

Performance Identification of Eutectic Fatty Acid-PLA Based Phase Change Material Board Installed in a Mini-Cubicle System

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ABSTRACT

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Thermal comfort regulation in buildings located in hot climates, such as Indonesia, remains highly dependent on air conditioning (AC) systems, leading to substantial energy consumption. Integrating Phase Change Materials (PCM) into building envelopes offers a passive thermal management strategy to reduce cooling loads. This study investigates the thermal performance of a gypsum-based wall incorporating a eutectic fatty acid PCM (laurate–stearate) of 85:15 (wt%) modified with polylactic acid (PLA) at three PCM:PLA ratios (1:0.6, 1:0.8, and 1:1), alongside a control sample without PCM. Samples were fabricated at laboratory scale and evaluated using a mini-cubicle system under controlled charging and discharging conditions. Energy performance was assessed through temperature change rates and heat transfer (q) analysis at three measurement points (T1, T2, T3). Results demonstrate that PLA modification significantly enhances PCM performance, with the 1:0.8 ratio (bPCM) exhibiting optimal behavior. During charging, bPCM achieved the lowest temperature change rates of 4.75 °C/h at T1, 1.15 °C/h at T2, and 0.65 °C/h at T3 and the minimum heat transfer from T2 to T3 of 32.049 J. Similarly, during discharging, bPCM maintained the smallest temperature change rates of 2.2 °C/h at T1, 1.0 °C/h at T2, and 0.65 °C/h at T3 with the lowest heat transfer to the indoor zone of 32.033 J. These findings confirm that optimized PLA-modified eutectic PCM significantly improves heat absorption, latent heat storage, and thermal insulation performance compared to non-PCM and non-optimized compositions. The proposed composite wall system demonstrates strong potential for passive cooling enhancement and building energy efficiency improvement in hot-climate regions.

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I. Introduction

Indonesia, as an equatorial country receiving year-round solar radiation, experiences persistently high ambient temperatures. Consequently, a large proportion of building occupants rely heavily on air conditioning (AC) systems to maintain indoor thermal comfort. However, extensive AC usage significantly increases electricity consumption, resulting in high operational costs and energy inefficiency. Moreover, excessive reliance on AC contributes to greenhouse gas emissions, thereby exacerbating global warming and climate change [1].

Building walls play a critical role in heat transfer from the outdoor environment into indoor spaces, as they are directly exposed to solar radiation. The thermal properties and material composition of walls substantially influence indoor temperature conditions [2,3]. During peak solar hours—typically between 11:00 a.m. and 4:00 p.m.—exterior walls absorb significant amounts of heat, which is



subsequently conducted into the interior space. Under such conditions, AC systems must operate at higher loads to offset the increased thermal gain, leading to greater energy consumption.

Several mitigation strategies have been proposed, including the use of heat-resistant wall materials or the installation of additional insulation systems. However, these approaches often involve considerable initial costs and may experience performance degradation due to physical damage over time, requiring periodic replacement. In response to these challenges, renewable energy-based technologies have emerged as alternative solutions for building energy conservation. One promising approach is the integration of Phase Change Materials (PCM) into building envelopes to enhance passive thermal regulation and reduce cooling energy demand.

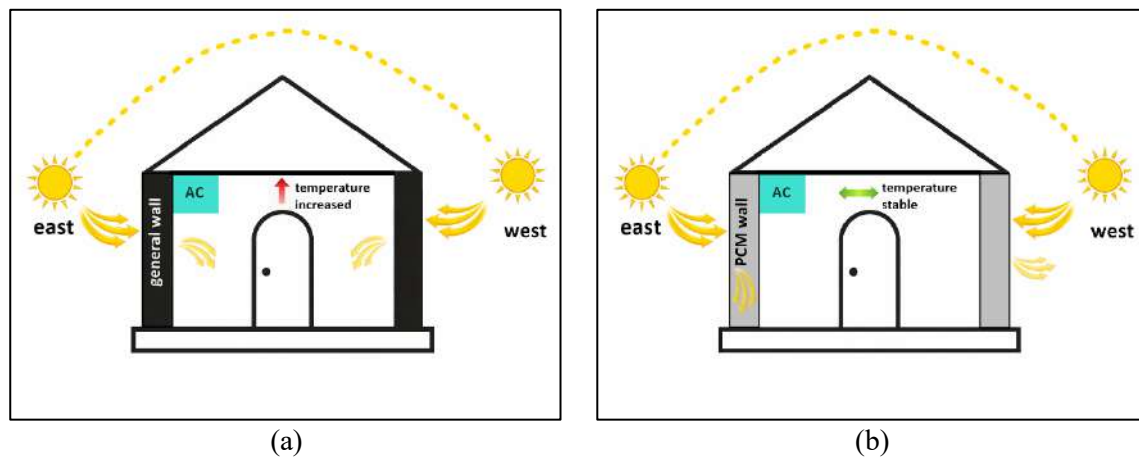


Fig 1. (a) Typical Building Wall Condition under Solar Radiation. (b) PCM-Integrated Building Wall Condition under Solar Radiation

Phase Change Materials represent one of the most efficient methods of thermal energy storage. PCM can be utilized for both energy storage and temperature regulation due to their ability to absorb and release heat during phase transitions. In building applications, PCM can be incorporated into wall structures to absorb solar heat from the external environment, store it temporarily, and subsequently release it outward, thereby preventing excessive heat transfer into indoor spaces [4]. Through this mechanism, PCM integration can reduce the operational load of air conditioning (AC) systems by stabilizing indoor temperatures and minimizing the influence of outdoor thermal fluctuations. With appropriately selected PCM, indoor temperatures can potentially be maintained within the typical human thermal comfort range (25–29 °C) without continuous reliance on AC systems [5]. This contributes not only to building energy efficiency but also to environmental sustainability and national energy conservation efforts. Beyond heat rejection, PCM can also store thermal energy for subsequent applications, provided that supporting systems are installed. Another advantage of PCM integration is its long-term durability when embedded within building walls, offering more permanent functionality compared to conventional insulation materials, which may degrade physically over time and require periodic replacement [6].

