Enhancing Thermal Efficiency in Building Materials: A Comprehensive Study of Phase Change Materials Integration and Performance

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Introduction

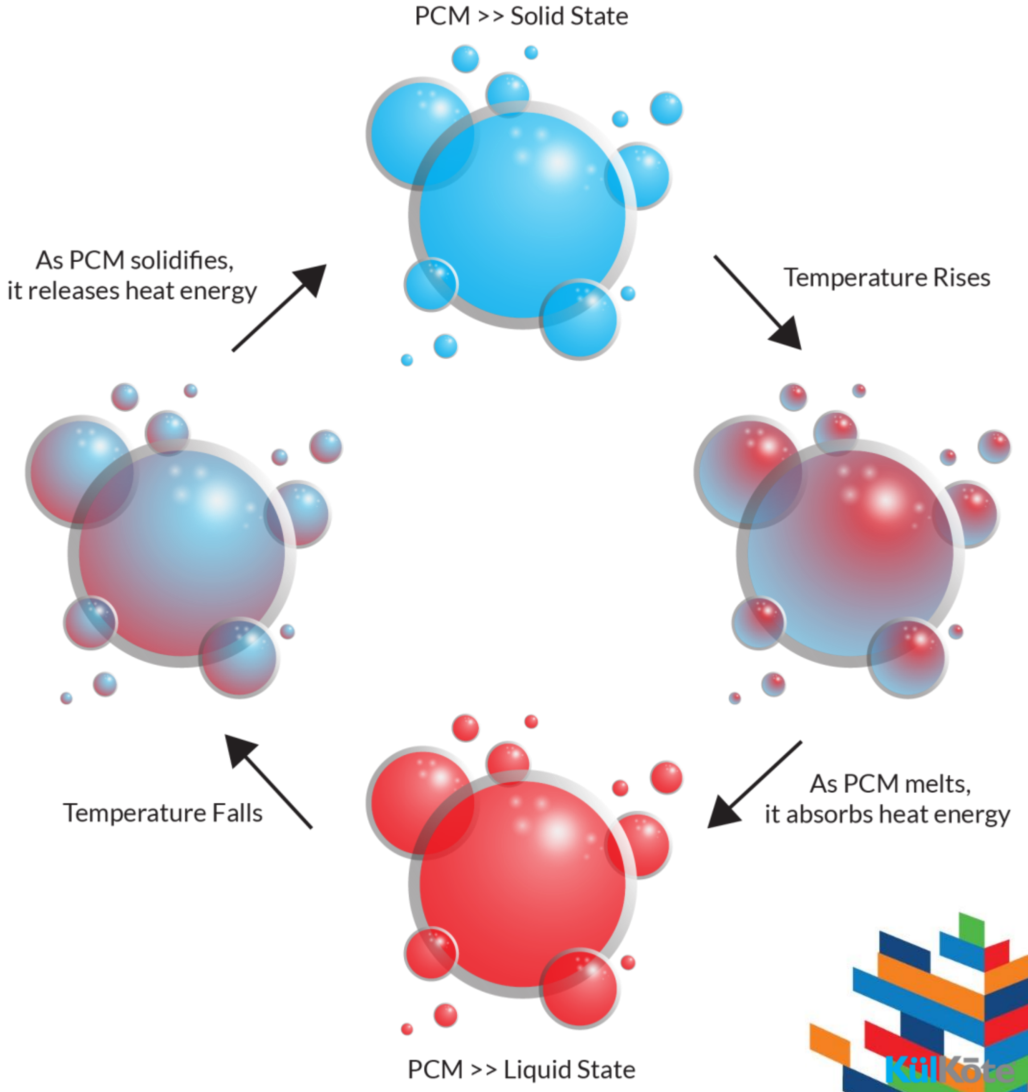
- The rapid increase in energy utilization on building industry for HVAC caused a significant increase in building industry energy demand

- The construction industry is accounted for 32% of global energy demand in 2010, which is increased to 36% in 2020.

- The construction industry is mainly responsible for 37% of energy-related CO_2 emissions.

Introduction

- Thermal energy storage (TES) is a method of storing and later releasing heat energy for various purposes.
- It involves collecting excess heat when available and then using it when needed.
- Phase Change Materials have the ability to hold or discharge significant amount of thermal energy at a specific temperature by undergoing phase transition.



Introduction

PCM advantages

- Narrowing the gap between peak and off-peak loads of electricity demand
- Shifting electrical consumption from peak periods to off-peak periods
- Saving energy and improving thermal comfort
- Continuous usage of renewable solar energy
- Reducing cooling load of air conditioning

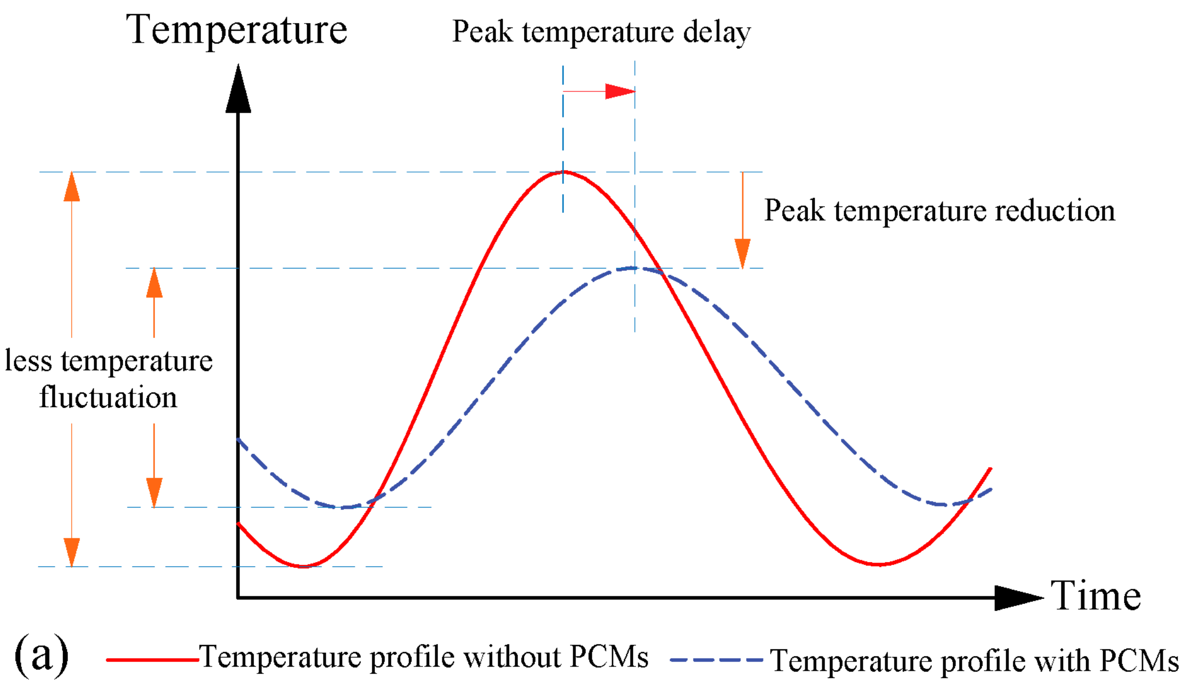
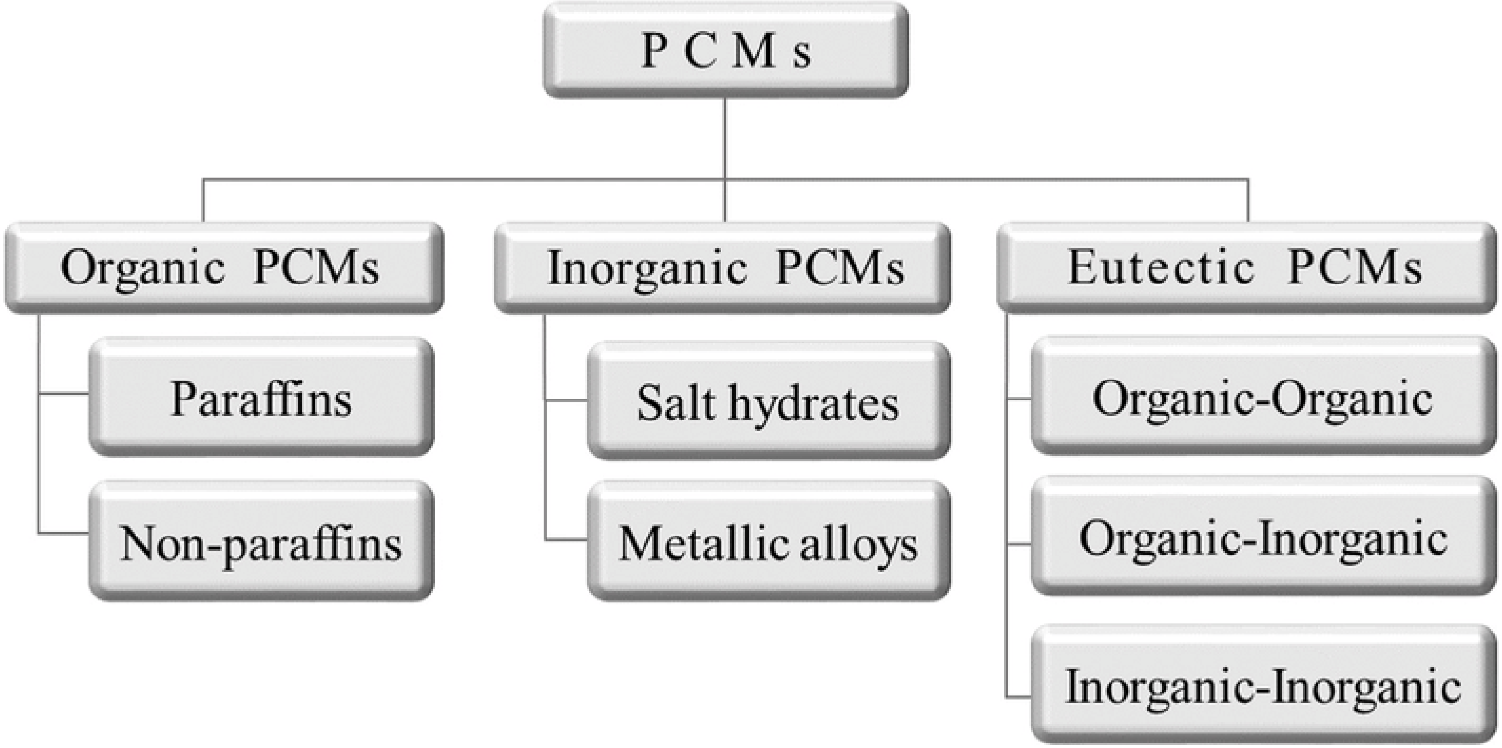


