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Investigate the Impact of PCM on the Thermal Performance of a Building Wall Under Hot Climates

Ahmed H. N. Al-Mudhafar[1*], Ali Lateef Tarish[2] and Akeel M. Ali Morad[2]

[1] Department of Thermal Mechanical Engineering, Basra Engineering Technical College, Southern Technical University, Basra, Iraq.
[2] Department of Fuel and Energy Engineering, Basra Engineering Technical College, Southern Technical University, Basra, Iraq.

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ABSTRACT

Southern Iraq, specifically Basrah, has a warm and arid climate. August has the greatest average temperatures in Basrah, with highs of 48°C. To overcome obstacles resulting from such major temperatures, Phase Change Materials (PCMs) are increasingly being used in building construction. This paper performed an experimental study to examine the energy efficiency of building walls that integrated with PCM under Iraq conditions. Additionally, the thermal performance of two different building walls was compared. The parameters investigated include the influence of heat gain, PCM temperature, and thermal load levelling (TLL) for both PCM and cement cases. Two test cases were exanimations. In the first case, the wall is made of blocks with cement filled holes. In the second case, the wall is made of blocks with PCM filling the holes. The outside conditions are controlled by using the hot water tank, and the cold-water tank represents the inside conditions for air conditioning space. The experimental analysis indicated that building blocks filled with PCM case achieve lower interior temperature and heat gain than cement case blocks. Furthermore, the peak heat flow was decreased by 75% when PCM-filled blocks were used instead of cement-filled blocks. The results revealed that PCM significantly minimize TLL by 42.6% as compared to cement. In conclusion, when the PCM is used to replace the cement, the interior thermal comfort improved and cooling energy use reduced.

1. Introduction

Buildings represent approximately 40% of the global energy demand and 33% of the carbon dioxide emissions. [1]. A significant part of this energy is used for heating and cooling in the buildings [2]. The cooling energy consumption are expected to increase dramatically in the world. Therefore, methods like passive cooling are required to lower energy usage in buildings. Phase change materials (PCMs) have a great potential for passive cooling, which can both increase interior thermal comfort and lower cooling energy requirements [3], [4]. Utilizing buildings envelop as a thermal mass, to store thermal energy has acquired significance in energy conservation and management. Usually, thermal mass is accomplished by building massive structure, which is old-fashion and expensive. Latent heat storage technologies could be utilized to boost the buildings thermal mass. This can be achieved by utilizing PCMs that release and absorb large amount of heat than conventional buildings materials [5]. The traditional building materials store thermal

[*] Corresponding author.
E-mail address: alalahmed@stu.edu.iq
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energy in sensible way compared to PCMs, which store heat in latent manner. Compared to conventional thermal mass materials, PCMs store large amount of heat in small temperature difference due to its high latent heat of melting [6]. Integration PCMs in building envelope help with wall thermal management such as shifting and decrease peak heat flux this lead to reducing the building energy consumption [7]. Many of the review papers discussed the advantages and limitations of integration PCM in building walls such as [8]–[11]. The most of a building's energy is being used by the HVAC. The optimum usage of PCMs in buildings envelope could lead to reduce peak cooling loads, this will reduce the required air conditioning systems required to cool the buildings.