PCM operates based on the principle of latent heat storage, absorbing thermal energy during heating and releasing it during cooling [7]. In building applications, PCM integration aims to reduce AC cooling loads and improve energy efficiency by storing thermal energy from the environment [8]. Generally, PCM can be incorporated into concrete matrices or retrofitted into existing buildings [9]. Previous studies have demonstrated significant energy-saving potential. Research conducted in the United States showed that bio-based PCM with a melting point of 23 °C reduced heating loads by up to 57% during winter [10, 11]. Meanwhile, simulation studies in Singapore using EnergyPlus indicated that a 1 cm PCM layer with a melting temperature of 28 °C installed within building envelopes reduced annual thermal fluctuations by 21–32%, and PCM-integrated gypsum boards combined with ventilation systems achieved energy savings of up to 73% [11]. When the phase transition temperature of PCM aligns with the indoor thermal comfort range, the material can effectively absorb excess heat and reduce heating and/or cooling loads. As ambient temperature rises above the PCM melting point, chemical bonds within the material weaken, enabling the absorption of additional thermal energy

while transitioning from solid to liquid state [12-15]. Conversely, when temperature decreases below the solidification point, the material releases stored energy and returns to its solid phase [14,15]. Another advantage of PCM lies in its high heat storage capacity within thin layers; PCM-based walls can be significantly thinner than conventional concrete walls while maintaining comparable thermal performance [16].

Among various PCM types, organic PCM are more widely applied than inorganic ones due to their lower supercooling tendency, absence of phase separation, wide phase transition temperature range, corrosion resistance, chemical stability, favorable reversibility, and commercial availability. Fatty acid-based PCM are among the most commonly studied organic materials. Recently, eutectic fatty acid mixtures have gained attention because their working temperature can be precisely tailored to specific applications [17,18].

Lauric acid and stearic acid are saturated fatty acids readily derived from vegetable and animal fats, particularly palm and coconut oil derivatives. These compounds are commonly used to modify melting characteristics, improve consistency, act as lubricants, and prevent oxidation. Recent developments in eutectic mixtures (combinations of two or more fatty acids) enable fine-tuning of phase transition temperatures and latent heat storage capacity. For example, Sari et al. utilized a myristic–capric acid eutectic mixture embedded into cement composites (28 wt%) using vacuum impregnation for latent heat storage (LHS) in buildings. The cement-based PCM exhibited a melting temperature of 21 °C and latent heat storage of 42 J/g, resulting in a 0.78 °C indoor temperature gradient reduction in cubic room testing. Similarly, other studies synthesized capric–palmitic eutectic mixtures integrated with fumed silica and carbon nanotubes to prevent leakage and enhance thermal conductivity [19]. Despite their advantages, direct application of organic PCM faces limitations such as leakage and instability during phase transition. To address these issues, shape-stabilized PCM composites have been developed [20,21]. While encapsulation techniques reduce leakage, they may increase system costs. Recently, microencapsulation and polymer-supported PCM systems have been extensively studied to improve structural stability during solid–liquid transitions [22]. PCM composites consist of PCM combined with supporting matrix materials. In this study, polylactic acid (PLA) was employed as a supporting polymer to prevent leakage of eutectic fatty acid PCM within a gypsum matrix through a direct mixing approach [22]. PLA is a renewable, biodegradable polymer derived from starch-rich crops such as cassava, sweet potatoes, bananas, and corn. It functions as a stabilizing agent that enhances structural integrity and improves the overall performance of single PCM systems [20-22].

In this research, a binary eutectic mixture of lauric acid and stearic acid (LA–SA, 85:15 wt%) modified with PLA was incorporated into a gypsum matrix to fabricate PCM-based wall panels. PLA content was varied at PCM:PLA weight ratios of 0.6:1, 0.8:1, and 1:1, alongside a non-PCM control sample. The fabricated samples were designed to function as building wall components capable of reducing solar heat penetration into indoor spaces. Thermal performance was evaluated by analyzing temperature change rates and heat transfer characteristics using a simplified building model (mini-cubicle system). Comparative analysis between PCM-integrated walls and conventional gypsum walls without PCM was conducted to determine the effectiveness of the proposed system in enhancing indoor thermal stability.

II. Materials and Methods

A. Materials

Lauric acid (99% purity) and stearic acid (98% purity) (Merck) with melting points of 44.2 °C and 69.6 °C, respectively, were used as the phase change materials. Commercial lactic acid (Merck), distilled water, and gypsum powder were also employed. The experimental setup consisted of standard laboratory equipment including a digital balance, beakers, stirrers, oven, gypsum molds (30 × 30 × 1.25 cm³), magnetic stirrer with hot plate, K-type thermocouples, a 60 W incandescent lamp, a polystyrene (styrofoam) test chamber, an electrical cables, and a data logger system.

B. Sample fabrication using the direct mixing method

A binary eutectic mixture of lauric acid and stearic acid was prepared at a weight ratio of 85:15 (wt%), with a total mass of 250 g [23]. The components were melted using a hot-mixing method at 80 °C under continuous stirring until a homogeneous liquid phase was obtained. Subsequently, lactic acid (PLA precursor) was incorporated into the molten eutectic mixture to produce three PCM formulations with different PCM-to-PLA weight ratios: 0.6:1 (aPCM), 0.8:1 (bPCM), and 1:1 (cPCM). A control sample without PCM (PCM0) was also prepared. Each mixture was stirred continuously for 30 min to ensure uniform dispersion [24]. Separately, gypsum powder was mixed with water at a weight ratio of 1.25:1 (1 kg gypsum to 800 g water) until a homogeneous slurry was obtained. The prepared PCM composites were then incorporated into the liquid gypsum at 25 wt% of the gypsum mass and mechanically mixed until uniform. The resulting mixture was cast into molds ($30 \times 30 \times 1.25 \text{ cm}^3$) and allowed to cure and harden under ambient conditions. After complete solidification, the fabricated wall panels were subjected to thermal performance evaluation.