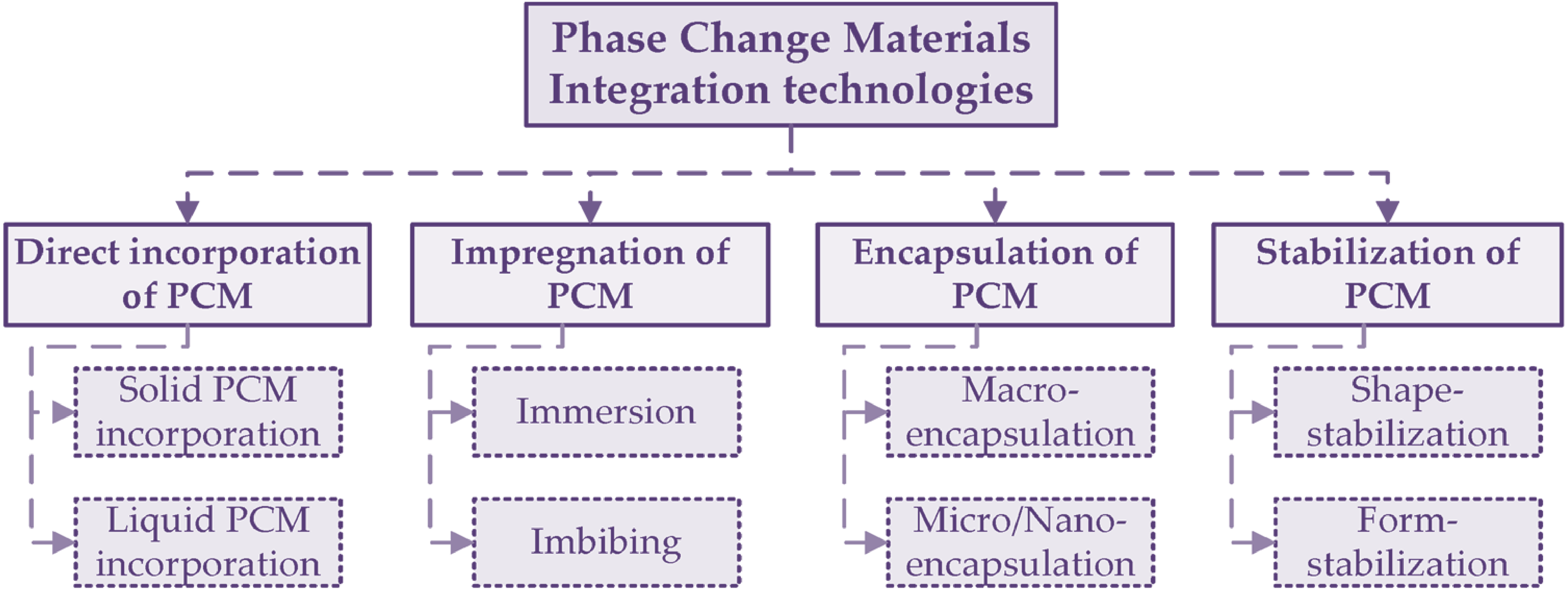
Fig. 1. Role of PCMs application in regulating a building's indoor temperature

Introduction

- Solid-Liquid PCMs: Most suitable TES due to their high latent heat storage capacity and compatibility with building materials.
- Low thermal conductivity (around 0.2 W/m K)
- Availability in a large temperature range
- Good compatibility with other materials



How to Incorporate PCM into the Building Materials?