Barzin et al. [12] studied experimentally integration PCM in gypsum board to reduce cooling energy consumption. In this experiment two similar test huts were used. The first hut was constructed from gypsum boards integrated with PCM, while the second hut constructed from ordinary gypsum board. Results indicated that by employing night ventilation to charge the PCM with free cooling, the weekly electricity consumption could be reduced by more than 70% compared to using boards without PCM. Mi et al. [13] study the influence of using PCM on energy consuming in multistory building located in China. Results indicated that the energy saving by utilizing the PCMs were more prominent in cold regions. Ansuini et al. [14] integrated PCM in a piped radiant floor, designed to store thermal energy in winter season and to reduce heat gain during summer season. The results showed that during summer, the PCM-floor save around 25% of the water used for cooling. Marin et al. [15] studied numerically the application of PCM in light weight relocatable buildings to save energy. The results highlighted that the integration PCM in gypsum boards for light weight buildings reduce energy consumption during cooling and heating seasons. Kishore et al. [16] numerically investigated integrating PCM in building walls located in different US cities to reduce cooling and heating energy consumption. The results showed that using PCM in building walls not necessary lead to reducing cooling and heating energy consumption, in fact incorrect usage of PCM (such as using PCM with unsuitable melting temperature or incorrect location of PCM in the walls) could lead to increase cooling or heating energy consumption. So, choosing the appropriate PCM depend on the climate of the location. In summary, while PCMs have the potential to enhance energy efficiency in buildings, their effectiveness is contingent upon proper application, alignment with building usage, environmental conditions, and compatibility with existing systems. Misapplication or misunderstanding of these factors can lead to scenarios where energy consumption is inadvertently increased, highlighting the importance of careful planning and implementation in PCM integration. Hamidi et al. [17] studied employing PCM to decrease building air conditioning energy consumption in many locations representing Mediterranean region. Many PCMs with different melting temperature were tested. Results indicated that the air conditioning energy consumption can be decreased by 56% by utilizing PCM with appropriate melting temperature. Mahdaoui et al. [18] studied numerically integrating PCM in building hollow bricks used to construct building external wall located in Morocco. Results indicated that by employing PCM in the brick, the indoor temperature fluctuation reduced. Jaworski [19] constructed a ceiling panel, the ceiling was constructed from a composite contain 27% PCM in the shape of parallel channels to allow air to flow. This ceiling was utilized to store the cooling in the PCM during night by passing the outdoor cold air over the panel. While, during daytime the indoor hot air pass through the panel to release the heat and cool the indoor air. Stritih et al. [20] used TRNSYS software to analyze a composite wall made up of various PCMs and validate it in preparation for incorporation in a prospective passive net zero energy building. The results showed that integration PCM in the walls can reduce building energy consumption and could help to build net zero energy building. Salihi et al. [21] numerically investigated integrating PCM in building walls under the semi-arid climate. Many parameters were tested to evaluate their effects on the performance of PCM such as phase change temperature range, location, thickness, configuration, and mechanical ventilation. Results indicated that integrating PCM in walls enhance the indoor thermal comfort and reduce temperature fluctuations and cooling load. Moreover, the usage of double layer of PCM was more effective compared to single layer. The effects of incorporating PCM into building walls on interior thermal comfort were investigated experimentally by Khan et al. [22]. Tests were carried out to study the influence of PCM position in building wall to find the optimum position. Results showed that putting PCM closer to outdoor wall layer reduce the outside heat gain compared to the PCM layer closer to the indoor wall layer. Moreover, integrating PCM in wall reduce the indoor temperature and reduce its fluctuation compared to the wall without PCM [22]. To the authors' knowledge, there is no published literature experimental study that examines the energy efficiency of building walls made from block (local Iraqi building material) that integrated with PCM. Rahi et al. [23] numerically studied the effect of using PCM capsules on reducing the inner roof temperature. 3D numerical model was used in the simulation. The outcomes indicated that integrating the PCM in the rooftop slab reduce the highest inside roof temperature by 3.2℃. Haemin et al. [24] tested three separate specific heat capacity models to determine the thermal performance of a concrete wall using Portland cement (PC). According to the findings, the non-central F-distribution function is the most effective specific heat model for accurately describing the thermal properties of PCM and improving the overall thermal performance of a PCM-containing PC concrete wall. Guixiao and associates [25] A novel concept for a dynamic PCM wall is created for buildings to use passive solar heating. Others reduce the PCM content to 0.32 kg/m3, which is just half of what is found in static walls. Energy savings range from 49 to 89% when compared to a wall that is traditionally insulated. The thermal behaviour of PCES walls was investigated using energy consumption studies, finite element numerical models, and unstable heat transfer tests. The findings indicate that 0.6°C is taken off the maximum temperature of the inner surface of the wall when PCMs are applied on the interior side, and 0.8 h is taken off the maximum temperature lag. The findings further demonstrate that, in comparison to typical structures, buildings using these PCES walls as the exterior shell have a yearly decrease in cooling energy consumption of around 7.6% and a yearly decrease in greenhouse gas pollution of almost 2% [26]. Based on the literature review mentioned above, there are few experimental studies about integrating PCMs in buildings in hot climates locations, especially southern of Iraq. The impact of PCM on the thermal performance of a building wall is experimentally investigated in the current study under Iraq-Basrah conditions. Addresses gaps in the literature regarding the specific application of PCMs in hot climates, particularly in the context of Iraqi building materials and practices. The current study presents several unique contributions to the field of building thermal performance, particularly in hot climates. This study is conducted in Basrah, Iraq, addressing a geographical area that has not been extensively covered in prior research regarding PCMs in building applications. The research specifically examines the performance of PCMs under very hot climate conditions, providing valuable insights for similar regions. The study employs two different wall models: First, incorporates PCM directly into the holes of concrete blocks, simulating a common local building practice. Second, uses cement to fill the holes, serving as a control to evaluate the impact of PCM. Third, the experimental setup allows for a direct comparison of thermal performance between the two models, enhancing the robustness of the findings. The effects of heat gain, temperatures, and TLL on building walls were investigated in detail. The results indicate that incorporating PCM into building block is a potential method for improving interior thermal comfort in buildings. The findings suggest that integrating PCM into conventional building materials can significantly enhance interior thermal comfort, offering a practical solution for builders and architects in hot climates. By utilizing locally common materials and methods, the study presents an accessible approach for improving building performance in the region. Finally, provides a basis for further investigations into PCM applications, encouraging more studies in similar environmental conditions.

