Paper ID:403

Numerical Investigation on the Thermal Performance of a Building Integrated with Phase Change Material in the Roof

Medur Rodoshi Aungshu[1], Mohammad Ariful Islam[2]
[1]Department of Energy Science and Engineering
Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
[2]Department of Mechanical Engineering
Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
E-mail: medurrodoshi@gmail.com, ariful@me.kuet.ac.bd

Abstract

This study analyzes the thermal functionality of phase change materials (PCM) integrated into the roof of a single-story building in Bangladesh. Integrating PCM can enhance thermal convenience and decrease energy usage. The computational model was developed using Design-Builder. Simulations are performed for Dhaka and Jessore in Bangladesh, considering the country's climatic conditions. This study used lightweight aggregate concrete (LWAC) instead of conventional RCC roofs because of better thermal performance. Commercially available PCM, RubiTherm RT-Line (RT28HC), is used for this study. On a particular day in June, Dhaka experienced a decrease of 5°C in interior temperatures. Jessore experienced a reduction of 1.5°C while maintaining a modest temperature in the winter climate without requiring extra heating for both cities. Moreover, there is a notable 14% decrease in energy usage in Jessore City and 13.8% in Dhaka City, demonstrating PCM's efficacy in lowering energy requirements.

Keywords: Phase Change Material (PCM), Lightweight aggregate concrete (LWAC), Design-Builder

1. Introduction

Because of the world's increasing industrialization and population expansion, there can be seen rapid increase in energy demand [1]. In countries like Bangladesh that have subtropical climates, about 35 percent of Bangladesh's overall energy usage is accounted by the building [2]. The energy demand may be significantly decreased through an effective envelope design[3]. One of the most promising technologies is incorporating phase change material (PCM) in building envelopes. PCM has a significant energy storage ability within a particular temperature range and operates on the latent heat thermal energy storage (LHTES) concept. It can conserve and assimilate energy during phase change and discharge it when needed [4]. Due to solar radiation, room temperature rises during the day. Due to solar radiation, PCM changes phases from solid to liquid when integrated into the building structure. This mechanism for phase transition is endothermic. Until the PCM is melted, the heat energy is constantly stored. The PCM solidifies and releases heat as the temperature decreases throughout the nighttime. The working principle of PCM is shown in **Fig. 1**. Peak hourly heat transmission rates can be decreased and the change in interior temperature can be eliminated by integrating phase transition materials into walls, floors, and other building components [5]. In the last several years, research on using PCM in buildings has increased to improve thermal convenience. The viability of using PCM to lower the ambient temperature and enhance the thermal convenience of a Melbourne room was examined by Jamil et al. [6] In the PCM-incorporated room, thermal discomfort hours decreased by 34%, and a 1.1°C decrease in ambient indoor temperature during the day. Although PCMs have great promise, their practical implementation and study in places such as Bangladesh are still limited. This study aims to fill the gap by concentrating on the practical integration of PCM into building roofs, which is crucial for heat management in tropical areas such as Bangladesh. The goal is to maintain mechanical strength while successfully absorbing PCM by using lightweight particles instead of traditional concrete. The main purpose of this work is to investigate the thermal performance and to analyze the energy consumption of the building integrated with PCM on the roof.