Experimental Work

Use of microencapsulated PCM

Fig. 2. Use of MPCM in cementitious composites

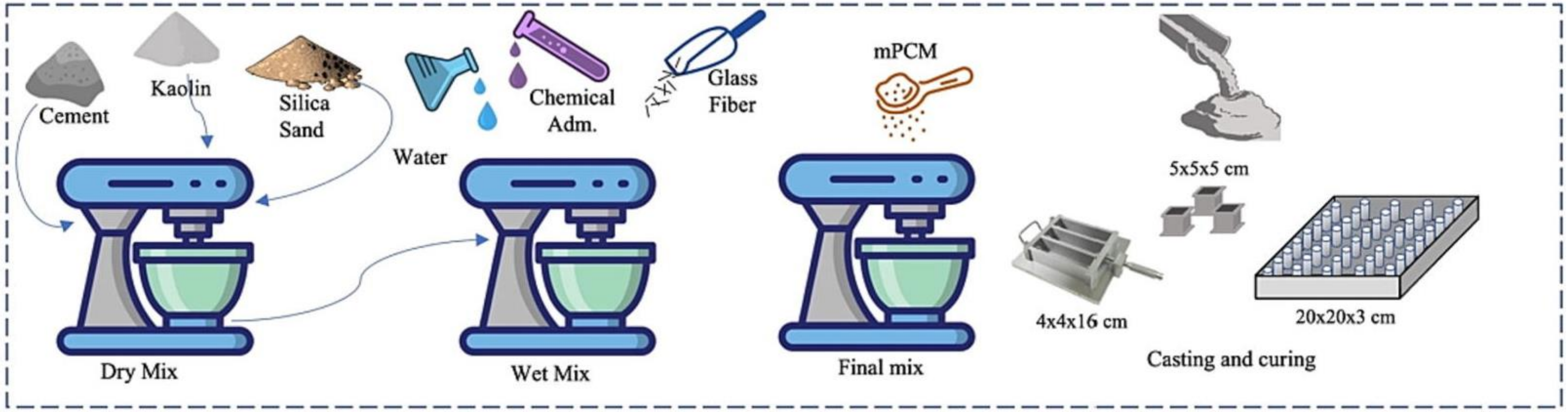
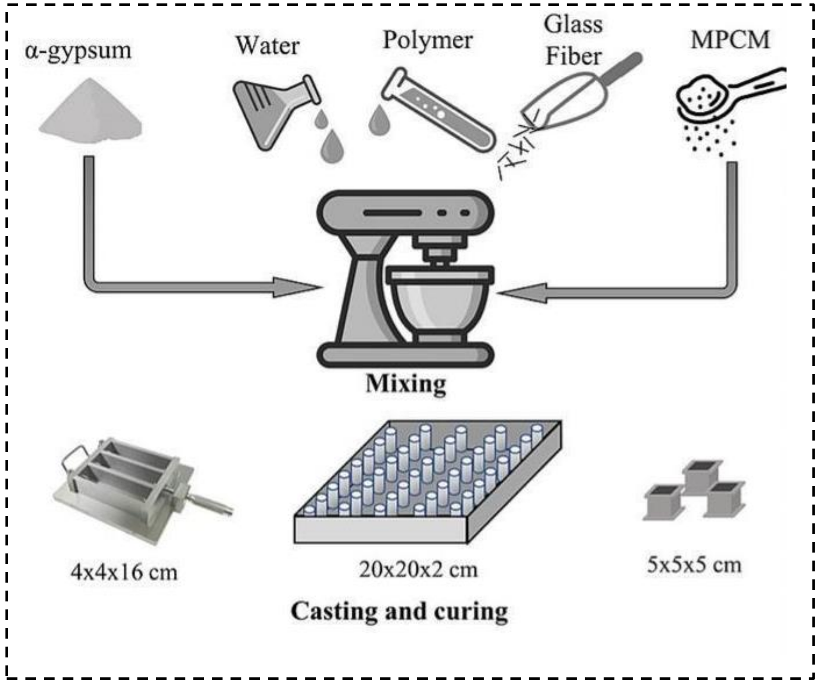


Fig .3. Use of MPCM in gypsum composites



- Leakage of PCMs affects cement hydration and concrete performance.

- Encapsulation with thin shells (1 μm to 1000 μm) of natural or synthetic polymers prevents PCM leakage into the matrix, improves PCM efficiency and provides higher heat transfer rates.

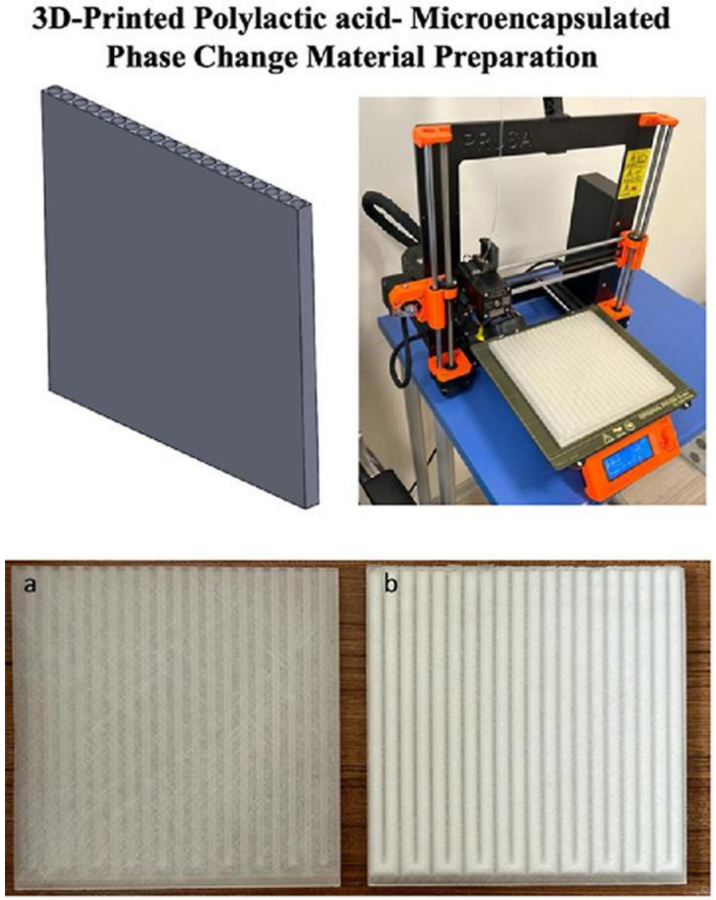
- MPCM offers stable chemical structure and thermal reliability during phase transition,

- MPCM can be incorporated via substituting cement, sand, and mineral additives or as supplementary material.

Experimental Work

Use of microencapsulated PCM

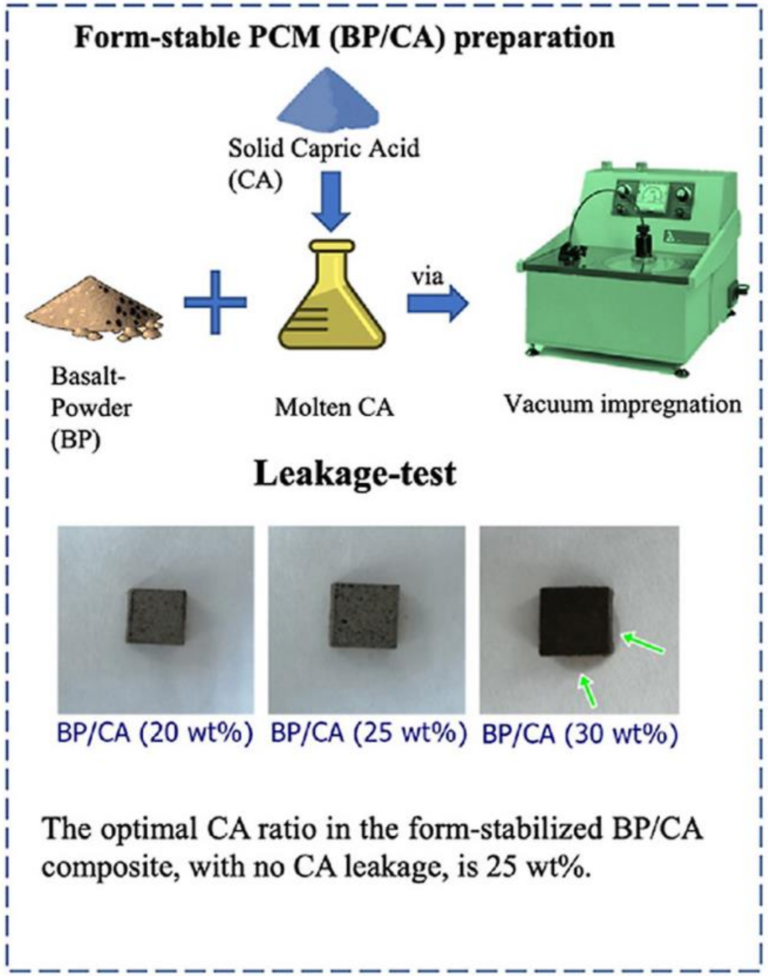
Fig.4. Use of MPCM in 3D PLA composites



- Solar thermoregulatory characteristics of PLA/PCM are evaluated.
- 3DP PLA –MPCM structures targeting a more efficient thermoregulation in foundational architectural sections such as walls, floors, and ceilings.