2. Experimental description

2.1. Built model

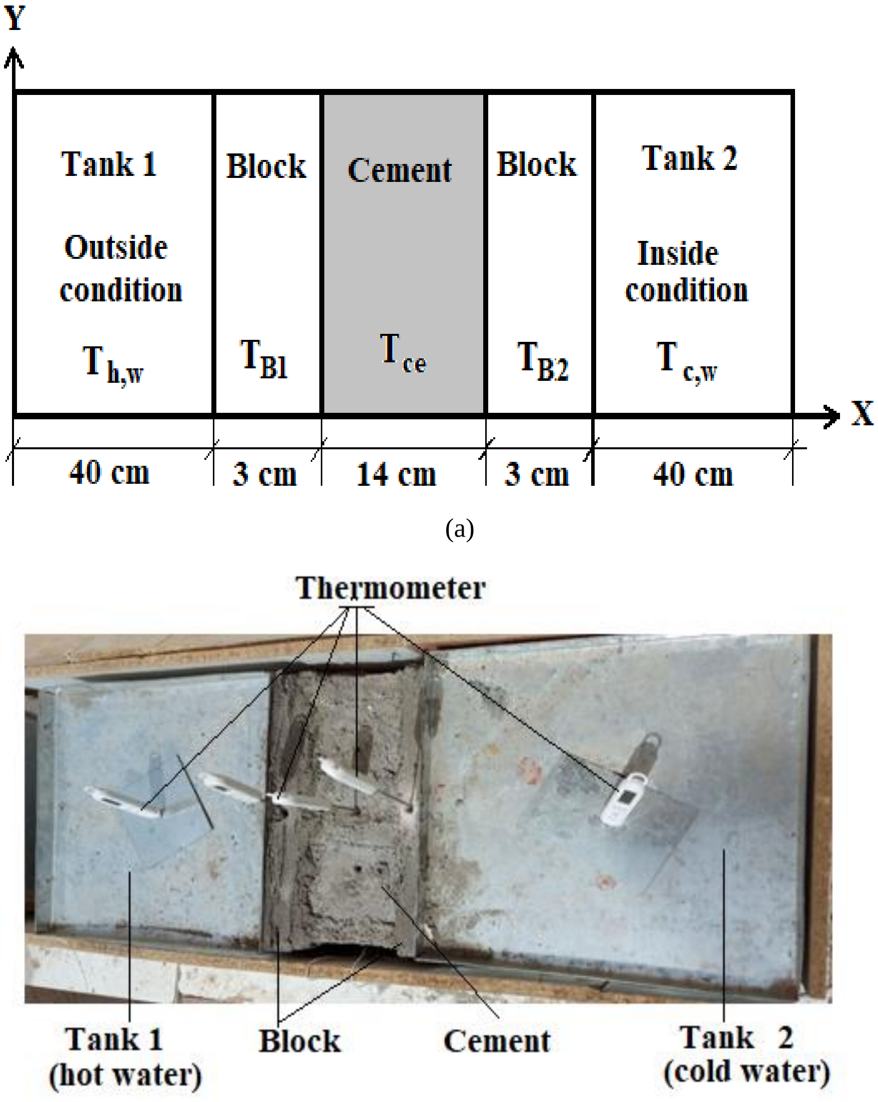
Two models of building walls layers that were built to investigate the thermal performance of the building walls. The first model consisted from cement block where its holes filled with PCM, and the second model consisted from cement block where its holes filled with cement. The PCM is used in this study because its melting temperature is suitable for Basra weather. For one-dimensional heat conduction through the wall, the models have been completely insulated with wood. There were two water tanks (made from galvanize iron plate) in each model. An electric heater was installed in one of the water tank (hot water tank) which used to heat the water to represent the outdoor environment, while the second water tank (cold water tank) represents the indoor space. Each water tank dimensions were 0.4 m (length) × 0.4 m (width) × 0.4 m (height). In the first experimental model as shown in Figure 1.a, there were two cement blocks one over each other, each block dimension: 0.2 m (length) × 0.4 m (width) × 0.2 m (height). The holes of the blocks were filled with cement as shown in the Figure 1.b. While, the second experimental model as shown in Figure 2.a, there were two cement blocks one over each other, each block dimension: 0.2 m (length) × 0.4 m (width) × 0.2 m (height). The holes of the blocks were filled with PCM as shown in the Figure 2.b. The hot water tank was heated by using 2 kW electric heater. The temperature was measured at different layers of the models by using pen type thermometers. The thermo physical properties of the PCM and the different building materials are shown in Table 1.

2.2 Climate conditions

Two building wall layer models were set up in a temperature-controlled room with adequate room for ventilation. The atmosphere within the chamber was set up to replicate the hot weather and summertime conditions seen in Basrah, Iraq. The southern Iraqi city of Basrah is classified as BWh under the Köppen climate classification system. This type of weather zone designation indicates a warm, dry climate. This categorization is mirrored in the typical weather seen across Basrah, which shows notable yearly variations in a range of meteorological markers. At 41.8°C at highs and 26.1°C at lows, August has the highest average temperatures in Basrah [28]. Figure 3 shows the change in temperature in Basrah City in 2023. Figure 4 depicts the sun and daytime hours in 2023. Figure 5 shows the variations of outdoor temperatures for August 2023.

Table 1: Building materials' and PCM thermophysical characteristics [27] [31].

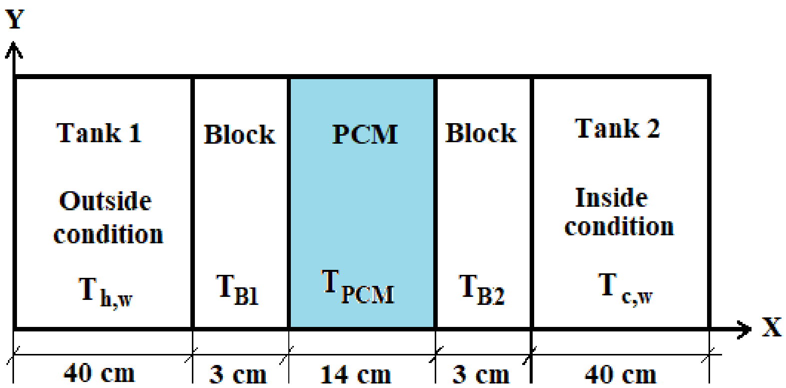
Material	Density (kg/m^3)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Melting temperature (°C)	Latent Heat (kJ/kg)	Thermal expansion coefficient (1/K)
Paraffin wax (PCM)	900	0.25	1840	30	250	0.001
Concrete block	2243	1.31	837	-	-	-
Galvanized steel	7833	65	465	-	-	-



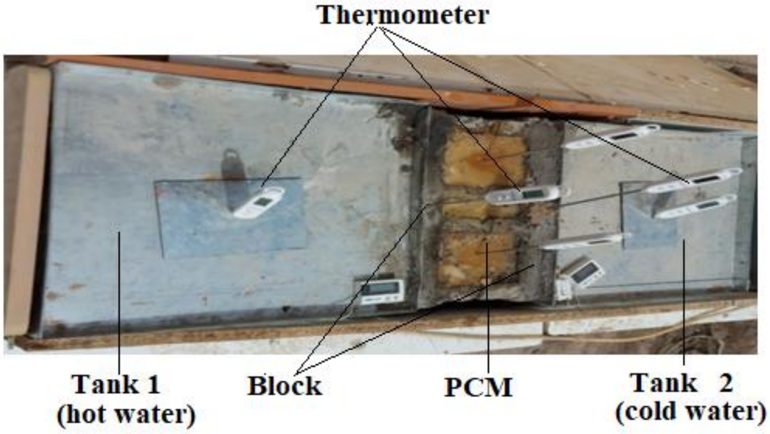
(a)

(b)

Figure 1. Configuration of building wall model (cement case); (a) Schematic diagram with dimensions and locations of temperature sensors, (b) Real view of the wall



(a)



(b)

Figure 2. Composition of building wall model (PCM case); (a) Schematic diagram with dimensions and locations of temperature sensors, (b) Actual view of Experimental setup.

