Using Phase Change Materials (PCMs) in a Hot and Humid Climate to Reduce Heat Gain and Energy Consumption

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Abstract: Twenty percent of the world’s energy is consumed by the construction sector, including commercial and residential buildings, where 13% is consumed by the residential sector only. Half of the total energy consumed by buildings in Saudi Arabia is specifically attributed to the hot summer season, which, unlike in many other countries in the Middle East, continues for more than 5 months annually. The use of a phase change material (PCM), as an insulator in building materials, can be a solution to provide a comfortable indoor temperature and reduce energy consumption. This study examined two different melting ranges for PCMs RT35 and RT35HC inserted into hollow clay bricks to investigate their thermal behavior and heat storage capacity and compare them with polystyrene foam. To perform this experiment, four chambers were constructed using cement plastering. The data were collected at Jeddah, Saudi Arabia, from mid-November 2020 to the end of February 2021. When the highest temperature was reached during the experiment, PCM RT35 provided a better cooling effect by 13% compared to 24% and 28.56% for PCM RT35HC and foam, respectively, compared to hollow bricks alone. However, when the lowest temperature was reached during the experiment, PCM RT35HC performed better than the other chambers in saving energy and keeping the chamber warm, which was 9.5% for the reference chamber, 7.0% for the foam chamber, and 2.8% for PCM RT35. The maximum energy saving of PCM RT35 was around 1920 kJ, which is around 0.533 kWh, for one wall only, and for PCM RT35HC, it was 2880 kJ, or 0.8 kWh, which can reduce energy consumption of the HVAC system by 97 kWh/m² and 146 kWh/m² per year, respectively.

Keywords: phase change material (PCM); hollow bricks; thermal behavior; latent heat; thermal comfort

1. Introduction

Twenty percent of the world’s energy is consumed by the construction sector, including commercial and residential buildings, where 13% is consumed by the residential sector only [1]. Half of the total energy consumed in Saudi Arabia is by buildings, which is specifically attributed to the hot climate that, unlike in many other countries in the Middle East, continues annually for more than 6 months [2]. The hot weather and the economy, along with population growth, have influenced the increasing use of air conditioning. Moreover, during the summer, temperatures may become higher by about 50%. Such scorching conditions necessitate the use of air conditioners, which alleviate the heat and allow people to have a comfortable place to live and work [3]. However, the increased use of air conditioners results in increased electrical energy consumptions. Even with the recent
energy price reforms that doubled utility energy bills, for typical households, over the last 5 years, several energy efficiency measures remain cost-ineffective for KSA households [4]. The cost of replacing AC systems, in particular, can be significant as most of the houses use several single AC units serving different rooms [5]. This global problem has been studied by scientists to find solutions. One of these solutions is the use of phase change materials (PCMs). This technique has been studied thoroughly by researchers during the last decade. PCMs have been chosen because of their many features, such as their ability to increase thermal energy by storing it and then releasing it at a constant temperature over a long period of time [6–8]. Another feature is that they can be melted at different temperatures.

The above-mentioned features have encouraged researchers to recommend the use of PCMs in refrigerators, supermarkets [9], and buildings [10–12] or as HVAC systems [13–15]. There are some techniques that have been tested by researchers, using PCMs with building materials, such as (a) direct mixing with mortar, cement, or gypsum; (b) direct immersion of brick or wallboard to absorb the PCM by dipping it into the PCM liquid; (c) encapsulation, where the PCM is encapsulated or packed in a container before being used with building materials; and (d) shape-stabilized PCM, using supporting materials such as high-density polyethylene (HDPE), styrene, and butadiene with the PCM. Then, the PCMs are melted at high temperatures and mixed together [7,16]. The first two of the above-mentioned techniques have many disadvantages, for instance, leakage of the PCM during the melting phase and the mechanical and durability properties of the PCM being affected with time, which leads to structural failure [8,17]. However, the third technique, that is, encapsulation, comprises two methods: microencapsulation, where the PCM particles are encapsulated in a shell sized from 0.05 µm to 5000 µm, and macroencapsulation, where the PCM is encapsulated in larger containers of up to a few liters, such as tubes, shells, thermal packs, cylinders, or polymer bags [18]. The advantages of the encapsulation technique include preventing the leakage of the PCM during the melting phase. The PCM can also be designed to fit inside the building materials to give high durability and high thermal stability. Alternatively, the PCM, using the encapsulation technique, must be protected from distortion, such as from drilling holes or nailing on the walls. In the last technique, shape-stabilizing materials such as high-density polyethylene (HDPE) or styrene are mixed with the PCM to create a shape-stabilized PCM [8,19,20].