Experimental Work

Fig. 6. Basalt Powder-Capric Acid PCM

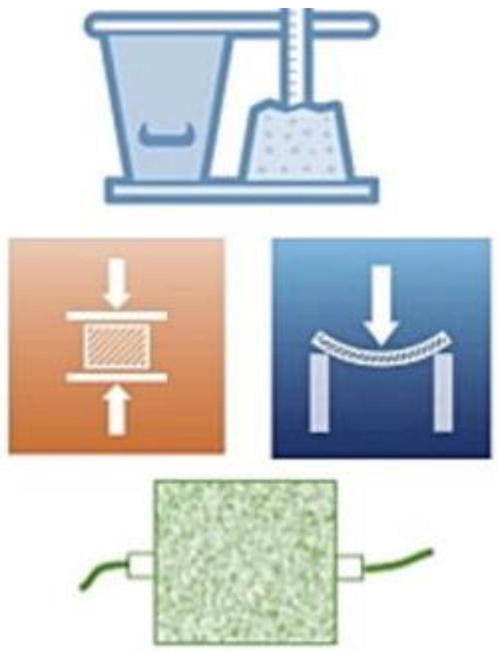


Use of form/shape stable PCM

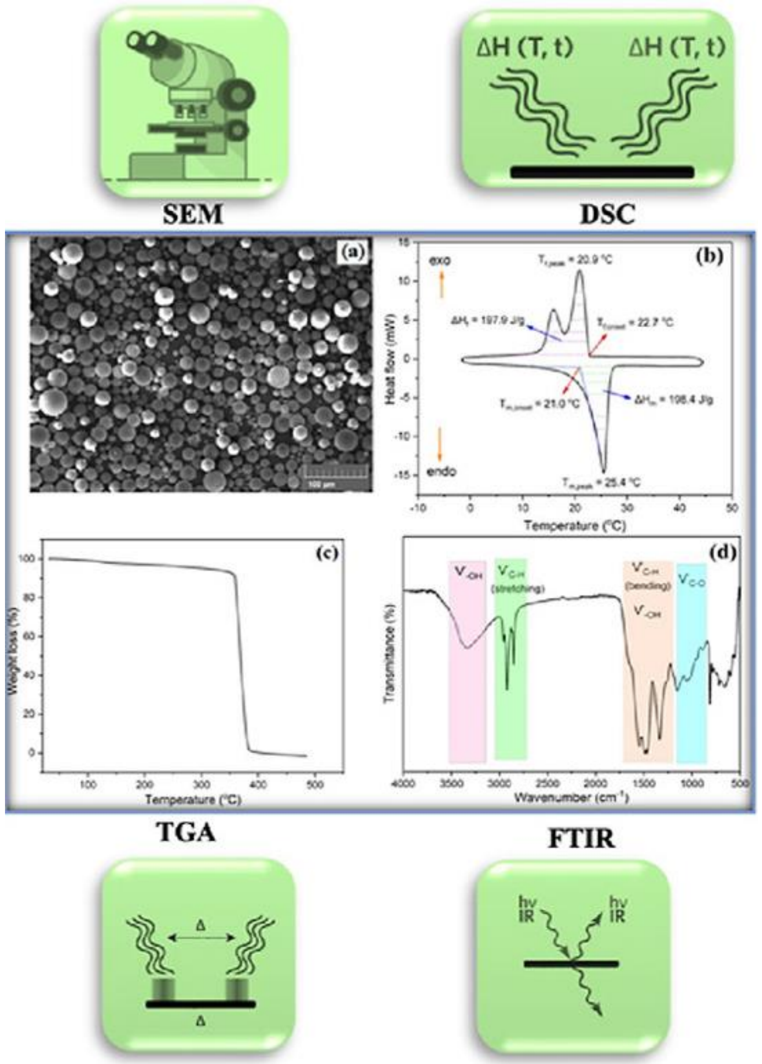
- Environmentally friendly novel foam concrete with basalt-PCM composite has been developed.
- Basalt powder selected as a carrier material for its lightweight and porous nature.
- REG-PCM in mortar, promoting eco-friendly construction.

Fig. 7. REC-nOD PCM

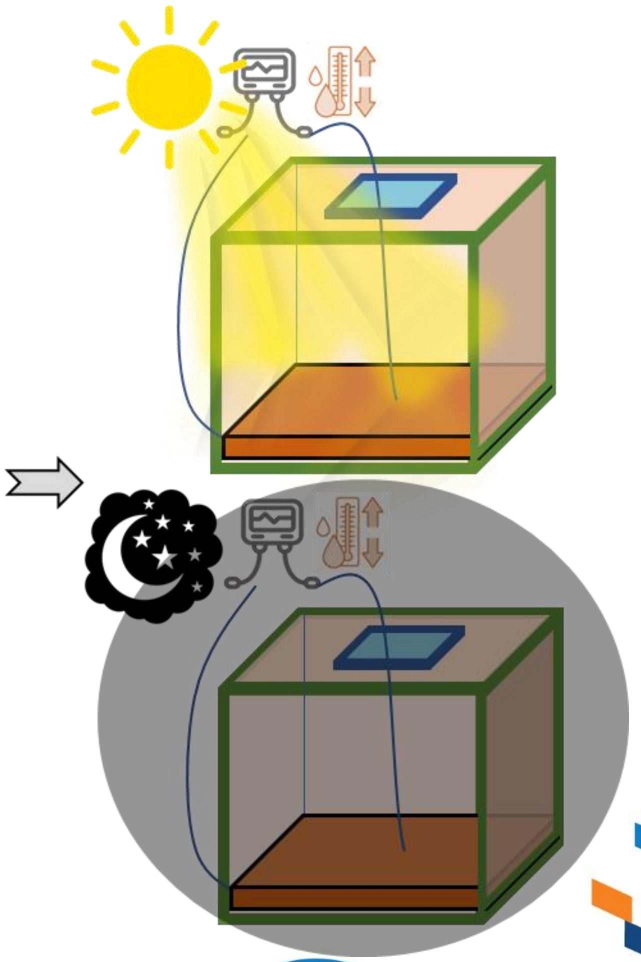
What/How to Test?