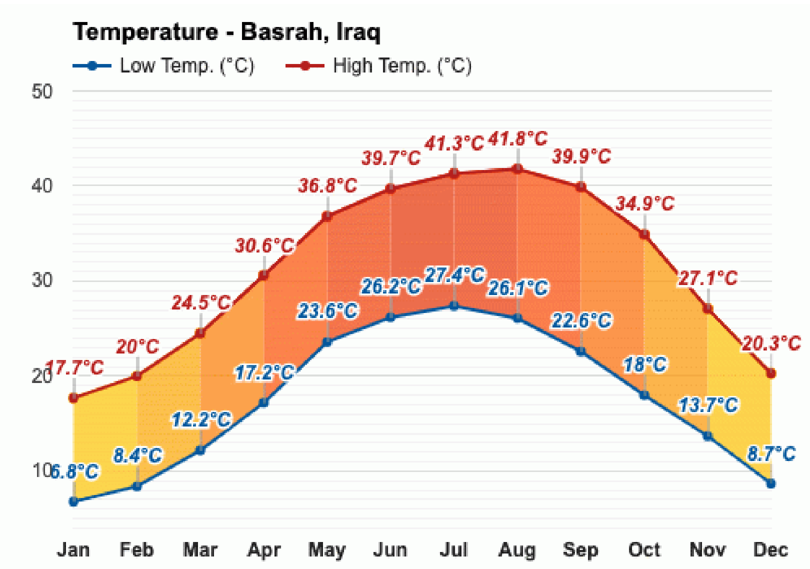


Figure 3. Variation in temperature in Basrah City in 2023 [28].

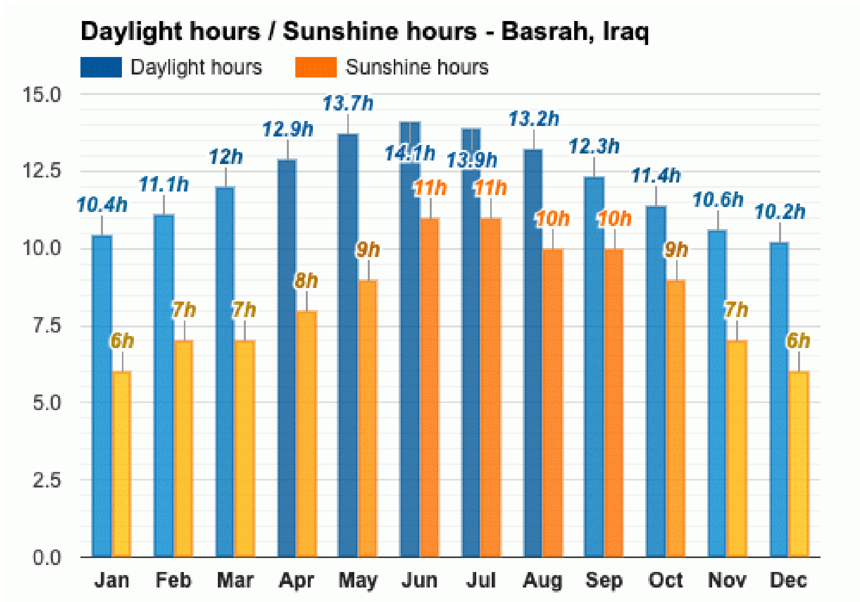


Figure 4. Sunlight and daylight hours during the 2023 [28].

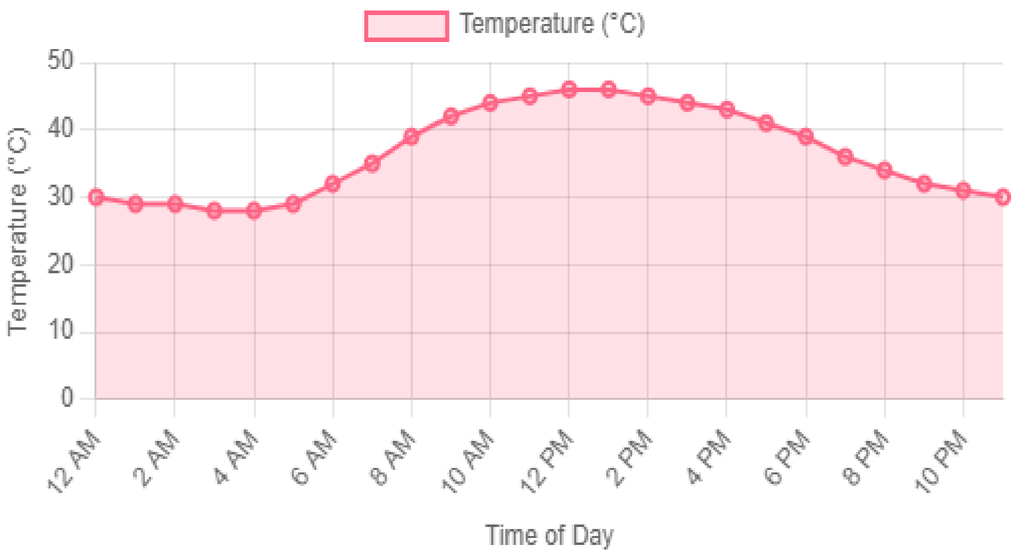


Figure 5. Outdoor temperature variations (August 2023).

