat (J/g.K)</td>
<td>3.14</td>
<td>1.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Melting temperature (°C)</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freezing temperature (°C)</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat (J/g)</td>
<td>200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*(Al-Absi et al., 2020) **(Shah et al., 2016)

Table 2: The PCM’s temperature curve.

<table>
<thead>
<tr>
<th>Temperature curve</th>
<th>High temp difference</th>
<th>Peak temp</th>
<th>Low temp difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting curve</td>
<td>1K</td>
<td>27°C</td>
<td>1K</td>
</tr>
<tr>
<td>Freezing curve</td>
<td>1K</td>
<td>26°C</td>
<td>1K</td>
</tr>
</tbody>
</table>

Building models and variants

In this study, twelve variants of PCM-I BW were created to determine their thermal performance. The variants were created by varying the composition, orientation, thickness, and position of the PCM, as shown in Table 3. The thickness of the PCM varied in multiples of one sheet of macroencapsulated PCM, which was used in a previous study (Al-Absi et al., 2020).

The PCM-I BWs were installed in buildings with two different area variations: 3x3 m² and 6x6 m², both with a height of 3.2 m. There are 20 cm high openings on all four sides of the upper walls to provide cross ventilation (Figure 3). In air-conditioned buildings, these openings are closed with glass. The floor and roof of the building...
are made of concrete slabs, with the floor surface covered with tiles. The PCM-I BW is placed on one side of the wall with four orientation variations: north (0), east (90), south (180), and west (270). The remaining three sides of the wall are made of concrete, with the exterior surface covered with cement render and the interior surface covered with cement plaster. All walls, including the variants and base case (V-00), have a thickness of 13 cm. The material properties of the V-00 wall are the same as the properties of the regular walls (Table 3).

Table 3: Variations with the thickness in cm

<table>
<thead>
<tr>
<th>Variant</th>
<th>variant bamboo</th>
<th>variant concrete</th>
<th>variant PCM</th>
<th>variant -</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1.0</td>
<td>9.6</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td>02</td>
<td>1.0</td>
<td>10.2</td>
<td>1.8</td>
<td>-</td>
</tr>
<tr>
<td>03</td>
<td>1.0</td>
<td>10.8</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>04</td>
<td>2.4</td>
<td>9.6</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>05</td>
<td>1.8</td>
<td>10.2</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>06</td>
<td>1.2</td>
<td>10.8</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>07</td>
<td>1.0</td>
<td>2.4</td>
<td>8.6</td>
<td>1.0</td>
</tr>
<tr>
<td>08</td>
<td>1.0</td>
<td>1.8</td>
<td>9.2</td>
<td>1.0</td>
</tr>
<tr>
<td>09</td>
<td>1.0</td>
<td>1.2</td>
<td>9.8</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>8.6</td>
<td>2.4</td>
<td>1.0</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>9.2</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>12</td>
<td>1.0</td>
<td>9.8</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Simulation study

The study used EnergyPlus (E+) simulations to examine a bamboo wall’s thermal performance and energy efficiency integrated with phase change material (PCM). E+ is a widely accepted tool for PCM simulations and has been validated in previous studies for accurately predicting the thermal behavior and performance of buildings integrated with PCMs (Al-Abisi et al., 2020; Lee et al., 2016; Lei et al., 2016; Tabares-Velasco et al., 2012). This simulation engine uses a one-dimensional conduction finite difference (CondFD) solution as the heat balance algorithm. Another advantage of E+ compared to Computational Fluid Dynamics is the availability to calculate the cooling load of the AC and the operational energy consumed by the building, making it a valuable tool for the study.

Achieving accurate results should follow the guidelines, including using a time step of less than or equal to three minutes and considering that PCM modeling with strong hysteresis can lead to accuracy issues (Tabares-Velasco et al., 2012; Zastawn-Rumin et al., 2020). The new version of E+ addressed these challenges by providing two separate freezing and melting curves with user-specified temperature data, enhancing the accuracy of the results.