Physical-mechanical tests



Thermoregulation Test



Test Results

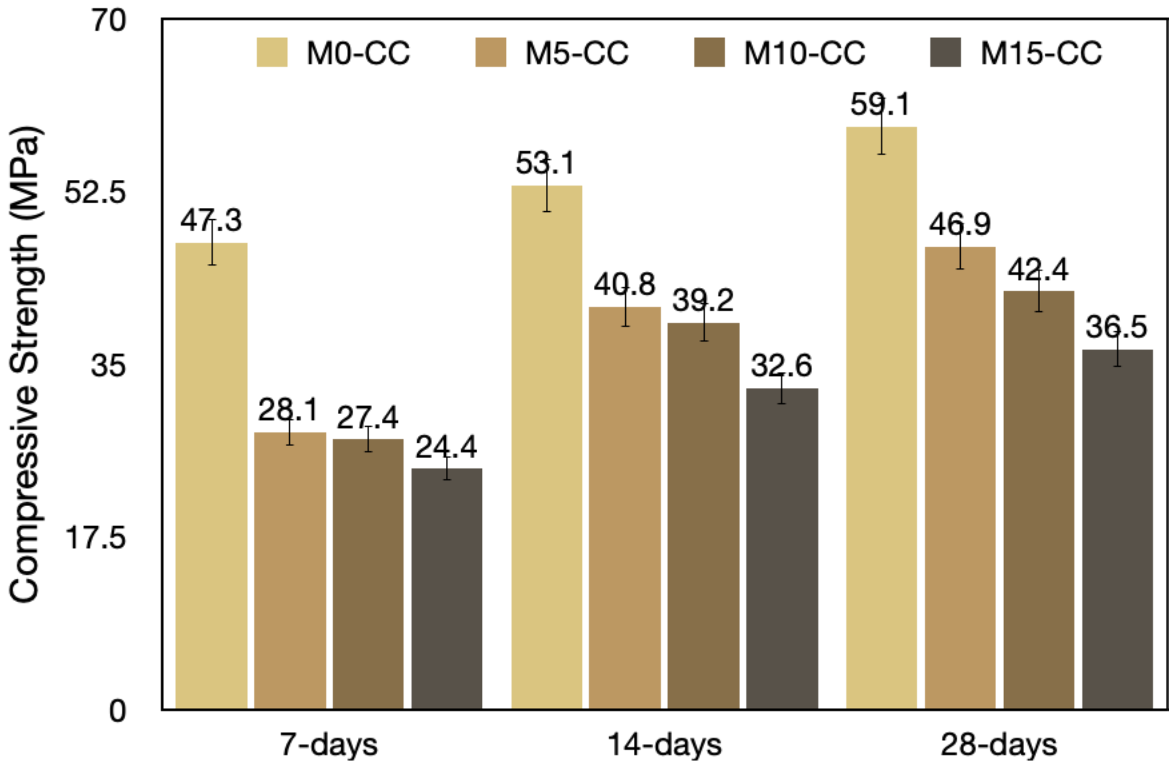


Fig. 8. Compressive Strength of cementitious composite with MPCM.

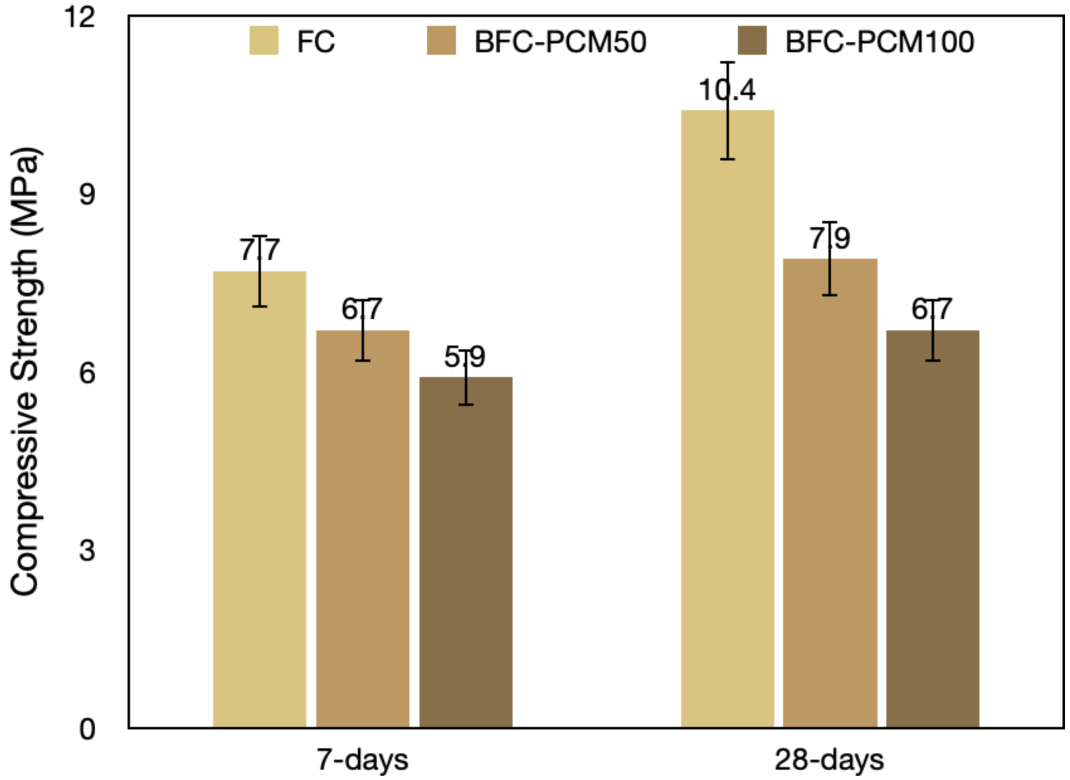
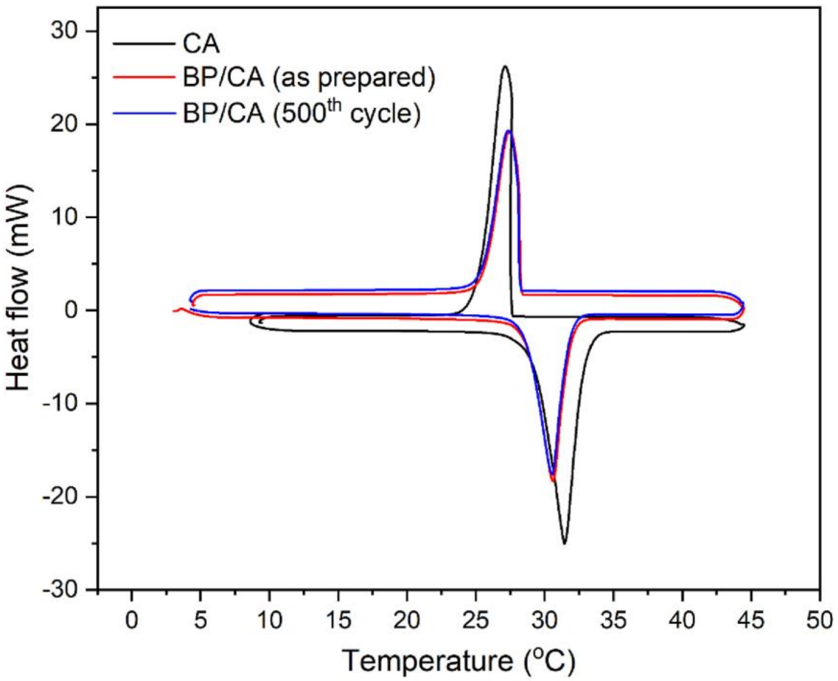


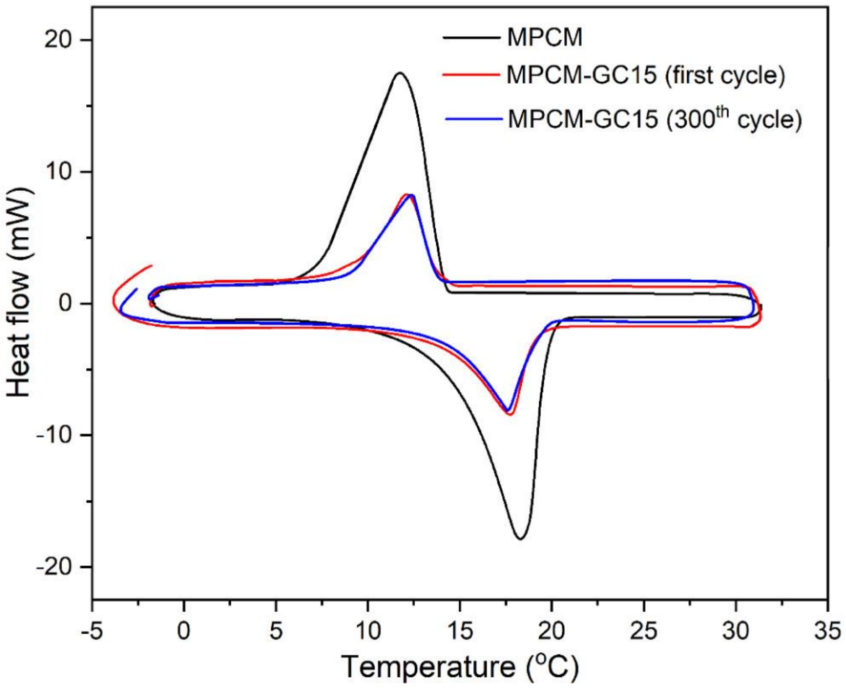
Fig. 9. Compressive Strength of Foam Concrete with Basalt Powder/Capric Acid PCM.

Fig. 10. Heat flow curves of CA, BP/CA, and BP/CA after 500th cycle.