Fig 2. PCM Sample Fabrication Process

C. Thermal Performance Evaluation Using a Mini-Cubicle System

The heat transfer performance of the PCM wall samples was evaluated using a custom-built experimental setup designed to simulate a simplified building model, as illustrated in Fig 3. The system consisted of a cubic chamber ($30 \text{ cm} \times 30 \text{ cm} \times 30 \text{ cm}$) and a 60 W heat source representing solar radiation. The mini-cubicle system was constructed using five polystyrene boards and one gypsum wall panel ($30 \text{ cm} \times 30 \text{ cm} \times 5 \text{ cm}$). The distance between the heat source and the gypsum panel was fixed at 25 cm. Three temperature sensors were installed at different locations within the system: the exterior surface of the wall (T1), the interior surface of the wall (T2), and the center of the indoor space (T3). Each temperature sensor was connected to a digital thermometer interfaced with a data logging system. Two Mastech MS6514 K-type thermometers were used, each equipped with dual USB ports and connected to thermocouples. A laptop installed with the Thermometer Data Logger software (MS6513/6514 version) was employed for real-time data acquisition. Each USB thermometer was connected to the laptop, and the software interface was operated in two parallel windows. The corresponding USB communication ports (e.g., COM1, COM2, etc.) were configured accordingly to enable simultaneous temperature recording.

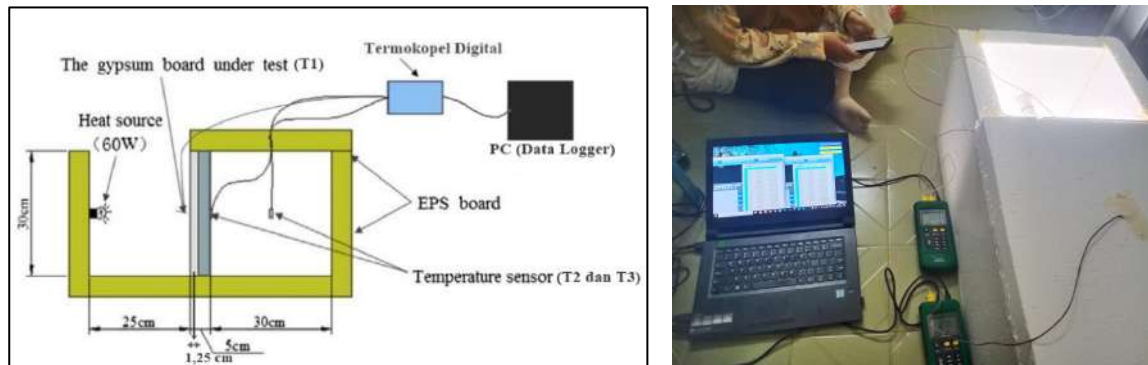


Fig 3. Position of the Experimental Setup for PCM Performance Testing Using the Mini-Cubicle System [20]

D. Heating (Charging) Process Procedure

The mini-cubicle system was prepared as the primary testing apparatus. A wall specimen (30 cm × 30 cm × 5 cm) was installed at the center of the system, with each sample tested sequentially. Prior to testing, the temperature at all measurement points was stabilized at 27 °C to ensure consistent initial conditions. Subsequently, the heat source (LED lamp) was switched on, and the mini-cubicle system was fully enclosed to minimize the influence of ambient environmental conditions. The charging process was initiated simultaneously by activating the CONNECT function in the data logging software. The heating phase was conducted for 2 hours, during which temperature data were automatically recorded by the system. Temperature measurements were collected starting from 0 min and subsequently at 10 min intervals over a total duration of 120 min (2 h). After completion of the 2-hour charging period, the DISCONNECT function was activated to terminate the data acquisition process.

E. Cooling (Discharging) Process Procedure

The testing sequence began with the completion of the charging phase. After 2 h of heating and termination of the charging process, the discharging phase was initiated by switching off the LED heat source. The cooling process was then started by simultaneously activating the CONNECT function in the data logging software. The discharging phase was conducted for 2 h, during which the cooling behavior of the samples was monitored. Temperature data were automatically recorded by the data acquisition system throughout the testing period. Measurements were collected starting at 0 min and subsequently at 10 min intervals over a total duration of 120 min (2 h). Upon completion of the 2-hour discharging period, the DISCONNECT function was activated to terminate the measurement process.

III. Result and Discussion

A. PCM Heat Absorption Performance during the Charging (Heating) Process and Energy Analysis

During the charging phase, heat absorption occurs within the wall specimens. This stage determines the heat storage capacity of each sample as well as its resistance to external thermal penetration (thermal insulation performance) in maintaining indoor temperature stability. The temperature profiles recorded at three measurement points for all four wall specimens during the heating (charging) process are presented in Fig 4.