Design Builder was used as the graphical user interface for the E+ simulations. To simplify modeling the 3D bamboo layer, the researchers ignored macroencapsulation. The researchers selected hysteresis as the phase change method, a novel simulation algorithm in E+ used for modeling the hysteresis of PCM. Hysteresis produced less than 1% calculation error, significantly lower than the error observed without hysteresis, as confirmed by a verification conducted in a previous study (Zastawn-Rumin et al., 2020).

The thermal performance of PCM-i BWs in naturally ventilated buildings was evaluated based on their indoor air temperature. Meanwhile, the thermal performance of PCM-i BWs in air-conditioned buildings was evaluated based on the cooling load. The air temperature was set at 24 °C in the simulations of air-conditioned buildings. A parametric feature in Design Builder was utilized to compare the thermal performance of the bamboo walls integrated with phase change material to a V-00. Four specific dates were selected for analysis, and hourly temperature curves for each of these dates were simulated to investigate the daily peak phase change temperature and the lower and higher temperature ranges of the phase change for melting and freezing. March 21 was chosen due to the sun's location above the equator line, while December 22 was selected because it represents the date when the sun is farthest from the location. June 21 is the date when the sun is farthest from the location. June 21 is the date when the sun is located in the tropic of Cancer, whereas May 15 is the hottest day. Cooling load simulations were carried out for seven days around each of these dates to assess the walls’ thermal (energy) performance. Using the results from cooling load simulations enables a more accurate measurement of the thermal performance of each variant compared to using the results of indoor air temperature simulations.

Results

Thermal performance

The first simulations of all variants, including the V-00, were analyzed parametrically, and the results were presented in Figures 3 and 45 for all variants in March. These figures show a consistent pattern, with simulations
applied to 36 m² buildings/areas exhibiting more contrast patterns than those applied to other building areas. However, this discussion will focus on the simulation results of all variants applied in buildings or rooms with a 9 m² area. Such areas are more commonly found than those with a 36 m² area, making them more practical to study.

Figure 3: Parametric analysis of all variants applied in a 36 m² building on 21st – 23rd March.

Figure 4: Parametric analysis of all variants applied in a 9 m² building on 21st – 23rd March.

Figure 5: Parametric analysis of all variants applied in a 9 m² building on 21st – 23rd June.

Figure 6: Parametric analysis of all variants applied in a 9 m² building on 21st – 23rd December.

Overall, the study found that the PCM-i BW has effective thermal performance in reducing indoor air temperature, with PCM-concrete-bamboo being the best composition throughout the year. However, the composition's performance varied depending on the month, with some variants having lower thermal performance than the base case in certain months.

in December, the compositions of bamboo-concrete-PCM, bamboo-concrete-PCM-bamboo, and bamboo-PCM-concrete-bamboo all had lower thermal performance than the V-00.

Proceedings of the 18th IBPSA Conference
Shanghai, China, Sept. 4-6, 2023
https://doi.org/10.26868/25222708.2023.1276
Thermal behaviour

The simulation results depicted in Figure 3-7 raise several questions, as outlined below:

1. Is the diurnal indoor air temperature created by V-06 lower than the V-00?
2. Why does V-04, which has the same composition and a thicker PCM layer, exhibit lower thermal performance than that V-06?
3. Why does V-01, which has a thick PCM layer, exhibit the same or even lower thermal performance than the V-00?
4. How does the bamboo layer influence the thermal behaviour of V-03, V-06, and V-09?
5. Why do V-09 and V-10 with different positions and PCM thickness facing north (0°), exhibit the same thermal performance in June?

Therefore, diurnal indoor air temperatures from the variants mentioned above were simulated as hourly indoor air temperature curves over 24 hours and compared with each other.

According to Figure 8, it is evident that the indoor air temperature of a building that utilizes V-06 is consistently lower than that of a building that does not use PCM for over 24 hours. The temperature difference between the two buildings reaches a maximum of 4.12K at 19:00, while the minimum difference is 0.31K at 10:00.