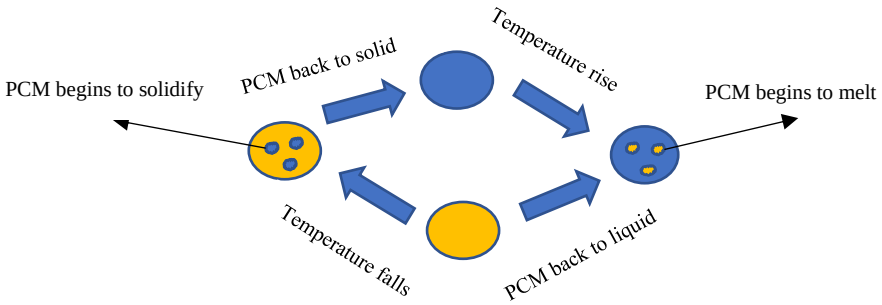


Fig. 1. Working principle of PCM

2. Methodology

To investigate the thermal performance of PCM, a model building was developed using Design Builder software. For the analysis, two cities in Bangladesh, Dhaka and Jessore, were considered, and the weather data files for the two cities were used for the simulation. The air temperature is set to inside while conducting the simulation. For heating, the setpoint is 18°C while the setback is 12°C. For cooling, the setpoint is 26°C, and the setback is 28°C. A one-storied residential building has been chosen for this study, as shown in **Fig. 2** [7]. The system provided intricate information regarding the building's occupants, illumination, equipment, climate conditions, construction materials, and HVAC system. The EnergyPlus simulation engine then processed these inputs, conducting a variety of simulations to evaluate the building's energy consumption and thermal performance.

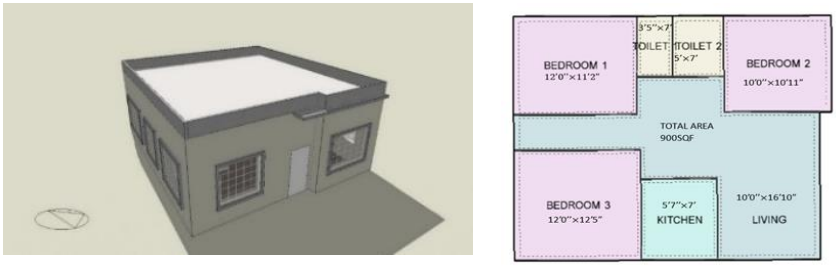


Fig. 2. Model and plan of the building

This study uses commercially available PCM, RubiTherm RT-Line (RT28HC). It is a pure PCM that can effectively store heat and has a melting point between 27°C and 29 °C. Fig. 3 shows the detailed arrangement of the roof with PCM and wall. The thermophysical characteristics of building materials used in this study are listed in **Table 1.**

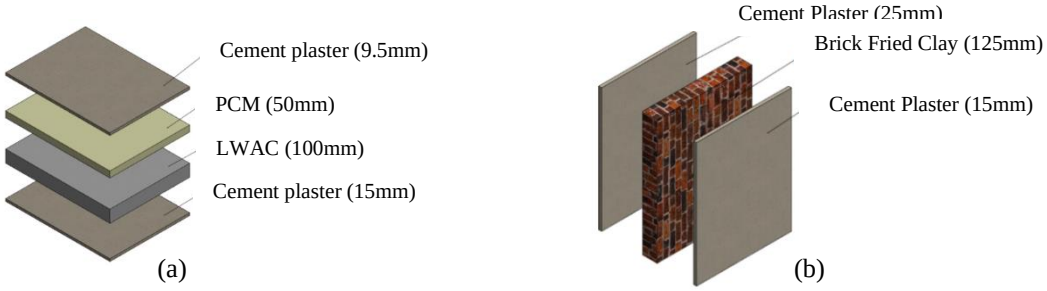


Fig. 3. (a)Detail of the roof with PCM and (b) Detail of the wall of the building

Table 1. The thermophysical characteristics of building materials in roof and wall

	Roof				Wall		
Material	Plaster	PCM	LWAC	Plaster	Plaster	Brick Fried Clay	Plaster
Thickness (m)	0.0095	0.05	0.1	0.015	0.025	0.125	0.015
Thermal conductivity (W/m.K)	0.691	0.2	0.38	0.691	0.691	0.895	0.691
Density (kg/m³)	1858	770	1390	1858	1858	1922	1858
Specific heat (J/kg.K)	837	2000	1080	837	837	790	837