- CA has a melting temperature of 29.4 °C and a latent heat of 194 J/g,
- BP/CA were measured at 28.5 °C and 28.2 °C, respectively, with corresponding latent heat values of 48.1 J/g during melting and 47.7 J/g during solidification.
- Maintaining 99.5% capacity after 500 cycles.

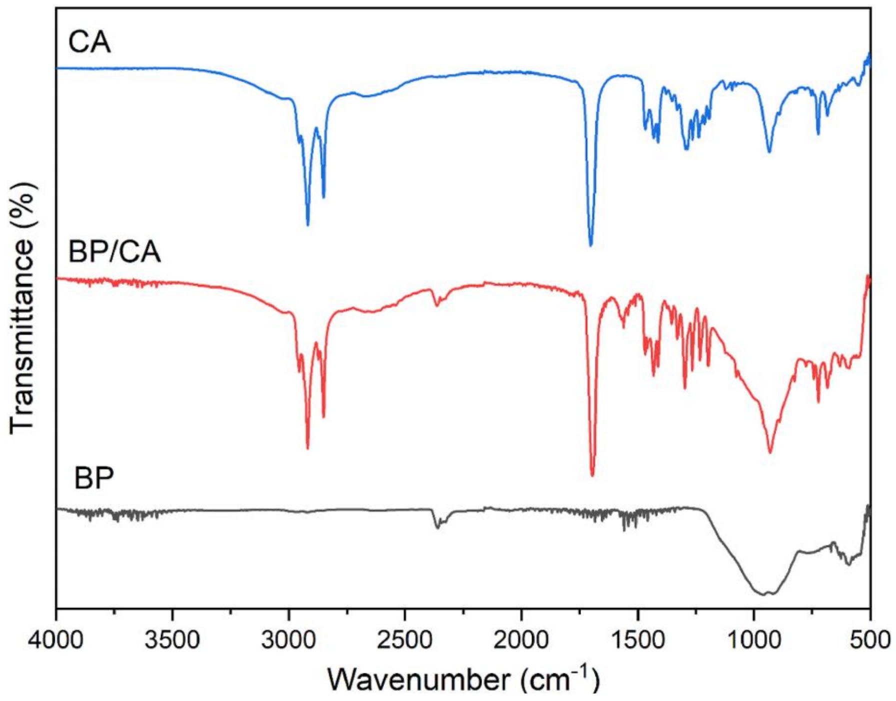
Fig. 11. Heat flow curves of MPCM, MPCM-Gypsum Composite.



- MPCM-containing gypsum composites exhibit phase transition behavior similar to pure MPCM

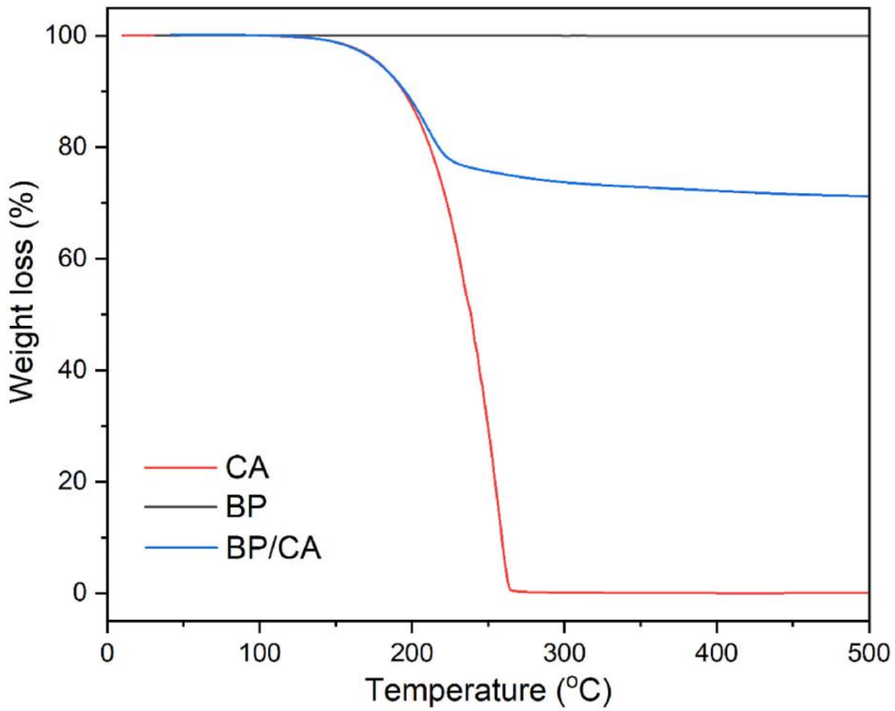
Test Results

Fig, 12. FTIR spectrum of CA, BP and BP/CA.



- Peaks at 2916 and 2850 cm^{-1} C–H (–CH3 and –CH_2) bonds are present.
- Peaks at 2642 and 1700 cm^{-1} O–H and C=O bond.
- Peaks of CA can be seen in the spectrum of BP/CA composite.

Fig. 13. TGA curves of BP, CA and BP/CA.



•BP showing no notable mass loss even at temperatures up to 500 °C.

•Thermal decomposition of the BP/CA composite closely resembled that of CA.

•Composite retained approximately 75% of its mass at 500 °C.