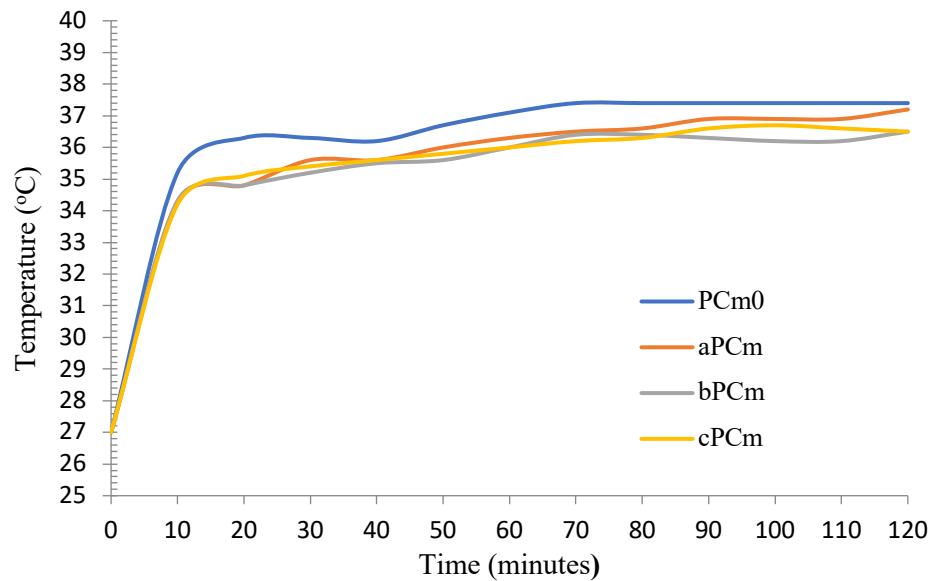


Fig 4. Combined Temperature Profile of the Exterior Wall (T1)

All samples exhibited a significant and nearly linear temperature increase during the first 15 minutes of heating. The temperature rose from the initial 27 °C to approximately 34 °C for most specimens, whereas the PCM0 sample (non-PCM) reached 36 °C within the same period. At the end of the charging process, PCM0 recorded the highest temperature, reaching 37.4 °C, indicating more intense heat accumulation compared to the PCM-containing samples.

This dominant temperature rise in PCM0 can be attributed to the absence of latent heat storage material. Without PCM, the wall lacks a heat absorption mechanism; thus, thermal energy supplied by the lamp is rapidly conducted through the gypsum matrix and transmitted into the interior space. As reported in [19], the application of paraffin-based organic PCM in hotel building walls reduced the average indoor temperature by 0.81 °C, as the absorbed solar heat was stored within the PCM before being transferred indoors. In the present study, the incorporation of PCM into the gypsum matrix allows the material to absorb and temporarily store thermal energy within its structure, thereby delaying heat propagation through the wall.

Additionally, this behavior can be explained in terms of thermal conductivity properties. Materials with higher thermal conductivity transfer heat more rapidly. Pure gypsum (PCM0) possesses higher thermal conductivity compared to PCM-modified gypsum. A similar trend was reported in [21], where the incorporation of eutectic fatty acid PCM (capric acid–palmitic acid) into gypsum reduced its thermal conductivity by approximately 0.1 W/m·K. The reduction in thermal conductivity contributes positively to limiting heat transfer from the wall to the indoor space, which is desirable for building envelope applications such as those investigated in this study.

The temperature profile shows that the PCM0 sample increased by approximately 4 °C during the first 15 minutes, rising from 27 °C to around 31 °C. Subsequently, PCM0 exhibited the highest temperature increase among all samples, reaching a maximum of 32.5 °C. In contrast, the aPCM specimen maintained a relatively stable temperature range between 30.8 °C and 31.5 °C from the 20 minute onward. For the bPCM and cPCM samples, the increase in interior wall temperature (T2) from 0 to 40 minutes followed a similar trend. However, beyond the 50th minute, the bPCM sample demonstrated greater thermal stability compared to cPCM, exhibiting a more moderated temperature rise and improved resistance to heat propagation.

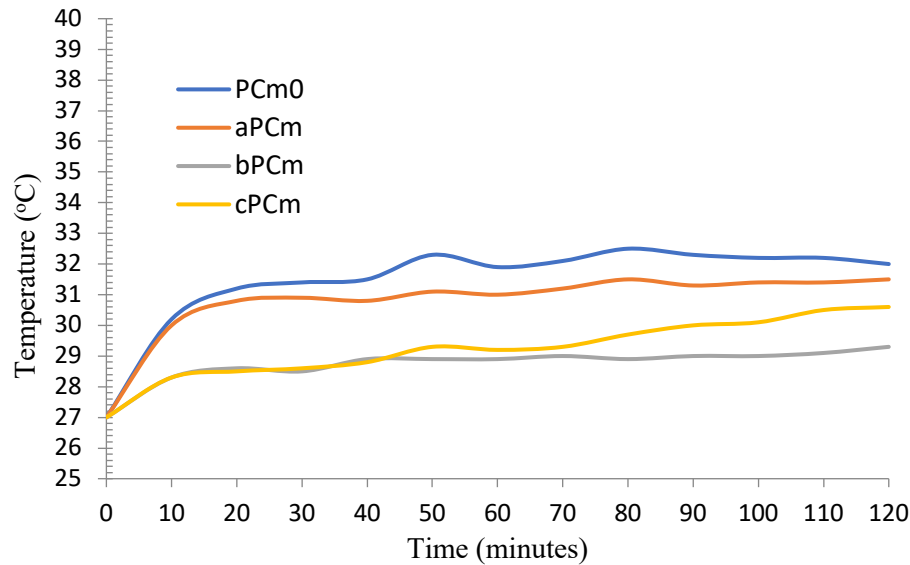


Fig 5. Combined Temperature Profile of the Interior Wall (T2)

The role of PCM embedded within the wall matrix is clearly evident from these results. The presence of PCM reduces the rate of heat transfer toward the interior wall surface. Distinct differences are observed among the tested samples, particularly for the 0.8 PLA composition (bPCM), which exhibits the lowest heat transfer tendency. As reported in [40], eutectic fatty acid-based PCM (laurate–stearate) becomes thermally active at its melting temperature. When the wall temperature approaches approximately 33 °C due to external heating, the PCM begins to undergo phase transition from solid to liquid. During this melting process, the material absorbs latent heat from its surroundings. This latent heat absorption temporarily suppresses further heat propagation through the gypsum matrix, thereby limiting the temperature increase at the interior wall surface (T2). Consequently, the PCM-modified walls exhibit improved thermal buffering behaviour compared to the non-PCM sample.