2.3 Thermal load level

The variations in surface temperatures (interior conditions) for the block filled with PCM and block filled with cement were evaluated using the thermal load level (TLL), which is often used to assess greenhouse effectiveness [29], TLL for PCM and cement is described as follows:

$$TLL_{PCM} = \frac{(T_{max} - T_{min})_{PCM}}{(T_{max} + T_{min})_{PCM}} \quad (1)$$

$$TLL_{ce} = \frac{(T_{max} - T_{min})_{ce}}{(T_{max} + T_{min})_{ce}} \quad (2)$$

where T_{PCM} is the temperature of the PCM, and T_{ce} is the temperature of the cement for inside condition.

2.4 Experimental procedure

One-dimensional steady state conduction experiment was performed on the building walls models. The parameters that were measured included the temperatures of the wall layers, the temperature of the hot water, and the temperature of the cold water. The temperatures reading was registered every 20 min. The hot water was heated by using electric heater to simulate the outdoor environment, the cold water was initially at room temperature and then received the heat from the wall to represent the indoor environment. To utilize the root sum square method for uncertainty propagation, the observations must be a set of values with a regularly distributed, uncorrelated distribution and no regular errors. The measurement variables' uncertainties have been determined, as seen in Table 2. The engineering equation solver (EES) program was used for investigation into the measurement variables' uncertainty.

Table 2: Temperature absolute accuracy of measurements.

Temperature	Accuracy
$T_{h,w}$	±0.4601 °C
T_{wb}	±0.3824 °C
TB1	±0.4650 °C
TB2	±0.2546 °C
Tce	±0.4372 °C
T_{PCM}	±0.4759 °C

2.5. Mathematical Model

The formula for calculating heat flux (q) is provided by Fourier's equation of heat conduction, which indicates the rate of heat transfer through a medium is proportional to the negative gradient of temperature and the area through which the heat is flowing. The formula is given by:

$$q=-k\times A\times(dx/dT) \quad (3)$$

In this case, (q) represents the heat flux (W/m²), (k) the thermal conductivity of the substance (W/m·K), (A) the area of heat transfer (m²), and (dT/dx) the temperature differential (K/m). When using a water tank to simulate the thermal environment, it's essential to consider heat transfer through the tank walls. The heat transfer through the tank wall can be modelled similarly.

The thermal performance of the building walls was evaluated in term of heat flux reduction. The overall heat flux (q/A) in (W/m^2) through the building wall (block) was considered as shown below:

$$q/_A=\frac{T_{cw}-T_{hw}}{\frac{\Delta x_1}{k_1}+\frac{\Delta x_2}{k_2}+\frac{\Delta x_3}{k_3}} \quad (4)$$

Where T_{cw} and T_{hw} are the wall surface temperatures of the cold and hot water tanks, respectively, and Δx is the thickness of each layer of the wall.

3. Results and discussion

3.1 Block filled with cement case

The type of material used for the cement-filled block's case and the locations of the thermometers are shown in Figure 1. Figure 6 illustrates the temperatures of the various cement-filled block layers of the wall as well as the temperatures of cold and hot water. The data presented here clearly shows that as the wall layer moved away from the heat source, its temperature dropped (hot water tank). Due to its high thermal conductivity, the cement in the block holes warmed up over time. The link between the temperature of the cement-filled block layers in the wall and their distance from the heat source is clearly shown by the data. In order to preserve energy efficiency and comfort in building design, effective heat transmission and retention are made possible by cement's high thermal conductivity, which is a key component of this process. The $T_{h,w}$ curve (shown in red) starts at a high value and gradually decreases over time. This decreasing trend in $T_{h,w}$ indicates that the thermal heat flux is reducing as the experiment progresses. The decrease in $T_{h,w}$ can be attributed to the phase change process of the phase change material within the system. As the PCM absorbs heat and undergoes the phase transition from solid to liquid, it is able to regulate the temperature, leading to a reduction in the overall thermal heat flux. The T_{B1} and T_{B2} curves exhibit a relatively stable trend throughout the experiment. These temperature measurements at different locations within the system remain relatively constant, indicating that the PCM is effectively regulating the temperature and maintaining a more stable thermal environment. The decrease in T_{ce} suggests that the outer surface temperature is reducing as the experiment progresses. This can be attributed to the insulating effect of the air layer within the ceiling and roof, which has a lower thermal conductivity compared to the PCM. The decrease in $T_{c,w}$ indicates that the temperature of the ceiling is also reducing over time. This is likely due to the same insulating effect of the air layer, which slows down the heat transfer to the ceiling. In summary, the observed behaviour of the curves can be attributed to the phase change and thermal regulation properties of the PCM, as well as the insulating effect of the air layer within the ceiling and roof. The data clearly demonstrates a temperature gradient, with higher temperatures close to the heat source (a hot water tank) and a progressive drop in temperature as the source moves farther away. Similar investigations have shown that when exposed to heat sources, materials with strong thermal conductivity, such as cement, display noticeable temperature gradients. For example, Ravelo et al. [30] supported the existence of a thermal gradient by seeing a noticeable temperature decrease in concrete walls at increasing distances from heating units.