Ahmad (2016) conducted a study in the construction sector in Al Ain, UAE [21]. The experiment involved using three small rooms containing three concrete blocks. Two of them contained a PCM in different arrangements. The study revealed that the use of a PCM positively affected the reduction in heat transmission by 44% and 10.5% for blocks B and C, respectively, with the peak temperature delayed by 2.6 h. A thin layer of PCM was used in the two test houses for the south and west walls, which reduced the heat flux by 51.3% and 29.7%, with a delay in peak heat flux time by 6.3 h and 2.3 h, respectively [22]. A PCM was evaluated inside a dynamic wall simulator, with three different arrangements near the inlet, in the middle, and near the exit. The PCM near the inlet of the wallboard gave a greater reduction in heat flux, especially when the temperature indoors was high, whereas when the temperature of the inside became cooler, the PCM in the middle layer provided a higher heat flux reduction [23].

In another experiment conducted on three wall specimens M1, M2, and M3, the first wall M1 was used as a reference, the M2 wall used a PCM, and M3 used a PCM and 10-mm-thick XPS insulation [12]. M2 and M3 registered 50% and 80%, respectively, heat transmission reduction compared to the reference. Another experiment used 10 samples with different shapes of an integrated PCM in concrete blocks to determine its thermal behavior [24]. The 10 samples, including the reference block, included PCMs with different amounts in two blocks of cuboid shape, two of cylindrical shape, four of plate shape, and one of spherical shape. The result of the spherical shape showed the fastest melting time for the PCM. This was due to the large heat transfer surface and the equal distribution. However, the cuboid shape, with a thick layer of PCM at 1.5 kg, showed a longer melting
time and lower heat transfer. Finally, the plate-shaped PCM samples showed different thermal behaviors, depending on their position, thickness, and orientation.

The photovoltaic PCM attic roof showed a 30% reduction in roof-generated heating loads compared to a conventional shingle attic in winter. However, during summer, the attic-generated cooling loads, from the PV-PCM attic, were 55% lower than a shingle attic [25]. The PCM’s behavior, during cooling and heating, depends on its melting temperature [26,27], place [28], and location of the air cavity associated with the PCM or any other insulation used with the PCM [29].

The government of Saudi Arabia decided to implement efforts and initiatives targeted at lowering energy consumption in numerous areas, including the building industry. This is due to the high energy consumption in the building sector. One of the most significant actions taken by the government was the implementation of a new building code. This code became necessary for residential structures in August 2020 [30]. This study is a step in this direction, as the impact of PCMs on energy consumption in buildings in Jeddah, Saudi Arabia, under hot and cold weather conditions was investigated and compared to that of polystyrene foam and bricks.

2. Theory

A PCM starts to absorb heat as latent heat along with sensible heat during the melting phase. The heat transfer in this experiment was considered to be by conduction \( q''_{\text{cond}} \) in Equation (1).

\[
q''_{\text{cond}} = q_x = -k \frac{dT}{dx}
\]

where \( k \) is the thermal conductivity \( (W/(m*K)) \), which is provided in Table 1, \( dT \) is the difference in temperature, and \( dx \) is the width.

To evaluate the rate of heat transfer and heat flux through hollow bricks based on the collected data, the following assumptions were made:

- The heat transfer and the airflow are one-dimensional.
- There is a steady-state heat flow.
- Heat loss from the corners and edges is neglected.
- The used material has constant properties.
- The heat transfer is only by conduction.