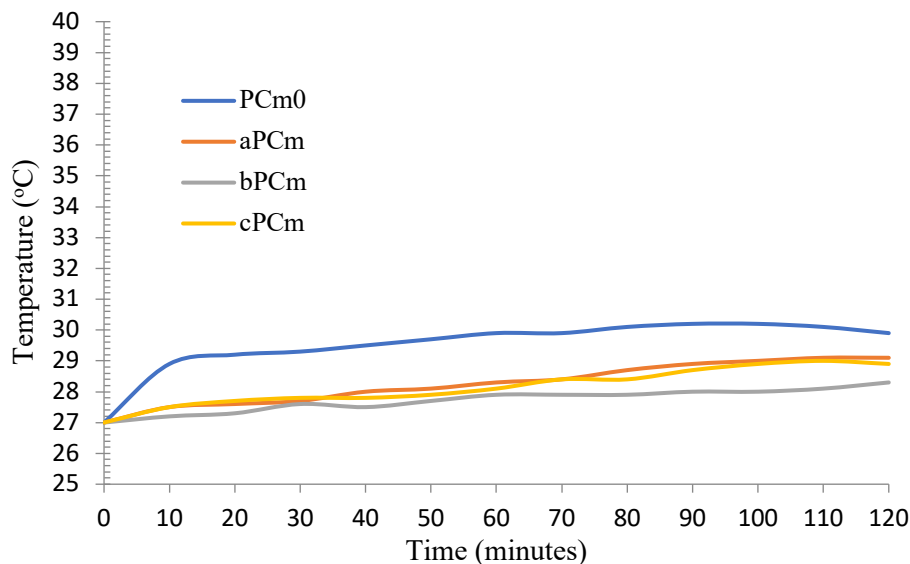


Fig 6. Combined Temperature Profile of the Indoor [T3]

This measurement point represents the most critical indicator for evaluating the thermal performance of the tested PCM wall samples. Under identical boundary conditions, the key parameter observed was the magnitude of temperature variation transmitted from the exterior surface (T1) through the wall to the indoor centre (T3). The temperature profile shows that the PCM0 sample exhibited a significantly different trend compared to the PCM-modified walls. From the initial minute to the end of the heating period, the temperature increased from 27 °C to 29.9 °C, corresponding to a total rise of 2.9 °C. In contrast, the bPCM and cPCM samples displayed relatively similar profiles. However, closer examination reveals that bPCM exhibited the most gradual temperature increase,

rising only from 27 °C to 28.3 °C ($\Delta T = 1.3$ °C), while cPCM increased to approximately 28.9 °C ($\Delta T = 1.9$ °C). The bPCM curve is visibly flatter, indicating superior thermal buffering capacity.

A similar trend to that observed at T1 and T2 is evident at T3: the incorporation of PCM enables the indoor temperature to remain close to its initial modulated value. This demonstrates the functional role of PCM in indoor thermal regulation. By attenuating external heat transfer, PCM reduces the cooling demand imposed on air-conditioning systems, particularly under rising ambient temperatures, thereby contributing to energy savings.

The amount and composition of PCM significantly influence thermal performance. Based on the temperature profiles presented in Figures 5–7, the bPCM wall demonstrates the most favourable heat absorption and retention characteristics. As reported in [23], latent heat values obtained from DSC analysis for similar eutectic compositions indicate higher latent heat storage capacity, which directly correlates with improved thermal energy storage performance. This suggests that the eutectic LA–SA composition combined with 0.8 PLA provides enhanced latent heat absorption while minimizing conductive heat transfer to the interior space.

Consistent findings were reported in [24], where the incorporation of 0.8 PLA in palmitic-acid-based PCM yielded improved thermal stability and performance. PLA, as a derivative of carboxylic acid, contains carbonyl (C=O) functional groups with relatively high bond energy (~745 kJ/mol), contributing to structural stability [24]. Moreover, PLA exhibits favourable crosslinking interactions with compatible fatty acids such as lauric acid (LA) and stearic acid (SA), resulting in synergistic structural reinforcement within the composite.

PLA also possesses inherent thermal resistance, which enhances PCM stability during repeated heating cycles. The stabilizing effect of PLA mitigates excessive expansion or leakage of molten PCM under thermal stress, as reported in [25]. Additionally, PLA is derived from renewable biomass resources, making it an environmentally sustainable supporting material for renewable energy applications, including PCM-based thermal storage systems.

In contrast, the aPCM and cPCM samples exhibited lower thermal buffering performance compared to bPCM. Although the eutectic LA–SA composition remained constant, variations in PLA content significantly influenced the resulting thermal behavior. Comparison among PCM0, aPCM, and bPCM confirms that the 0.8 PLA modification provides the most effective heat absorption capability.

However, an inconsistency was observed in the cPCM sample. Increasing the PLA content beyond the optimal ratio resulted in a decline in heat absorption and thermal retention performance. This behavior is attributed to PLA overloading, which adversely affects the composite morphology and disrupts the functional role of LA and SA as the primary latent heat storage materials. As reported by [24], excessive PLA content leads to the formation of additional voids within the microstructure, facilitating heat penetration through the wall and reducing mechanical integrity. Similar observations were reported in [25], where imbalanced PLA content deteriorated PCM physical stability and consequently reduced thermal performance. Therefore, this study concludes that the optimal composition for achieving superior thermal buffering performance is the 0.8 PLA-modified PCM (bPCM), representing a balanced synergy between latent heat storage capacity and structural stabilization.