On December 22nd, during the cold month when solar radiation intensity is relatively low, two buildings were compared based on their diurnal indoor temperature. The buildings were constructed using variants with PCM-concrete-bamboo composition but with different PCM thicknesses. Figure 9 illustrates that the building with a thicker PCM layer (V-04) had a higher indoor temperature than the building with a thinner PCM layer (V-06) for 16 hours. The maximum temperature difference observed was 1.69K at 8:00. However, from 14:00 to 21:00, the situation reversed, and the indoor temperature of the building with V-06 was higher than that of the building with V-04, with a maximum temperature difference of 1.02K.

On June 22, the diurnal indoor air temperature of a building with PCM-i BWs was studied. Two variants were compared: V-03, which had a bamboo-concrete-PCM composition, and V-09, which had a bamboo-PCM-concrete-bamboo composition. The PCM thickness in both variants was 12mm. Figure 11 shows that V-03 exhibited better thermal performance than V-09. However, V-09 and V-10, which had the same composition but differed in PCM thickness and position, were found to have similar average thermal performance. On June 2, V-10, which had a PCM thickness of 2.4 cm and was positioned near the interior surface, showed a linear indoor air temperature pattern with no fluctuations. In contrast, V-09 had better thermal performance than V-10 from morning to afternoon (01:00-15:00) (Figure 12).
Building energy saving

The cooling load can measure the energy savings of buildings or the energy performance of all variants. Figures 13 and 14 depict the simulation results of the cooling load, which show patterns similar to the average indoor air temperature patterns in Figures 4-7. Among all the variants, V-06 demonstrates the best energy performance throughout the year. Furthermore, the PCM-concrete-bamboo composition with a thinner PCM layer has a 1-3% higher energy performance than the thicker one. Regarding the sun’s relative position, the PCM-i BWs work effectively (around 15%) during hot months like May and June, but only if their orientation faces north or east. The energy performance of PCM-i BWs is based on their orientation, with the east being the most effective, followed by north, west, and south, in sequential order. When facing north, this variant reduces the cooling load by 7-15%; facing east, it reduces the load by 12-15%; facing south, it reduces the load by 6-14%; and facing west, it reduces the load by 9%. These results indicate that the position of the PCM layer on the exterior side is the most critical factor in achieving high energy performance, and the orientation of the wall should be further considered.

Discussion

The thermal performance of various PCM compositions was analysed parametrically, and the results indicate that the position of the PCM layer is a significant factor, regardless of its orientation and room/building size. The study’s findings confirm those of previous research by (Al-Obaidi et al., 2022; Lei et al., 2016) that the highest thermal performances were observed in buildings with a PCM layer on the exterior wall surface. The thermal performance decreases as the distance between the PCM layer and the exterior increases. Among the compositions analysed, V-06, which comprises PCM-concrete-bamboo with a 1.2 cm PCM thickness, exhibited the highest thermal performance, resulting in a temperature decrease ranging from 0.31K to 4.12K. However, it was noted that in the PCM-concrete-bamboo composition, the thicker the PCM layer, the lower its thermal performance. Nevertheless, thicker PCM layers generally indicate higher thermal performance in other compositions where PCM is not used as an exterior layer. Regarding the effectiveness of PCM under different ambient conditions, it was found that the PCM-i BW demonstrated effective thermal performance during hot months, such as May and June, compared to V-00. However, in December, only the PCM-concrete-bamboo composition was effective. The PCM-concrete-bamboo combination demonstrated the best thermal performance.
when installed on the east or west side during March when the sun is at the equator. In May, when the sun is above the building, the north-facing PCM-concrete-bamboo composition achieved the best thermal performance. When the sun is on the Tropic of Cancer in June, the best thermal performance is achieved when the PCM-concrete-bamboo composition faces north. Finally, the south-facing PCM-concrete-bamboo composition achieves the best thermal performance when the sun is on the Tropic of Capricorn in December. These findings highlight that PCM has high thermal performance when installed on the exterior under relatively hot ambient conditions. As the PCM melts at 27°C and solidifies at 26°C, it works effectively when the surrounding temperature is ≥ 27°C.