To calculate the rate of heat transfer and the heat flux through the bricks, the thermal resistance \( (K/W) \) must be known, as shown in Equation (2). Figure 1a,b shows a layout of how the heat flows in one dimension through the brick and its thermal resistance location. The thermal conductivity of the air inside the small cavities of the bricks was found to be between 26.3 and 30 \( (W/(m*K)) \) at atmospheric pressure, depending on the temperature in absolute Kelvin \( (K) \) [31]. Fourier’s law was used to find the conduction heat transfer rate \( q \) in watts \( (W) \) in Equation (3), and the heat flux \( q'' \) was found by dividing the two equations by the area of the bricks \( (A) \) to get Equation (4). The direction of the heat flow was determined to be from the inside to the outside: \( \Delta T = (T_{\text{in}} - T_{\text{out}}) \). Moreover, the temperature used in the equation was the average of those captured by all the outside and inside sensors for all four chambers.

\[
R_{\text{tot}} = \frac{1}{R_b + R_a + R_{\text{cond}}}
\]

where \( R_b, R_a, R_{\text{ins}}, \) and \( R_{\text{cond}} \) are the thermal resistance of the bricks, air cavity, insulation (PCM or foam), and conduction heat flow, respectively.

\[
q_{\text{cond}} = \frac{kA}{L} \Delta T
\]
$L$, in meters (m), is the width of the brick, including its cavity, and $A$ represents the area of the resistance in square meters ($m^2$).

For conduction

$$q'' = \frac{q}{A} \tag{4}$$

3. Materials and Methods

The research methodology emphasized on using two types of PCM, i.e., RT35 and RT35HC, inserted into hollow clay bricks to study their heat gain effect and compare them with polystyrene foam insulation. Since all the chambers are fully insulated, the PCM will absorb the heat and reach the melting phase as a result of sunlight and heat conduction. Depending on the atmosphere, the cooling from the inside temperature is positively affected using a PCM, quantified by the temperature changes between the inner and outer surfaces of the bricks.

3.1. Experimental Setup

To conduct this study, four chambers of inside dimensions of 38 cm length, 36 cm depth, and 20 cm height were built using a hollow-clay-brick-type shield. This shield was manufactured locally under the roof of the engineering building of King Abdul Aziz University, Jeddah City, Saudi Arabia (latitude: 21.4237 N; longitude: 39.1112 E). One of the
chambers was left empty, “not filled with insulator”, so as to be used as a reference; two of the remaining chambers were filled with PCMs of different melting points, and the fourth chamber was filled with the insulator most commonly used in the construction sector in Saudi Arabia, which is polystyrene foam. As is shown in Figure 2a–c, all the walls and the roof of the three insulated chambers were insulated with 4 cm of either a PCM or foam.

![Figure 2a](image1.jpg)  
**Figure 2a.** A full view of the chambers.

![Figure 2b](image2.jpg)  
**Figure 2b.** Four bags each with 2 cm thickness of the PCM inside the hollow.

![Figure 2c](image3.jpg)  
**Figure 2c.** A 4-cm-thick polystyrene foam inside the hollow bricks.

For the study, the weather in the city in which the experiment was conducted was the most important parameter. This was because the chambers were fully closed, and the effect was only from the ambient temperature. This factor helped determine the result of using these materials. After reviewing the annual report provided by the Saudi National Center of Meteorology for the average daytime and nighttime ambient temperatures for Jeddah, it was found that the peak temperatures reached in the summer season, from May to October, are approximately 45 °C and 35 °C for daytime and nighttime, respectively, as shown in Figure 3. Moreover, the humidity in Jeddah is considered to be high because of the city’s location next to the Red Sea. The test was conducted between November 2020 and February 2021 to ensure that the PCMs would reach their solidification point at night, even in the hottest month of the year.
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Figure 3. The report as per the Saudi National Center of Meteorology.

3.2. PCM and Polystyrene Foam Selection

Among the types of PCM used for isolation purposes, the type used for this study was classified as an organic commercial paraffin PCM with two different melting points, RT35 and RT35HC. One study suggested that the maximum energy storage is obtained during the daytime and that the PCM melting temperature must be the same as or close to the average room temperature [32]. However, other studies have suggested using a PCM with a melting temperature higher than the average temperature of the room by 3% [33,34]. The melting and solidification ranges presented in Table 1, which were provided by the manufacturer of PCMs, were investigated based on the suggestion mentioned previously, to find their maximum energy storage during the summer of Jeddah City [35].
Table 1. Thermophysical properties of materials used in the experiment.