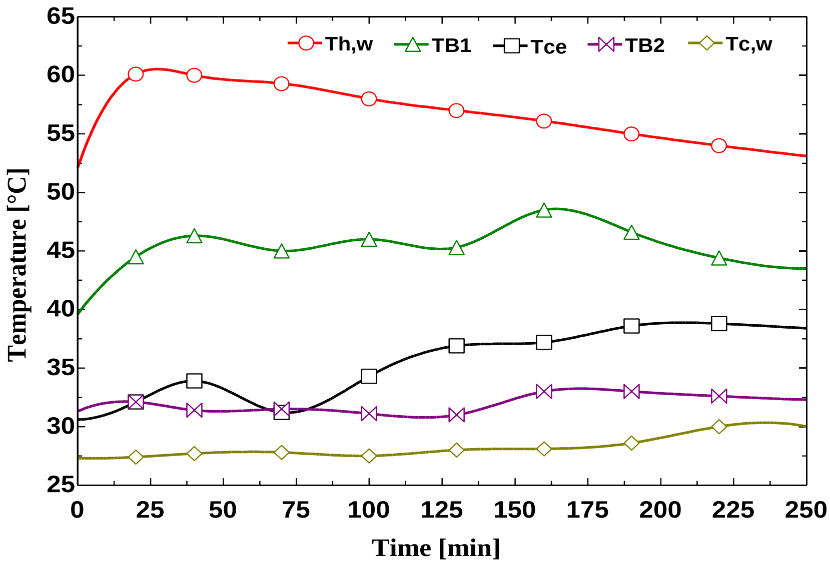


Figure 6. Temperatures of different layers for block filled with cement case.

3.2 Block filled with PCM case

The composition of the case of the block filled with PCM and the locations of thermometers are shown in Figure 2. The temperatures of different layers of the wall consisted of block filled with PCM in addition to the temperature of hot cold and hot water are illustrated in Figure 7. The results demonstrate that when the wall layer travelled from the heat source, its temperature dropped. (hot water tank). Due to the cement case's limited thermal conductivity, the temperature of the PCM in the block holes increased more slowly than it occurred in the cement case. Based on the Figure 7, the temperature difference between the phase change material (T_{PCM}) and ($T_{c,w}$) exhibits the following behaviour: From 75 minutes to 135 minutes: The temperature difference between T_{PCM} and $T_{c,w}$ decreases during this period. This is despite the fact that the temperature of the hot water tank ($T_{h,w}$) is decreasing during this time.

After 135 minutes: The temperature difference between T_{PCM} and $T_{c,w}$ starts to increase again. This occurs even though the temperature of the hot water tank ($T_{h,w}$) continues to decrease. The explanation for this behaviour is likely related to the phase change process of the PCM material: During the 75 to 135 minute period, the PCM is undergoing the phase change process, absorbing heat from the ($T_{c,w}$). This causes the temperature difference to decrease, as the PCM is able to maintain a relatively constant temperature during the phase change. After 135 minutes, the PCM has likely completed the phase change process. As the hot water tank temperature ($T_{h,w}$) continues to decrease, the temperature of the PCM also starts to decrease, leading to an increasing temperature difference between T_{PCM} and $T_{c,w}$.

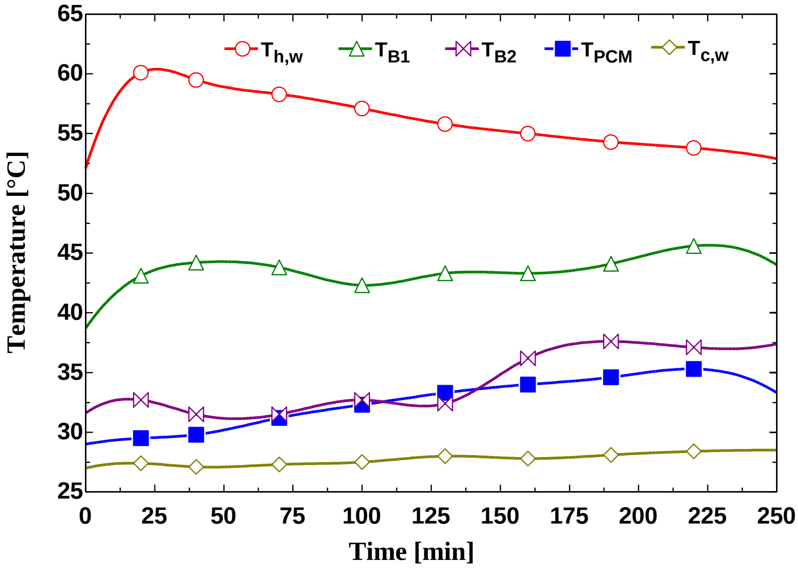


Figure 7. Temperatures of different layers for block filled with PCM case.

3.3 Comparing two cases

In order to evaluate the effect of integrating PCM on building wall, the thermal performance of block filled with PCM compared with block filled with cement. Figure 8 show temperature rise of cold water (indoor environment) for block filled with PCM case and block filled with cement case. It’s clear from this figure that the cold-water temperature (indoor condition) is lower in case of using PCM in the holes of block compared to using cement in the holes of the block. This happens due to the ability of PCM to store high amount of heat during phase change and its low thermal conductivity. The temperature difference between the cement and the PCM increases in the period from 200 minutes to the end of the experiment. The reason for this increase in temperature difference can be attributed to the following: Depletion of the PCM's phase change capacity: As time progresses, the PCM has likely completed its phase change process and can no longer absorb or release heat at a constant temperature. This means the PCM's temperature starts to follow the decreasing trend of the cement temperature, leading to an increasing temperature difference between the two. Continued heat loss from the system: The overall system is losing heat over time, as indicated by the decreasing temperatures of both the cement and PCM. However, the PCM's temperature decrease is more gradual compared to the cement's, causing the temperature difference to grow larger. Thermal inertia of the PCM: The PCM has a higher thermal mass and lower thermal conductivity compared to the cement. This means the PCM takes longer to respond to the decreasing heat input, resulting in a slower temperature drop and a widening temperature difference. Figure 9 show the comparison of heat flux for block filled with PCM case and block filled with cement case. It's obvious from this figure that the heat flux in case of using PCM is reduced compared to the case without PCM. Moreover, the peak heat flux reduced by 75% in case of using blocks filled with PCM compared to case of using blocks filled with cement. This occurs as a result of the high heat storage capacity of PCM during the phase change process. This indicates that adding PCM to building walls will improve thermal comfort and use less energy for cooling. The lower cold water temperature in the PCM-filled blocks demonstrates that the PCM can effectively absorb heat from the surrounding air. The main reason for this is that it can go through phase changes, which enable it to store a lot of thermal energy without experiencing a noticeable rise in temperature. PCM functions as a buffer against heat transmission, as seen by the material's notable 75% decrease in heat flux. As a result, there will be less heat transfer through the wall, maintaining a more constant temperature within.