Tabel 1. Energy Analysis Results During the Charging (Heating) Process

Sample	Rate of Temperature Change (°C/hour)			q T ₁ to T ₂ (joule)	q T ₂ to T ₃ (joule)
	T ₁	T ₂	T ₃		
PCm0	5,2	2,5	1,45	84,006	32,943
aPCm	5,1	2,25	1,05	85,013	32,854
bPCm	4,75	1,15	0,65	85,538	32,049
cPCm	4,8	1,8	0,95	85,422	32,845

Table 1 summarizes the temperature change rates recorded at the three measurement points over the 120-minute testing period, together with the calculated heat transfer values (q) from T1 to T2 and from T2 to T3. These parameters were used as quantitative indicators to evaluate the thermal performance of the PCM-integrated wall systems. Based on the tabulated results, the bPCM sample exhibited the most favorable thermal behavior. It recorded the lowest temperature change rates at all measurement points, namely 4.75 °C/min at T1, 1.15 °C/min at T2, and 0.65 °C/min at T3. The reduced temperature gradient indicates a slower heat propagation rate through the wall assembly, thereby contributing to improved indoor thermal stability. This behavior confirms the enhanced thermal buffering capability of the bPCM configuration.

The heat transfer analysis further supports this observation. The bPCM specimen demonstrated the highest heat absorption from T1 to T2 (85.538 J), reflecting its superior latent heat storage capacity. Simultaneously, it yielded the lowest heat transfer from T2 to T3 (32.049 J), indicating effective suppression of heat transmission into the indoor space. Collectively, these findings confirm that the bPCM composition provides the most balanced performance in terms of heat absorption, thermal resistance, and indoor temperature stabilization among the tested samples.

B. PCM Heat Absorption Performance during the Discharging (Cooling) Process and Energy Analysis

During this phase, heat release occurs as the stored thermal energy is discharged from the wall specimens. The discharging process serves to evaluate the quality of the PCM in terms of its thermal energy storage capability over the testing duration, as well as its insulation performance. The retained thermal energy may be further utilized for secondary applications, such as poultry house heating or space heating systems. Figure 7 presents the temperature profiles recorded at the three measurement points for all four wall specimens during the cooling (discharging) process.

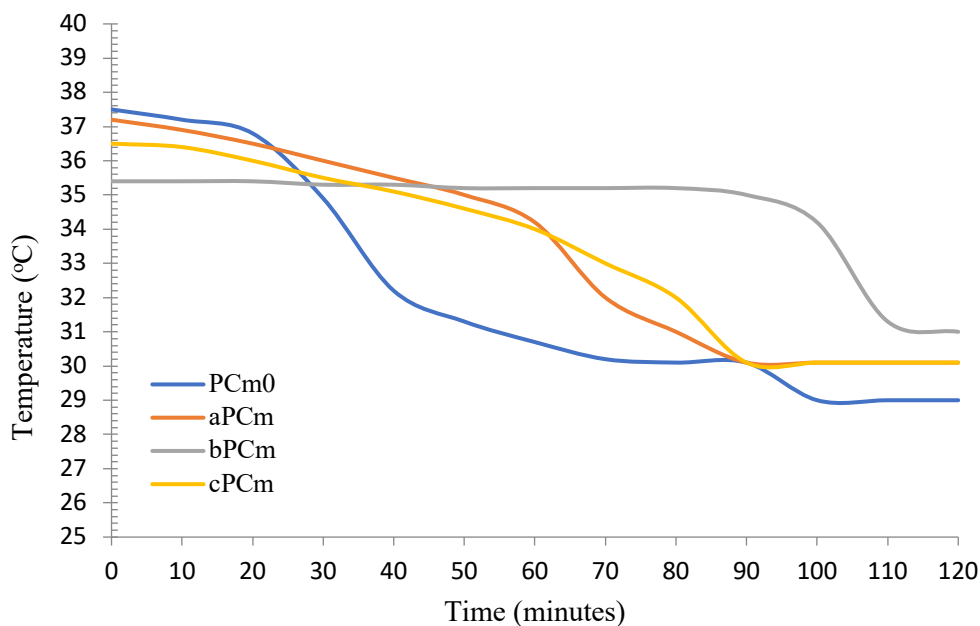


Fig 7. Combined Temperature Profile at the Exterior Wall [T1]

Clear differences in the temperature decay patterns among the samples can be observed during the discharging process. In this phase, the latent heat stored in the PCM is released from the wall structure as the material undergoes a phase transition from liquid to solid when the temperature approaches its solidification point. Unlike the charging process, the initial temperatures during discharging varied among samples, corresponding to the final temperatures reached at the end of the heating phase. Similarly, the final temperatures recorded at the end of the cooling period were not identical. These variations are attributed to differences in the heat release capacity of each PCM composition. In addition to thermal conductivity, this behavior is strongly influenced by latent heat capacity. As reported in [24,25], lauric-acid-based PCM integrated into sodium carboxymethyl cellulose and modified with PLA exhibited an increase in latent heat from 86.40 J/g to 153.06 J/g, resulting in significantly enhanced energy storage capacity.

The selection of PCM type and composition depends on its intended application. In the present study, the discharging phase is particularly important for evaluating the wall system's suitability for indoor thermal regulation. This phase determines whether the released heat significantly increases the interior wall temperature and affects the indoor environment of the mini-cubicle system. Each PCM composition exhibits a different heat release rate. The cooling rate at T1 and the final temperature achieved serve as indicators of the material's energy retention capability. As stated in [26], a slower heat release rate reflects better energy storage performance, whereas a higher sustained temperature indicates longer usable thermal discharge duration before complete solidification occurs.