| Properties                  | Melting Point (°C) | Solidification Point (°C) | Latent Heat (J/kg) | Specific Heat Capacity (J/kg·K) | Thermal Conductivity (W/m·K) | Density (kg/l) |
|-----------------------------|--------------------|---------------------------|-------------------|--------------------------------|-----------------------------|----------------|
| PCM RT35 [35]              | 29–36              | 36–31                     | 160               | 2                              | 0.2                         | 0.86^5 0.77^l  |
| PCM RT35HC [35]            | 34–36              | 36–34                     | 240               | 2                              | 0.2                         | 0.88^5 0.77^l  |
| Brick [36]                 |                    |                           |                   |                                |                             | 0.378          |
| Polystyrene foam [37]      |                    |                           |                   | 0.033                          |                             | 0.032–0.035    |
| Epoxy resin                | 130                |                           |                   | 1                              | 0.2                         | 0.002          |
| Cement mortar              |                    |                           |                   | 1                              | 1                           | 1.8            |

PCM RT35 with a solidification point at 31 °C was selected to be almost exactly as the average nighttime ambient temperature, while PCM RT35HC was higher by 3% during the summer of Jeddah City, KSA. RT35 and RT35HC were melted and filled in polymer bags with dimensions of 16 cm × 20 cm and 2 cm for the thickness, as shown in Figure 4a,b. The sizes of the bags made them easy to install in the hollow bricks, leaving free space when solidified. Four bags were installed for each brick, which added up to about 28 bags for the whole chamber, as shown in Figure 2a. The foam was cut and reduced to 4 cm in thickness to fit inside the bricks since it was manufactured in only two thicknesses, 3 cm and 5 cm. The thermal properties of all materials used in the experiment were collected from the manufacturers and are presented in Table 1 [35–37].

3.3. Methodology

Type T thermocouples, made of constantan with uncertainty of ±1%, were used to measure the temperature of the chambers. The thermocouples were positioned at the center of the brick and glued with epoxy resin to the back surface and the interior of each wall, including the roofs of all chambers. There were a total of 32 thermocouples. Eight of them were glued on the back surface of the bricks; four of the eight thermocouples were positioned on the center of each roof. However, only one thermocouple for every wall of the reference chamber was installed, since all the chambers were located in the same space and affected by the same outside temperature. Figure 5 shows the layout of the remaining 25 thermocouples in the chambers. One thermocouple was positioned at the center of each wall, except for the ceiling, where two were used. The thermocouples were connected to a data logger and automatically recorded in an Excel file every 120 s. The data logger, from NI, contains “C Series Current Output Modules” that connect to a Compact RIO Chassis (model NI 9147).
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4. Results and Discussion

The PCMs, RT35 and RT35HC, with different melting ranges, and foam installed inside hollow bricks were experimentally investigated. The investigation was based on natural conditions since all the chambers were empty and had no windows to let the air enter. The first part of the examination concentrated on the temperature drops and thermal behavior of all chambers during the highest and lowest outside temperature reached during the experiment. To elaborate, this study aimed to determine how well a chamber can keep cool in summer and how warm it can be during winter. This determined what is called the “heat energy saving” of the insulation. This was studied through the indoor temperature. The second part, instead, focused on calculating the rate of heat transfer and heat flux based on the assumptions explained earlier.

4.1. Thermal Behavior

This part of the results focused on the temperature drops and thermal behavior in two sub-sections. The first section only considered the highest outside temperature reached during the experiment. The second section, in contrast, looked at the lowest outside temperature reached during the experiment. Each section focused on the specified hours and the walls that showed good results for all the days of the experiment. Thus, the results, for most of the days of the experiment, were somewhat repeated. This will be presented in the following sections, especially when the weather was clear, that is, no rain or clouds. For a better idea of the results, a full day of data recording was selected for each section. This was a sample representing the average temperatures of all the inside sensors during the specified hours.