The heat flux of the PCM (represented by the blue line) exhibits a peak around the 23-minute mark, which appears to be the highest value observed during the experiment. The reason for this peak in heat flux can be attributed to the phase change behavior of the PCM material: At the beginning of the experiment, the PCM is initially in a solid state. As the system is heated, the PCM starts to undergo a phase change transition from solid to liquid. During this phase change process, the PCM is able to absorb a large amount of heat energy while maintaining a relatively constant temperature. The peak in heat flux around 23 minutes corresponds to the point where the PCM is undergoing the most rapid phase change transition. As the PCM transitions from solid to liquid, it is able to absorb a large amount of heat energy from the surrounding cement, resulting in the observed peak in heat flux. According to the research, incorporating PCM into building walls may result in less energy being used for cooling, by lowering the amount of heat that enters the inside to keep the temperature at a reasonable level. In summary, the highest value of heat flux observed around 23 minutes is due to the rapid phase change transition of the PCM material from solid to liquid state. This phase change process enables the PCM to absorb a large amount of heat energy, resulting in the peak in heat flux during this critical transition period.

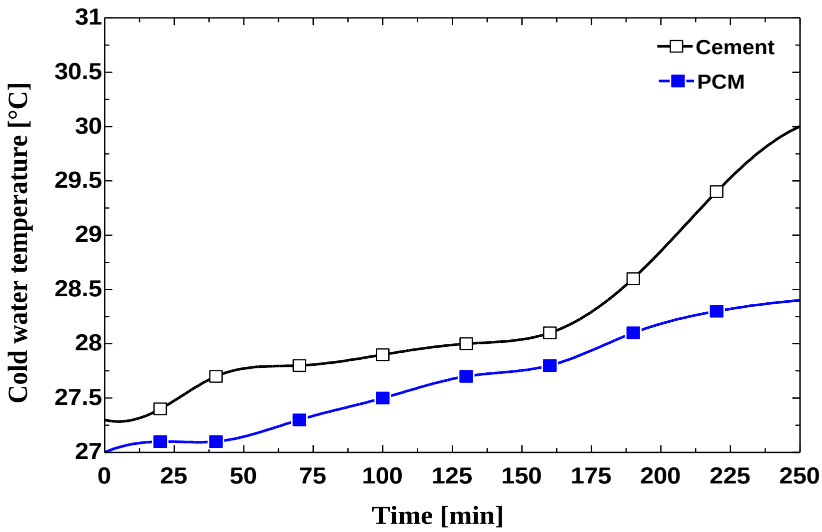


Figure 8. Temperature variation with time for PCM and cement.

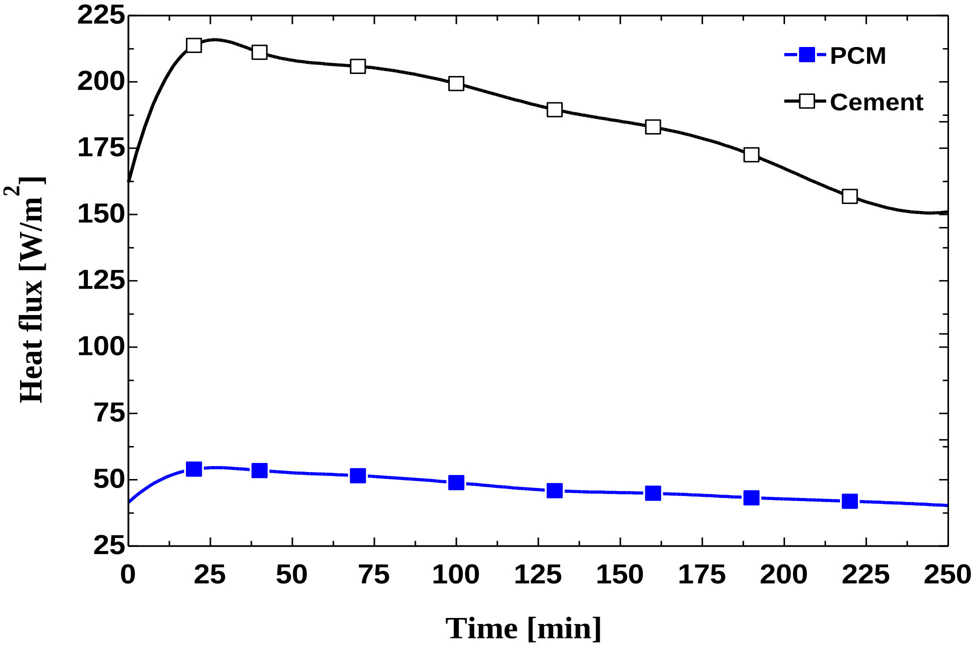


Figure 9. Variation of heat flux with time for PCM and cement.