3. Results and Discussion

3.1. The effect of using lightweight aggregate concrete

This study uses lightweight aggregate concrete (LWAC) instead of conventional RCC roofs for better thermal performance. LWAC is a specialized form of concrete that contains lightweight aggregates, including expanded clays, shale, pumice, perlite, or refuse materials such as oil palm shells, plastic, or fly ash. Compared to conventional concrete, these aggregates produce concrete with a lower density, which provides a variety of advantages, such as improved insulation, reduced dead load, improved fire resistance, and increased sustainability in construction projects. LWAC is frequently employed in applications that necessitate reduced structural weight, including flooring, bridges, and high-rise structures[8]. A study in Australia found the main reason for using PCM in LWAC. In that study, Mohseni et al. [9] investigated a new lightweight structural cementitious composite (Aggregates) with improved thermal energy storage (TES) capacities to improve building thermal regulation. Different properties of Normal Weight Concrete (NWC) and LWAC are compared in **Table 2**. These values exceeded the structural lightweight concrete requirements of LWAC by approximately 30%, and virtually no biological decay was observed after six months [8]. To evaluate thermal performance, the average indoor temperature is observed using a conventional roof of RCC and LWAC roof in the same model building as shown in **Fig. 4.** for a typical summer and winter day. It can be seen that during peak hours in the daytime, traditional roofing is more heat-absorbing than the LWAC roof. As conventional roofs absorb more heat, the average indoor temperature increases during the day. The amount of heat absorption by conventional and LWAC roofs is virtually identical at night.

Table 2. Different properties of Normal Weight Concrete (NWC) and LWAC

Properties	Density (kg/m³)	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Thermal Conductivity (W/mK)	Specific heat (kJ/kg K)
NWC	2369–2492	31.7–36.8	3.89–4.11	4.37–5.57	17.23–21.43	1.6 - 3.2	0.665
LWAC	1390	32.8–37.0	2.83–3.91	3.81–6.04	13.25–16.24	0.38	1.08

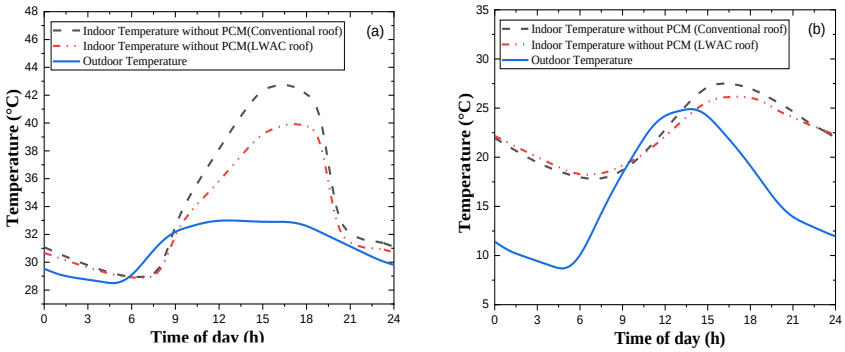


Fig. 4. The variation in average indoor temperature of the building using a conventional roof and LWAC roof for (a) a typical day of the summer season (10 June) and (b) a typical day of winter (16 January) at Dhaka

3.2 Effect of PCM integration in LWAC roof

To analyze the thermal performance, simulations have been performed for 10 June and 16 January in the climate of Bangladesh. **Fig. 5** shows that the average indoor temperature without PCM varies between 29-41°C while temperature with PCM varies between 28-36°C. The maximum temperature reduction achieved is 5°C. During the day, PCM absorbs heat and maintains a lower interior temperature than the non-PCM room model. It transforms into a solid state and emits heat into the atmosphere at night. It can be seen that the value of heat transfer is positive, which indicates that heat is gaining through the roof during peak hot hours without PCM. On the other hand, the heat transfer value is negative, indicating that heat leaves the interior through the roof when PCM is added.

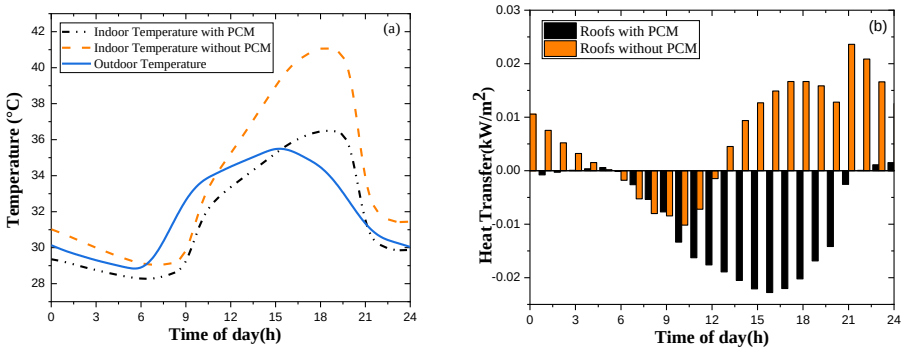


Fig. 5. (a)The average indoor temperature of the building and (b)heat transfer through the roof for 10 June at Dhaka