4.1.1. Highest Outside Temperature

The ambient temperature of all chambers increased from 7 a.m. until it reached a peak at 12 p.m. On some days, the peak was reached at 1 p.m., and then it started to drop. Figure 6 shows that the 14th of February 2021, as a sample day, presented the average of outside and inside sensors for each chamber. Figure 7 shows only some of the hours (11 a.m.–2 p.m.), during which the temperatures started to increase quickly and remarkably then began to drop. The sample day, 14th of February 2021, showed that both PCMs...
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Both figures show that the two PCMs performed better in absorbing heat and keeping the chambers in thermal comfort during the peak time than the foam and hollow bricks alone. Bearing in mind the average of all days for inside surface sensors, PCM RT35 absorbed more heat and provided better cooling than all chambers for the north wall only. At the peak time for indoor sensors (13:00, or 1 p.m., to 17:00, or 5 p.m.), the north wall sensor recorded the lowest temperature for all the days of the experiment, with a range between 35 °C and 39 °C for the reference chamber, 27 °C and 32 °C for the PCM RT35HC chamber, 31 °C and 36 °C for the foam chamber, and 27 °C and 32 °C for the PCM RT35 chamber for all the days presented in Figure 7. Taking 14 February 2021 as an example, at 12 p.m., $T_{out}$ was 50.77 °C, whereas the north wall recorded 26.7 °C for the reference chamber, 24.38 °C for the PCM RT35HC chamber, 25.28 °C for the foam chamber, and 24.87 °C for the PCM RT35 chamber. Both PCMs showed a better cooling temperature by 2 °C than the reference chamber and 1 °C better than the foam chamber for the north wall only.
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Figure 6. Sample day, which was the 14th of February 2021.

The chambers' indoor temperature, in contrast, at 12 p.m., with the average of all inside sensors, showed 29.3 °C for the reference chamber, 25.62 °C for the PCM RT35HC chamber, 27.7 °C for the foam chamber, and 23.8 °C for the PCM RT35 chamber; it started to increase until it reached its maximum at 17:28 (5:28 p.m.). For the reference chamber, it was 41.45 °C; PCM RT35HC chamber, 34.87 °C; foam chamber, 39.05 °C; and PCM RT35 chamber, 35.89 °C for the sample day. Both PCMs gave good results in general, that is, better cooling. The difference in the average of indoor sensors, between PCM RT35 and PCM RT35HC, started with a maximum of 19.69% at 4:10 a.m. and then declined to 13.2%
at 14:48 (2:48 p.m.). PCM RT35HC provided better cooling performance than PCM RT35 because its latent heat was higher by 33%, as shown in Table 1. The difference in the average of indoor sensors between PCM RT35 and foam, and the reference was 23.7% at 15:16 (3:16 p.m.) and 28.56% at 15:24 (3:24 p.m.), respectively. Then, it started to reduce until 6:22 a.m., with 9.7% for the foam and 8.56% at 5:48 am for the reference.

4.1.2. Lowest Outside Temperature Reached

This part focuses on the lowest ambient temperature of all chambers from the peak time, with a stable gradient, to reach the lowest temperature at 6 a.m. Figure 8 shows the results of 19 December 2020 as a sample day that showed the average of all outside and inside surface sensors for each chamber. The sample day, similar to the previous part, was among the days that recorded the lowest temperatures during the experiment. The lowest $T_{out}$ was recorded by the roof sensors of each chamber for an ambient temperature between 12.9 °C and 20.51 °C, depending on the day the experiment was conducted. Figure 9 represents the average of all outside sensors. Compared to the ceiling inside sensors, it showed the warmest temperature recorded inside the chambers. According to the results reached, both figures showed that the PCMs kept the chambers warmer than the foam or the bricks alone.

**AVERAGE OF OUTSIDE AND INSIDE SENSORS**

Figure 8. Sample day, which was the 19th of December 2020.

To discuss this result in detail, first let us take a close look at 19 December 2020 as an example. Figure 8 shows the lowest temperature during the day at 6 a.m. when the average $T_{out}$ was 17.23 °C; the inside temperature for each ceiling of the reference chamber was 25.3 °C; PCM RT35HC chamber, 28.87 °C; foam chamber, 25.47 °C; and PCM RT35 chamber, 26.4 °C. That is to say, the inside surface sensors of the PCM RT35HC ceiling chamber were warmer than those of PCM RT35 by 2 °C and 3 °C, respectively, compared to the foam and reference chambers. Second, both PCMs showed better performance than in the previous part. Specifically, both PCMs were able to preserve more heat in winter than they could absorb heat in summer.
that the PCM RT35HC chamber was 9.5% warmer than the reference chamber at 7:06 a.m., 7.0% warmer than the foam chamber at 4:36 a.m., and 2.81% warmer than the PCM RT35 chamber at 2:46 a.m. This emphasized the benefits of PCMs as effective materials used in buildings, especially in regions such as the Middle East.