Figure 7 shows that PCM-modified samples outperform the non-PCM wall in terms of controlled heat release. The bPCM sample exhibited the slowest cooling rate, maintaining a temperature of approximately 35 °C for nearly 1.5 hours. This behavior confirms its superior energy storage capacity, which can be attributed to the presence of PLA that enhances latent heat stability while reducing thermal conductivity. Similar findings were reported in [27], where PLA-modified PE-paraffin PCM composites demonstrated nearly double the heat release performance compared to pure paraffin.

In contrast, the PCM0 sample showed a rapid temperature drop at T1, decreasing sharply from 37.5 °C to 32.2 °C within 40 minutes. This rapid cooling indicates the absence of a latent heat storage mechanism, allowing heat to dissipate quickly without retention. The aPCM and cPCM samples exhibited intermediate cooling behavior with relatively similar decay patterns. Although the cPCM sample (1:1 PLA ratio) performed slightly better than aPCM, increasing PLA content beyond the optimal level did not enhance storage performance. Instead, excessive PLA resulted in performance degradation due to compositional imbalance.

PLA overloading adversely affects the composite morphology and disrupts the functional role of lauric acid (LA) and stearic acid (SA) as the primary latent heat storage components. Morphological observations of the cPCM sample revealed the formation of additional voids within the structure, facilitating heat penetration toward the interior wall surface and reducing the overall thermal buffering efficiency.

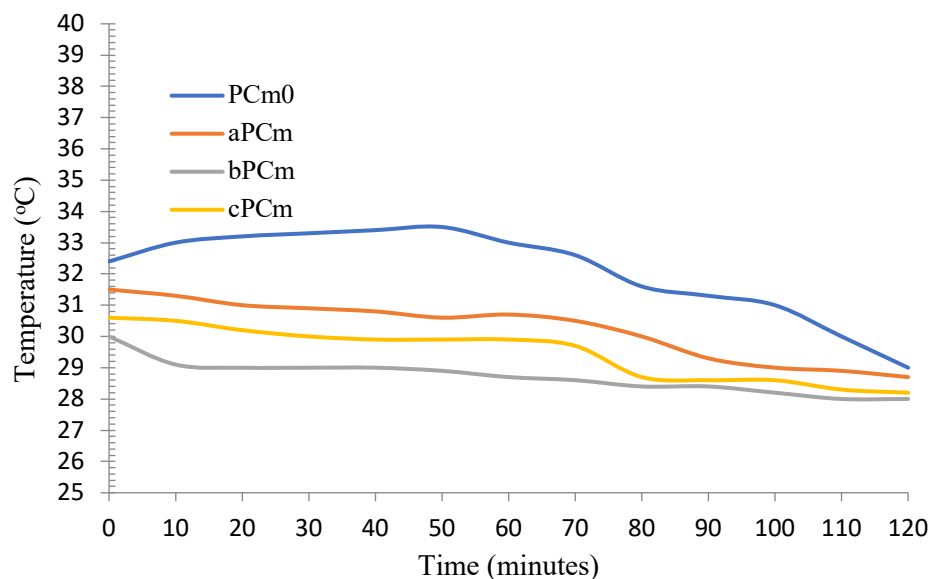


Fig 8. Combined Temperature Profile at the Interior Wall [T2]

The variation in interior wall temperature (T2) during the discharging phase further influences the overall performance evaluation of the samples. If the interior wall temperature increases despite the heat source being turned off, this indicates that residual heat from the exterior wall (T1) continues to propagate inward during the cooling process. Such behavior reflects limited effectiveness of the PCM in dissipating stored heat outward and is often associated with suboptimal PCM composition. The final temperature reached at T2 therefore serves as an important indicator of the sample's ability to reduce and stabilize indoor temperature conditions. The lower the final temperature achieved, the more effective the sample is in supporting indoor thermal comfort at T3.

The PCM0 specimen exhibited the poorest thermal performance. The interior wall temperature increased from 32.4 °C to 33.5 °C during the first 50 minutes, even though the heat source had already been switched off. This phenomenon indicates that heat stored at T1 was not only released outward but also conducted inward toward T2. A gradual temperature decrease only began after approximately one hour, eventually reaching 29 °C. This temporary temperature rise contributes to prolonged indoor overheating, as no latent heat storage mechanism is present to regulate thermal discharge.

In contrast, the PCM-modified samples demonstrated improved thermal regulation. Among them, bPCM exhibited the best performance. The interior wall temperature did not show any initial increase, indicating that no inward heat transfer occurred during discharging. Instead, the PCM effectively released heat outward. A rapid temperature decrease of approximately 1 °C from the initial 30 °C was observed within the first 10 minutes, followed by a gradual decline toward ambient indoor temperature, reaching 28 °C at the end of the testing period.

For the aPCM and cPCM samples, no temperature increase at T2 was observed, confirming that heat release predominantly occurred at the exterior wall surface. However, the final temperatures recorded for these samples remained slightly higher than that of bPCM, reaching 28.7 °C and 28.2 °C, respectively. These results further reinforce that the 0.8 PLA composition (bPCM) provides the most effective balance between heat storage and controlled heat release.