The study on the thermal behaviour of PCM-i BWs revealed that the thermal behaviour passes through the PCM layer within 24 hours. Most variations describe the minimum indoor air temperature at 09:00 and the maximum indoor air temperature at 17:00-21:00.

The influence of the thickness of the PCM layer on thermal performance within 24 hours was studied in variants with PCM-concrete-bamboo composition. The higher thermal performance of V-04 than V-06 during hot hours has the potential to reduce cooling loads in air-conditioned buildings. Similar results are shown in Figure 11, which compares the diurnal indoor air temperature of V-01 and V-00. The variants with a 2.4 cm thick PCM layer located near/on the interior surface (V-01 and V-10) and facing away from the sun's position formed a diurnal pattern of indoor air temperature that tends to be stable. The bamboo layer, which has relatively low thermal conductivity on the exterior side, the addition of thickness to the concrete layer, and the relatively low surrounding air temperature can stabilize indoor air temperature.

The influence of the bamboo layer placed on the exterior surface on thermal performance is more significant than the position of the PCM layer. Figure 9 illustrates that adding of a bamboo layer on the exterior increases the indoor air temperature by 1.03 K - 2.27 K. On the other hand, when the PCM layer is placed as the interior surface, the indoor air temperature is raised by 0.43 K - 1.72 K. The relatively low thermal conductivity of the bamboo layer hinders the heat absorption required to melt the PCM at 27°C. The PCM can no longer melt once the temperature drops to ≤ 26°C.

The energy performance based on cooling load shows a pattern similar to the thermal performance pattern with more measurable values. The application of the PCM-concrete-bamboo composition, especially V-06, produces the lowest cooling load, which can be attributed to the diurnal curve of indoor air temperature. The curve indicates that this composition creates indoor thermal conditions at ≤ 24°C for a relatively long period. Meanwhile, during the simulation, the indoor air temperature in the air-conditioned building is set at 24°C.

Conclusion

PCM-i BWs have been shown to have excellent thermal performance, especially when a 1.2 cm thick PCM layer is placed on the exterior side facing the sun. During hot months, the PCM layer effectively stores latent heat through a phase change. However, the effectiveness of the PCM layer is highly dependent on the surrounding air conditions, as the temperature must be at least equal to the melting temperature of the PCM to absorb heat effectively. Therefore, a thicker PCM layer is more effective during the daytime when the surrounding air temperature is above 27°C, as this accelerates the melting of the PCM and increases its heat absorption capacity. However, placing materials on the exterior side, especially those with low thermal conductivity, such as bamboo, can slow down or even prevent the PCM melting process.

The optimal PCM layer thickness is found to be 1.2 cm, compared to 1.8 cm and 2.4 cm, and using bamboo as the interior surface layer increases the ecological value of the wall while reducing the load on the wall and structure without hindering the latent heat storage and phase change process of the PCM. The results of the cooling load simulation on air-conditioned buildings with natural ventilation reinforce these conclusions. The placement of the PCM layer on the exterior side greatly determines the wall's energy performance. PCM integrated into bamboo walls with a composition of PCM-concrete-bamboo and a PCM layer thickness of 1.2 cm can reduce the cooling load by 6-15% compared to buildings with regular concrete walls. However, further investigation should explore the feasibility of employing a thinner layer as a means to achieve the optimal thickness.

Using EnergyPlus with Design Builder interface simplifies the study of PCM’s thermal and energy performance parametrically. To support the realization of low-carbon buildings, putting bamboo on the interior side is recommended, as the layer does not hinder the storage of latent heat and phase changes of the PCM. Future studies will be carried out to investigate the use of bamboo in PCM composites more innovative way.

Acknowledgement

Authors gratefully acknowledge Universitas Atma Jaya Yogyakarta for the research funding.

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