Figure 9. The ceiling of all chambers that showed the warmest temperature.

4.2. Rate of Heat Transfer and Heat Flux Based on The Collected Data

This part presents the calculated results based on the assumptions described in the Methodology section, with an uncertainty (Equation (5)) of 25.5% for the reference chamber, 19.12% for the foam chamber, 12.27% for the PCM RT35HC chamber, and 17.4% for the PCM RT35 chamber. Moreover, the rate of heat transfer and the heat flux focused only on the bricks and heat that flowed between their surfaces.

\[
U_{q''} = \left[ \left( \frac{dq''}{dR} \times U_R \right)^2 + \left( \frac{dq''}{dT} \times U_{\Delta T} \right)^2 \right]^{1/2}
\]

where

\[
U_R = \left[ \left( \frac{dR}{dL} \times U_L \right)^2 + \left( \frac{dR}{dA} \times U_A \right)^2 + \left( \frac{dR}{dk} \times U_k \right)^2 \right]^{1/2}.
\]

The uncertainty for \( L \) and the thermal conductivity assumed ±0.1 cm and 0.1 W m⁻¹ K⁻¹.

Figures 10 and 11 show the rate of heat transfer and the heat flux during the sample day when the hottest temperature was reached, and Figures 12 and 13 show the same for all the days. The negative sign in all the figures represents the heat flow direction when the outside temperature was higher than the inside. Figures 10 and 11 show that both the rate of heat transfer and the heat flux of RT35 showed a greater reduction in heat transfer at 0:00–9:00 h and 18:00–23:00 h. For instance, the heat flux for the RT35 chamber at 12 a.m. (time 0:00) had a 61.1% greater reduction than the reference chamber: for the foam chamber, it was 62.9%, and it was 68.2% for the RT35HC chamber.
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Figure 10. The rate of heat transfer for the 14th of February 2021.

Figure 11. The heat flux for the sample day during the hottest temperature outside.

Figure 12. The rate of heat transfer for the north wall.
4.3. PCM Energy-Saving Expectations

In this part, the economic analysis of the walls containing PCM is discussed. By comparing the initial cost of materials used in the experiment, one bag of PCM with a size of $16 \times 20 \, \text{cm}$ used in the experiment cost four times than the polystyrene foam board with a size of $125 \times 55 \, \text{cm}$ and the brick alone. Yet, the PCMs showed effectiveness in reducing energy consumption more than the polystyrene foam and brick alone, which can be for the long term. The PCM bag used in the experiment weighed approximately 3 kg, and each wall of the chamber contained one hollow brick, except the ceiling. The hollow bricks contained four bags of PCMs, with a total of 12 kg of PCMs. The stored heat $\Delta \mathcal{H}$ by the PCMs was calculated by Equation (7) [38].

$$\Delta \mathcal{H} = \mathcal{M} \Delta H$$

where $\mathcal{M}$ is the total mass of the PCM and $\Delta H$ the phase change latent heat.

The maximum energy saving, provided by PCM RT35, was about 1920 kJ, or 0.533 kWh, for one wall only and about 2880 kJ, or 0.8 kWh, for PCM RT35HC. Since the climate of Saudi Arabia is almost hot for most of the year, assuming the PCM will function 50% of the year (182.5 days) with maximum efficiency and the PCM phase change occurs once a day, a wall of PCM RT35 or PCM RT35HC can store about 97 kWh/m² or 146 kWh/m², respectively. With a room size of 10 m², PCM RT35 or PCM RT35HC can reduce the energy consumption of an HVAC system by 970 kWh or 1460 kWh per year, respectively.