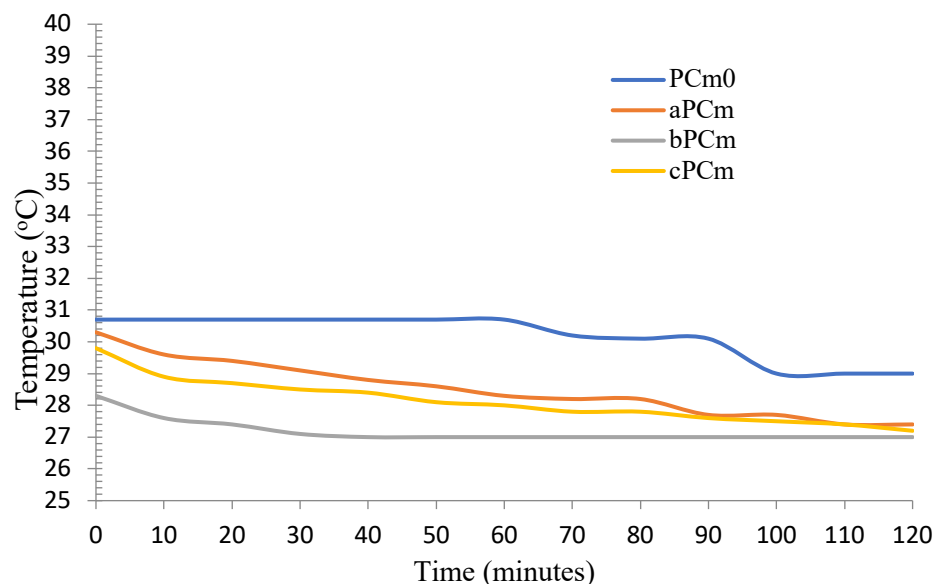


Fig 9. Combined Temperature Profile at the Indoor (T3))

The indoor temperature profile associated with the PCM0 specimen exhibited limited cooling capability, remaining relatively high throughout the discharging phase. The temperature stabilized at approximately 30.6 °C for nearly one hour, primarily due to the delayed heat release from the interior wall surface. A gradual temperature decline was observed thereafter, with a slow rate of change, reaching only 29 °C at the end of the testing period.

In contrast, the PCM-modified specimens (aPCM and cPCM) demonstrated more pronounced cooling behavior. The indoor temperature decreased from 31.5 °C to 28.7 °C ($\Delta T = 2.3$ °C) for aPCM and from 30.3 °C to 27.4 °C ($\Delta T = 2.9$ °C) for cPCM. However, despite these reductions, their overall performance remained inferior to that of the bPCM sample. The bPCM configuration exhibited the most favorable thermal response, with the indoor temperature (T3) decreasing rapidly and reaching a stable 27 °C within less than 30 minutes, maintaining this temperature until the end of the testing period. This rapid stabilization is particularly advantageous for heat-resistant wall applications, as the optimal PCM composition in bPCM effectively maintains indoor thermal comfort.

The integration of PCM within the gypsum wall enables stored thermal energy to be gradually released outward during the discharging phase, thereby preventing heat transfer into the indoor environment. Consequently, the indoor temperature decreases and stabilizes within the thermal comfort range. Conversely, in the absence of PCM, the wall—having accumulated heat during the

charging phase—continues to transfer residual heat inward during cooling. This sustained inward heat flow explains why indoor environments often remain warm even after external solar radiation has diminished, thereby increasing reliance on continuous air-conditioning operation to maintain thermal comfort.

Tabel 2. Energy Analysis Results During the Discharging (Cooling) Process

Sample	Rate of Temperature Change (°C/hour)			q T ₂ to T ₁ (joule)	q T ₃ to T ₂ (joule)
	T ₁	T ₂	T ₃		
	PCm0	4,25	1,7	0,8	83,600
aPCm	3,55	1,4	1,45	84,697	32,863
bPCm	2,2	1	0,65	85,368	32,033
cPCm	3,2	1,2	1,3	84,770	32,852

Based on the performance calculations of the PCM using the heat release indicator tabulated in Table 2, it can be observed that the PCM sample with the highest energy storage capability is bPCM. This is evident from both the Temperature Change Rate and heat release, where this sample exhibits the lowest Temperature Change Rate at each measurement point compared to the other samples, namely 2.2 °C/min at T1, 1.0 °C/min at T2, and 0.65 °C/min at T3. The low temperature change rates indicate that heat flow toward the exterior tends to be retained for a longer period without affecting the indoor temperature. This condition is advantageous, particularly when applied to space heating or similar applications.

Furthermore, considering the heat release factor from T1 to T2 and T2 to T3, the results are consistent. The bPCM sample demonstrates the highest heat release (q) from T1 to T2, amounting to 85.368 J, which is influenced by the magnitude of the average temperature difference. Meanwhile, the q from T2 to T3 is the lowest at 32.033 J due to a smaller average temperature difference. These findings confirm that the bPCM wall sample possesses a high energy storage capacity and exhibits the greatest effectiveness in maintaining indoor thermal comfort, as also reported by [25,27].

IV. Conclusion

Phase change material (PCM)-based building walls, designed to prevent solar heat from easily penetrating indoor spaces, have been successfully developed using gypsum as the base material combined with a eutectic mixture of lauric acid (LA) and stearic acid (SA) modified with polylactic acid (PLA). The use of this material combination demonstrates that integrating PCM into wall elements can enhance the thermal function of walls as passive heat barriers. The PCM modification process also plays a crucial role in optimizing its performance, where the addition of PLA at a ratio of 0.8 relative to the eutectic mixture significantly improves the PCM's capacity to absorb, store, and retain thermal energy. Performance testing during the charging process indicated that the bPCM sample was the most effective in maintaining indoor temperature, exhibiting the lowest temperature change rates at each measurement point compared to other samples: 4.75 °C/min at T1, 1.15 °C/min at T2, and 0.65 °C/min at T3, with a heat transfer (q) from T2 to T3 of only 32.049 J. Similarly, during the discharging process, the bPCM sample showed the lowest temperature change rates at all measurement points: 2.2 °C/min at T1, 1.0 °C/min at T2, and 0.65 °C/min at T3, and a minimal heat release (q) from T2 to T3 of 32.033 J. Overall, walls containing PCM, particularly the bPCM sample, demonstrated significantly superior performance in heat absorption, energy storage, and thermal insulation compared to conventional walls without PCM, highlighting their substantial potential to improve building energy efficiency.

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