3.4 Comparison with literature

The current study's findings can be validated even more by comparing them to other references [31]. Multiple studies examining the thermal behavior of PCM layers across different environmental circumstances and heat source configurations might help us better understand temperature management. To validate the influence of increasing PCM layer coverage on moderating interior temperatures, compare the time delay in temperature rise to findings from comparable trials. The variable substance used in Ref [30] was a PCM with a lower thermal conductivity (0.45 W/mK) and the ambient air (0.02 W/mK). Also, the PCM had a higher specific heat capacity (2.09 kJ/kg.K). The results (see Figure 10) were compared to Ref. [31] to determine the consistency and dependability of the observed trends, which had a deviation of 7%.

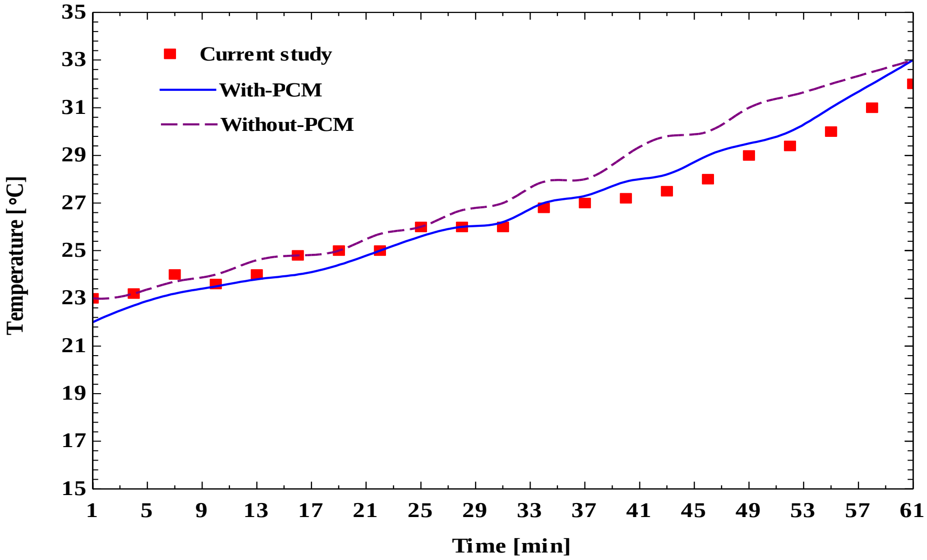


Figure 10. Comparison the current finding with Ref [31] for average temperature with time.

3.5. Thermal load performance (TLL)

The cement and PCM TLL findings are shown in Figure 11. It was shown that the TLL for PCM walls can decrease by 42.6% when compared to cement because of the larger temperature difference between the maximum and minimum temperatures for interior circumstances. In other words, even while a PCM wall can lower temperature more than cement, it can nevertheless withstand relatively small amounts of minor thermal load from the cement.

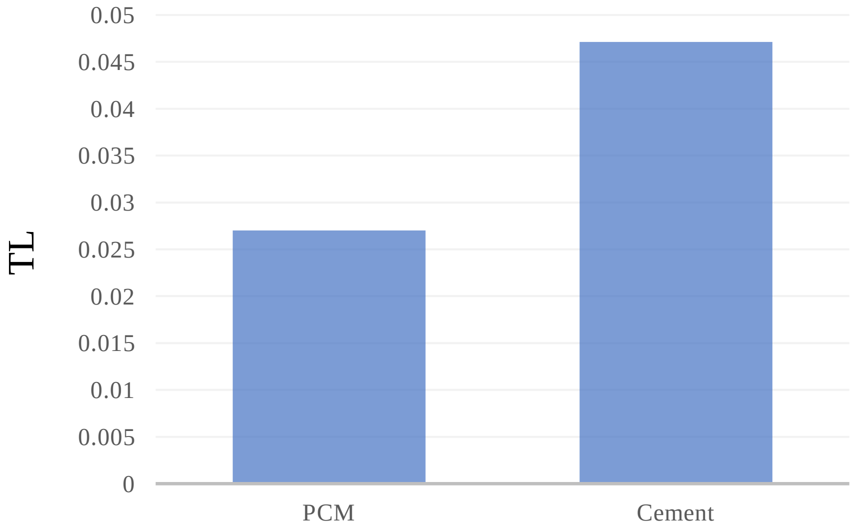


Figure 11. Variation in the TLL for the PCM and cement.

4. Conclusions

The effect of integrating PCM in building wall constructed from block was experimentally investigated. Two cases of building wall were compared. In the first case the block holes were filled with cement. In the second case the block holes were filled with PCM (paraffin wax). The main conclusion as the following:

1. The building wall filled with PCM had a lower interior temperature (as measured by the cold-water temperature) than the cement-filled wall. This shows that PCM effectively absorbs and reduces heat, resulting in a cooler interior atmosphere.
2. The heat gain in the PCM-filled wall was significantly less than the cement-filled wall. This decrease in heat gain, is critical for maintaining appropriate interior temperatures, particularly during peak summer months.
3. PCM-filled blocks had a 75% lower peak heat flux than cement-filled blocks. This significant drop suggests that PCM functions as an efficient thermal buffer, reducing heat transmission through the wall.
4. The results showed that the PCM can lower the TLL by 42.6% compared to the cement-filled blocks. This reduction further emphasizes the PCM's capability to enhance thermal performance.
5. Incorporating PCM into building walls lowers energy usage for HVAC (heating, ventilation, and air conditioning) systems while simultaneously improving thermal comfort. This can lead to significant energy savings and reduce environmental impact over time.

Nomenclature

Symbol	Description
$T_{h,w}$	Hot water temperature (°C)
T_{wb}	Cold water temperature (°C)
Δx	Thickness (m)
TB1	Blok first side temperature (°C)
TB2	Blok second side temperature (°C)
Tce	Cement temperature (°C)
T_{PCM}	PCM temperature (°C)
k	thermal conductivity (W/m.K)
Abbreviations	
PCM	Phase change material
TLL	Thermal load level

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