Test Results

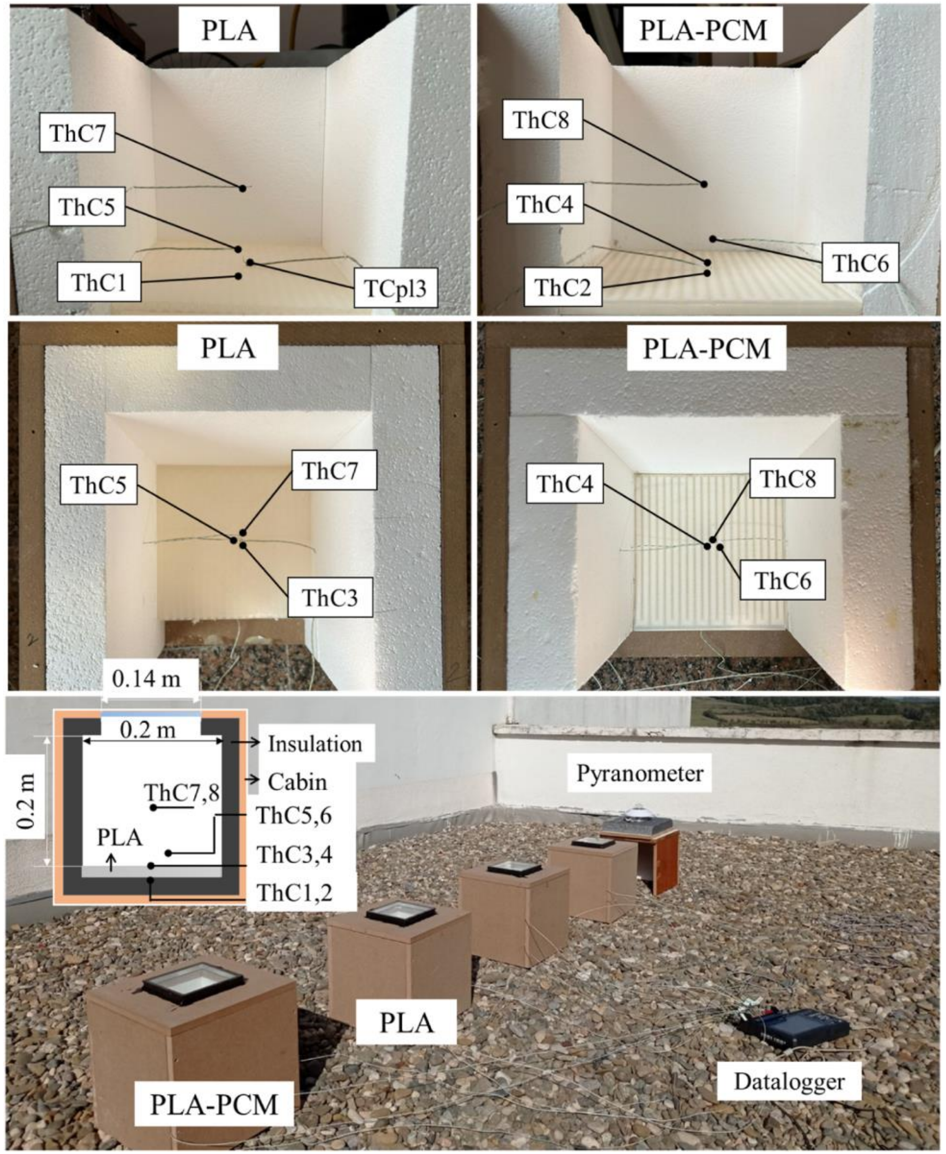
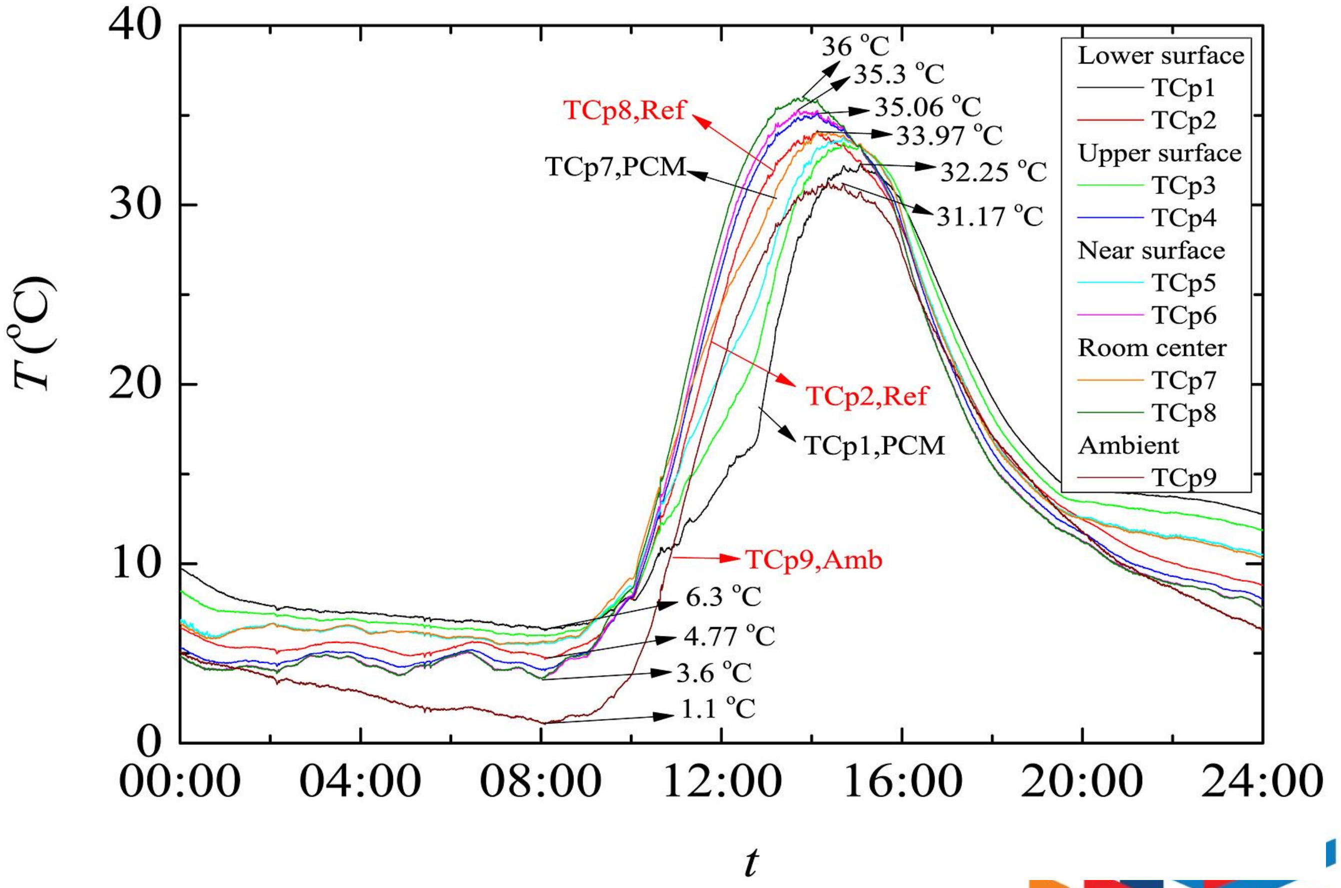


Fig. 14. Temperature alteration in the test cabin on a clear sky.



Test Results

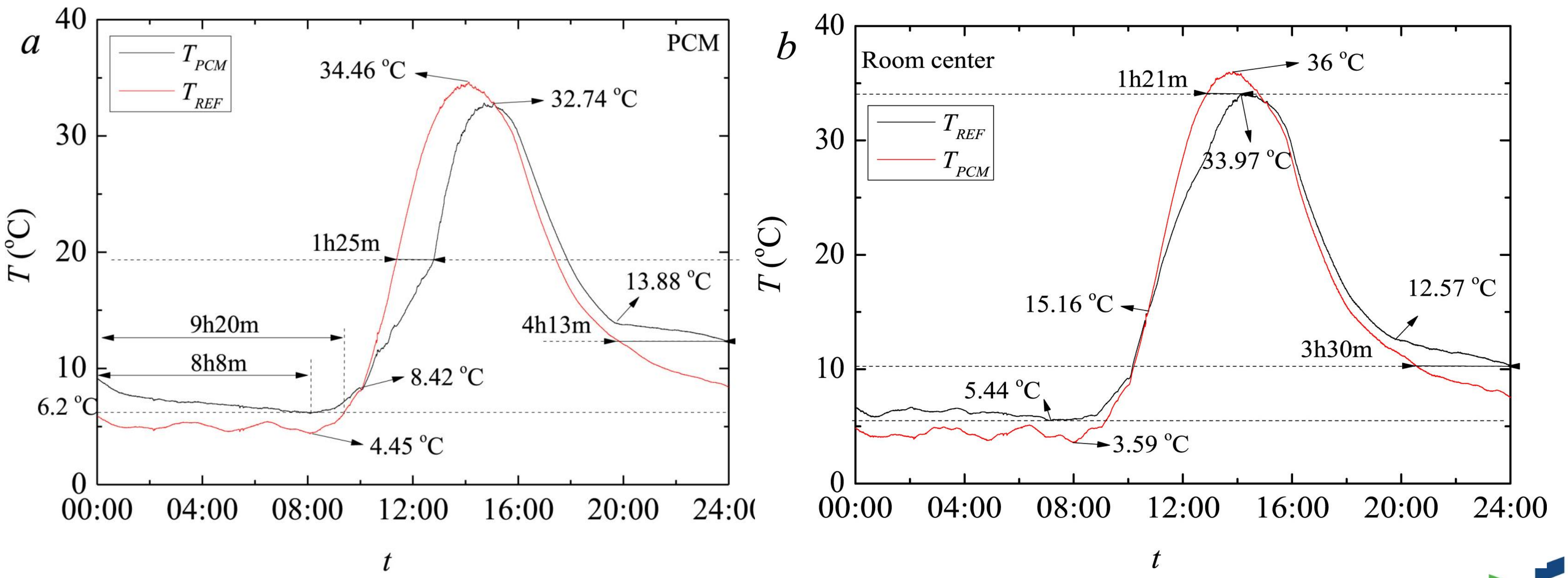


Fig. 15. Temperature variation for surfaces with/without PCM (a) and the temperature of room centers with/without PCM (*b*).