Fig. 6 shows that heat leaves the interior through the roof during morning and night without PCM. On the contrary, heat gains during this time through the roof when integrated with PCM. There is no significant variation in the average interior temperature during winter. The ambient temperature is significantly reduced during the night. PCM makes the indoor environment pleasant for occupants by releasing heat during this period.

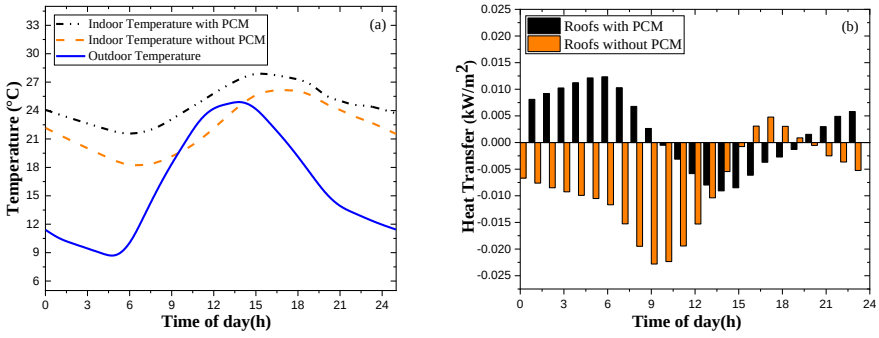


Fig. 6. (a)The average indoor temperature of the building and (b) heat transfer through the roof for 16 January at Dhaka

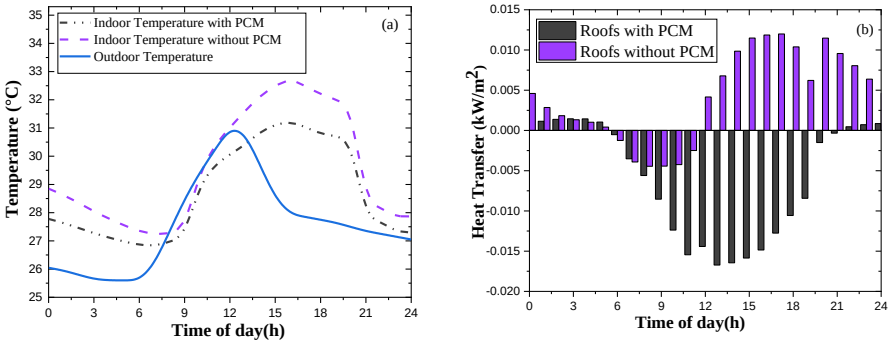


Fig. 7. (a)The average indoor temperature of the building and (b) heat transfer through the roof for 10 June at Jessore

Fig. 7 demonstrates that the average indoor temperature ranges from 27.5°C to 32.5°C without PCM. PCM maintains indoor temperature within the range of 27°C to 31°C. Incorporating PCM during summertime results in a maximum temperature reduction of almost 1.5°C.

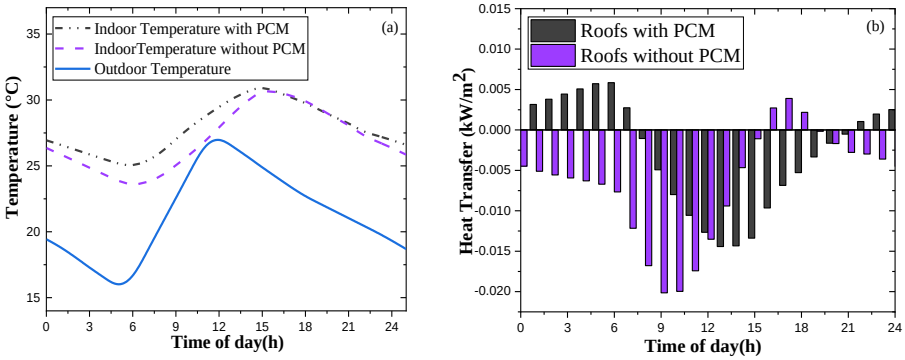


Fig. 8. (a)The average indoor temperature of the building and (b) heat transfer through the roof for 16 January at Jessore