4.4. Research Limitations

This experiment had some limitations that should be noted:

1. The experiment studied the performance of insulation in only one location, which is inside hollow bricks.
2. This experiment was just a small prototype to investigate PCMs as a building material and to study their thermal performance. The initial cost and energy consumption cost...
of 16 cm × 20 cm used in the experiment cost four times than the polystyrene foam board with a size of 125 cm × 55 cm and the brick alone. Yet, the PCMs showed effectiveness in reducing energy consumption more than the polystyrene foam and brick alone, which can be for the long term. The PCM bag used in the experiment weighed approximately 3 kg, and each wall of the chamber contained one hollow brick, except the ceiling. The hollow bricks contained four bags of PCMs, with a total of 12 kg of PCMs. The stored heat ΔQ by the PCMs was calculated by Equation (6) [38].

\[ \Delta Q = m \times \Delta h \]  

where \( m \) is the total mass of the PCM and \( \Delta h \) the phase change latent heat.

The maximum energy saving, provided by PCM RT35, was about 1920 kJ, or 0.533 kWh, for one wall only and about 2880 kJ, or 0.8 kWh, for PCM RT35HC. Since the climate of Saudi Arabia is almost hot for most of the year, assuming the PCM will function 50% of the year (182.5 days) with maximum efficiency and the PCM phase change occurs once a day, a wall of PCM RT35 or PCM RT35HC can store about 97 kWh/m² or 146 kWh/m², respectively. With a room size of 10 m², PCM RT35 or PCM RT35HC can reduce the energy consumption of an HVAC system by 970 kWh or 1460 kWh per year, respectively.

4.4. Research Limitations
This experiment had some limitations that should be noted:
1. The experiment studied the performance of insulation in only one location, which is inside hollow bricks.
2. This experiment was just a small prototype to investigate PCMs as a building material and to study their thermal performance. The initial cost and energy consumption cost for the same materials used in the experiment can possibly be investigated in future research on an actual scale.
3. The experiment chambers were fully closed, with no opening for ventilation to study the PCM behavior.
4. The chambers were designed to be small due to the limited amount of PCMs and the affordability of their price.
5. The experiment did not study the possibility of leakage when the PCMs reached the melting phase and became liquid.

All the noted limitations will be considered in future research by the authors.

5. Conclusions
This study was an experiment conducted to investigate the effect of the thermal behaviors of two types of PCM that have different melting ranges and compare it with that of polystyrene foam. To accomplish this experiment, we decided to study four chambers built from hollow bricks. One of them was kept empty as a reference, and each of the remaining chambers had the cavity inside filled with different types of insulation placed on the four walls and ceiling. The findings of the study revealed the following:

(1) At the highest temperature reached during the experiment:
   • Both PCMs showed better thermal behavior than polystyrene foam and bricks alone at peak time.
   • PCM RT35 produced a 13% better cooling effect than PCM 35HC; it was 24% better than foam and 28.56% better than hollow bricks alone.

(2) At the lowest temperature reached during the experiment:
   • The PCM RT35HC chamber showed better results in saving energy and kept the chamber warm than all other chambers; it was 9.5% better than the reference chamber, 7.0% better than the foam chamber, and 2.81% better than the PCM RT35 chamber.
Based on the assumptions indicated in the methodology, PCM RT35 showed a greater reduction in the heat flux by 61.1% than the reference chamber, 62.9% than the foam chamber, and 68.2% than the RT35HC chamber. The maximum energy saving for PCM RT35 was 1920 kJ, or 0.533 kWh, for one wall only and for PCM RT35HC was 2880 kJ, or 0.8 kWh, which can reduce the energy consumption of an HVAC system by 97 kWh/m² and 146 kWh/m² per year, respectively.

However, the PCMs indicated efficiency in decreasing energy consumption more than polystyrene foam and bricks, which possibly might be for the long term. This experiment is simply a small example of exploring and studying PCMs as effective building materials and investigating their thermal performance.

The primary cost and energy consumption cost for the equivalent materials used in practice can probably be studied in future research on an actual scale. However, this study initiated a relevant window of opportunity for additional experiments to determine the interrelatedness of the suggested uses of phase change materials (PCMs) with the assistance of empirical studies.

The phase change material (PCM) applications have strong experimental support and are creating greater demands for additional empirical studies to discuss the PCM applications more evidently. Excitingly, the literature reveals that the uses of PCMs retain the same importance and can be discussed in developing and developed countries.

It is recommended to use phase change materials and undertake more research to reduce heat gain and energy consumption in hot and humid climate countries, such as Saudi Arabia. Thus, the implications for energy consumption management and for future research on the uses of phase change materials were noted.

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