Fig. 8 illustrates that heat escapes from the inside via the roof in the morning and at night in the absence of PCM. Heat is absorbed via the roof when combined with PCM during this period.

3.3. Effect of PCM integration on electricity consumption

An analysis of monthly energy consumption incorporating PCM is presented in this section. PCM can be utilized to decrease energy consumption. From **Fig. 9**, Dhaka's highest energy consumption in August was 12 kWh /m². However, using PCM reduces the consumption to 10.2 kWh /m². For Dhaka, the maximum reduction in energy consumption occurs in August, almost 13.8%. The lowest energy consumption reduction was noticed in January, which is about 1.6%. **Fig. 9** shows Jessore's peak energy use in May is 11 kWh/m². However, when utilizing PCM, it decreases to 9.4 kWh /m². For Jessore, energy usage was cut by almost 14% in May by using PCM. In January, the energy usage is at its lowest, decreasing by around 1.3%. Refahi et al.[10] implemented green roofs in Bandar Abbas, Iran, as a passive cooling technique. They achieved this by incorporating vegetation and soil layers to insulate the roof and provide shading. This procedure resulted in a reduction of annual energy consumption by approximately 8.5%. On the contrary, Incorporating PCM into the roof of a one-storied building reduced annual energy consumption for Dhaka by 12.05% and for Jessore by 10.79%.

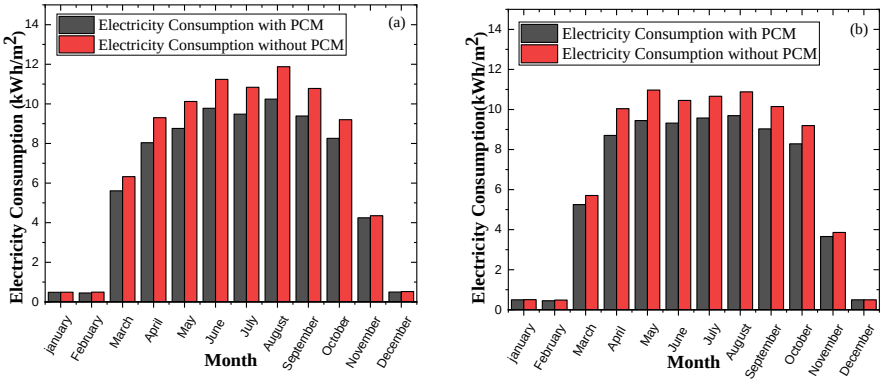


Fig. 9. Monthly energy consumption of the building at (a) Dhaka and (b) Jessore

3.4. Cost Analysis

LWAC typically has a higher cost than normal-weight concrete (NWC). For example, in major U.S. cities, the cost of NWC is approximately $189.65 per cubic meter, while LWAC is priced $229 per cubic meter[11]. The price of organic PCM ranges from $1.88–$2.00 per kg [12]. The cost of constructing the roof of the model building with lightweight aggregate concrete (LWAC) and phase change material (PCM) is $99.78 per square meter. In contrast, the cost of NWC is $28.42 per square meter. However, the total roofing cost using PCM and LWAC along with plaster is 34.42% higher than the conventional roof.

4. Conclusion

It is evident from the simulation results that adding PCM to LWAC lowers the interior temperature. Dhaka experienced a 5°C indoor temperature reduction on a particular day in June, whereas Jessore experienced about 1.5°C. Energy consumption is reduced by adding PCM to the roof of residential structures. The recorded decrease in energy usage is 13.8% in Dhaka and almost 14% in May in Jessore. Annual energy consumption is reduced by 12.05% for Dhaka and 10.79% for Jessore. The findings of the study indicate that for monthly energy consumption reduction, Jessore has experienced more favorable outcomes because Jessore encounters more significant temperature variations in comparison to Dhaka, PCM exhibits a more conspicuous efficacy in controlling interior climatic conditions. However, Dhaka experienced more favorable outcomes based on annual energy consumption reduction. Though the total cost of constructing the roof with lightweight aggregate concrete (LWAC) and phase change material (PCM) is 34.42% higher than the conventional roof, however, it reduces a significant amount of energy consumption.

5. References

[1] K. S. Kyaw, S. M. Fufa, and D. Kraniotis, "Adaptive reuse of industrial heritage building – comparative life cycle assessment using a case study in Norway," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1196, no. 1, p. 012107, Jun. 2023, doi: 10.1088/1755-1315/1196/1/012107.

[2] "GIZ2021_Energy_Efficiency_in_Public_Buildings_in_Bangladesh_BAT_Assessment.pdf." Accessed: Jan. 26, 2024. [Online]. Available: https://www.green-cooling-initiative.org/fileadmin/Publications/GIZ2021_Energy_Efficiency_in_Public_Buildings_in_Bangladesh_BAT_Assessment.pdf

[3] R. Baetens *et al.*, "Vacuum insulation panels for building application: a review and beyond," *Energy Build.*, vol. 42, no. 2, pp. 147–172, 2010.

[4] F. Carlucci, A. Cannavale, A. A. Triggiano, A. Squicciarini, and F. Fiorito, "Phase Change Material Integration in Building Envelopes in Different Building Types and Climates: Modeling the Benefits of Active and Passive Strategies," *Appl. Sci.*, vol. 11, no. 10, Art. no. 10, Jan. 2021, doi: 10.3390/app11104680.

[5] M. Song, F. Niu, N. Mao, Y. Hu, and S. Deng, "Review on building energy performance improvement using phase change materials," *Energy Build.*, vol. 158, pp. 776–793, Jan. 2018, doi: 10.1016/j.enbuild.2017.10.066.

[6] N. Zhu, N. Hu, P. Hu, F. Lei, and S. Li, "Experiment study on thermal performance of building integrated with double layers shape-stabilized phase change material wallboard," *Energy*, vol. 167, pp. 1164–1180, Jan. 2019, doi: 10.1016/j.energy.2018.11.042.

[7] Admin, "3 bedroom house plans with photos - Design of a three-bedroom residence at a low cost," SIRAJ TECH. Accessed: Nov. 19, 2024. [Online]. Available: https://sirajtech.org/3-bedroom-house-plans-with-photos/

[8] Y. Agrawal, T. Gupta, R. Sharma, N. L. Panwar, and S. Siddique, "A Comprehensive Review on the Performance of Structural Lightweight Aggregate Concrete for Sustainable Construction," *Constr. Mater.*, vol. 1, no. 1, pp. 39–62, Apr. 2021, doi: 10.3390/constrmater1010003.

[9] E. Mohseni, W. Tang, and S. Wang, "Development of thermal energy storage lightweight structural cementitious composites by means of macro-encapsulated PCM," *Constr. Build. Mater.*, vol. 225, pp. 182–195, Nov. 2019, doi: 10.1016/j.conbuildmat.2019.07.136.

[10] A. H. Refahi and H. Talkhabi, "Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs," *Renew. Energy*, vol. 80, pp. 595–603, Aug. 2015, doi: 10.1016/j.renene.2015.02.030.

[11] "Cost Comparison of Lightweight Concrete," ESCSI. Accessed: Nov. 19, 2024. [Online]. Available: https://www.escsi.org/e-newsletter/cost-comparison-of-lightweight-concrete/

[12] A. Bland, M. Khzouz, T. Statheros, and E. I. Gkanas, "PCMs for Residential Building Applications: A Short Review Focused on Disadvantages and Proposals for Future Development," *Buildings*, vol. 7, no. 3, Art. no. 3, Sep. 2017, doi: 10.3390/buildings7030078.