Test Results

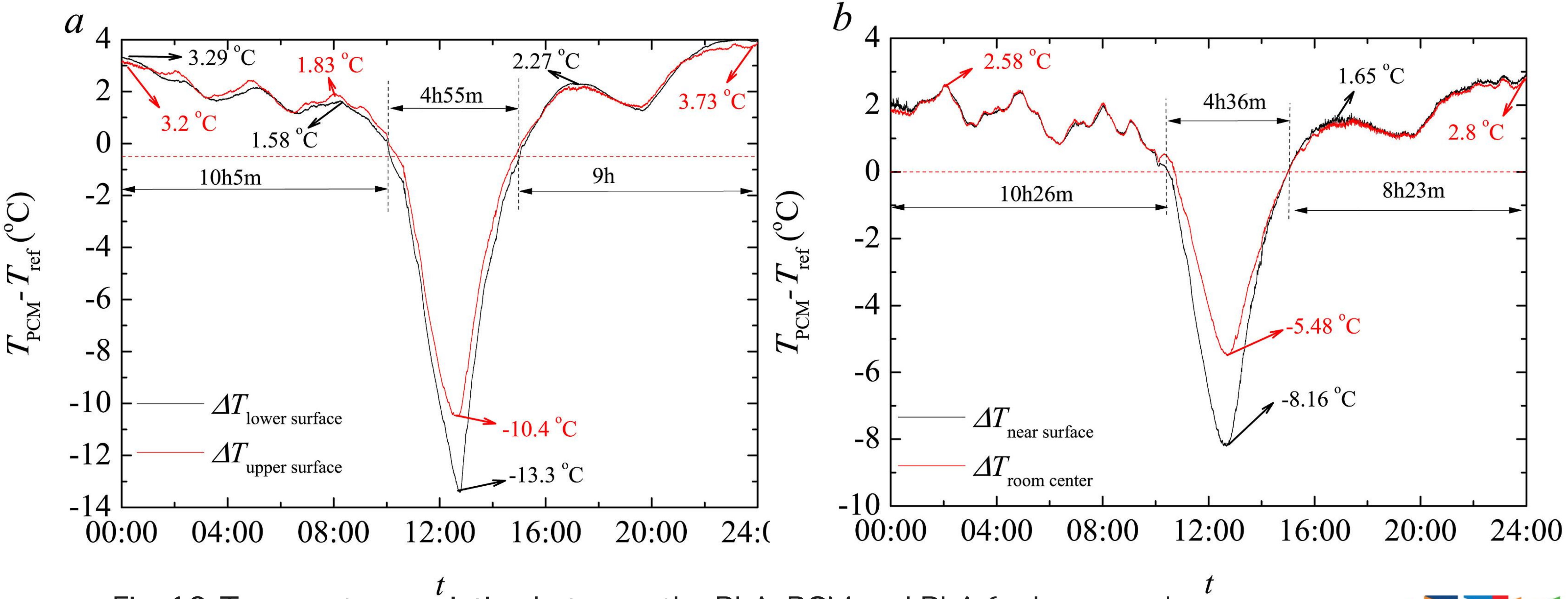
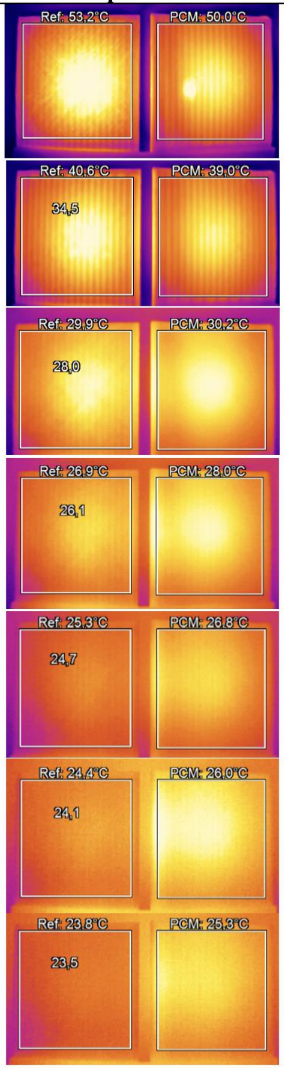
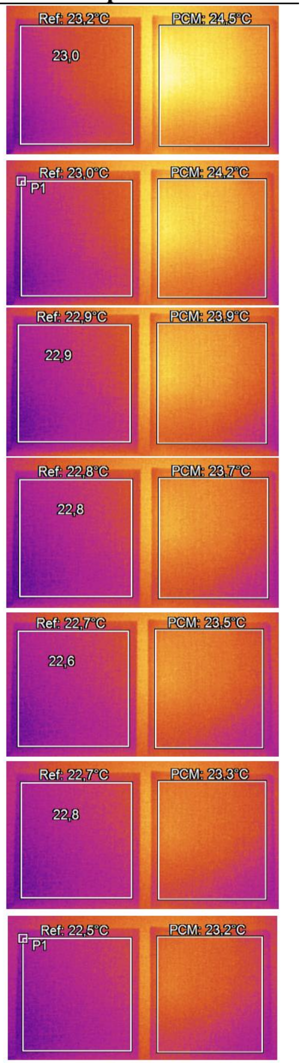


Fig. 16. Temperature variation between the PLA-PCM and PLA for lower and upper surfaces (*a*) and temperature difference between PLA-PCM and PLA for near surface and room center cases (*b*).

Table 1. Max ΔT in room center temperatures (PCM-REF) during daytime (cooling) and nighttime (heating) across diverse studies with varying composites and PCMs

Reference Work	Composite type	PCM Type	PCM	Support material	Max ΔT (PCM-REF) during the daytime (cooling)	Max ΔT (PCM-REF) during the nighttime (heating)
1	Polylactic acid	Microencapsulation	Nextek 24D-MPCM	-	-5.48 °C	2.80 °C
2	Gypsum	Microencapsulation	Nextek 18D-MPCM	-	-3.80 °C	6.60 °C
3	Unsaturated polyester resin	Microencapsulation	Nextek 24D-MPCM	UV cured polyester	-11.10°C	0.50 °C
4	Fiber reinforced cementitious composite	Microencapsulation	Nextek 18D-MPCM	-	-1.35°C	1.20 °C
5	Fiber reinforced foam concrete	Microencapsulation	Nextek 18D-MPCM	-	-1.91°C	1.98 °C
6	Cement-based mortar	Shape stabilization	Capric acid	Blast furnace slag	-5.78°C	0.61 °C
7	Cement-based mortar	Shape stabilization	Lauric-Myristic acid	Micronized expanded vermiculite	-3.60 °C	-
8	Cement-based mortar	Shape stabilization	n-octadecane	Recycled expanded glass powders	-10.60 °C	4.00 °C
9	Foam concrete	Shape stabilization	Capric acid	Basalt powder	-1.53 °C	0.54 °C

Elapsed Time (min)	Thermal camera images and temperature changes on sample surfaces during the cooling process	Elapsed Time (min)	Thermal camera images and temperature changes on sample surfaces during the cooling process
0	 Ref: 53,2°C PCM: 50,0°C	16	 Ref: 23,2°C 23,0 PCM: 24,5°C
2	Ref: 40,6°C 34,5 PCM: 39,0°C	18	Ref: 23,0°C P1 PCM: 24,2°C
4	Ref: 29,9°C 28,0 PCM: 30,2°C	20	Ref: 22,9°C 22,9 PCM: 23,9°C
6	Ref: 26,9°C 26,1 PCM: 28,0°C	22	Ref: 22,8°C 22,8 PCM: 23,7°C
8	Ref: 25,3°C 24,7 PCM: 26,8°C	24	Ref: 22,7°C 22,6 PCM: 23,5°C
10	Ref: 24,4°C 24,1 PCM: 26,0°C	26	Ref: 22,7°C 22,8 PCM: 23,3°C
12	Ref: 23,8°C 23,5 PCM: 25,3°C	28	Ref: 22,5°C P1 PCM: 23,2°C

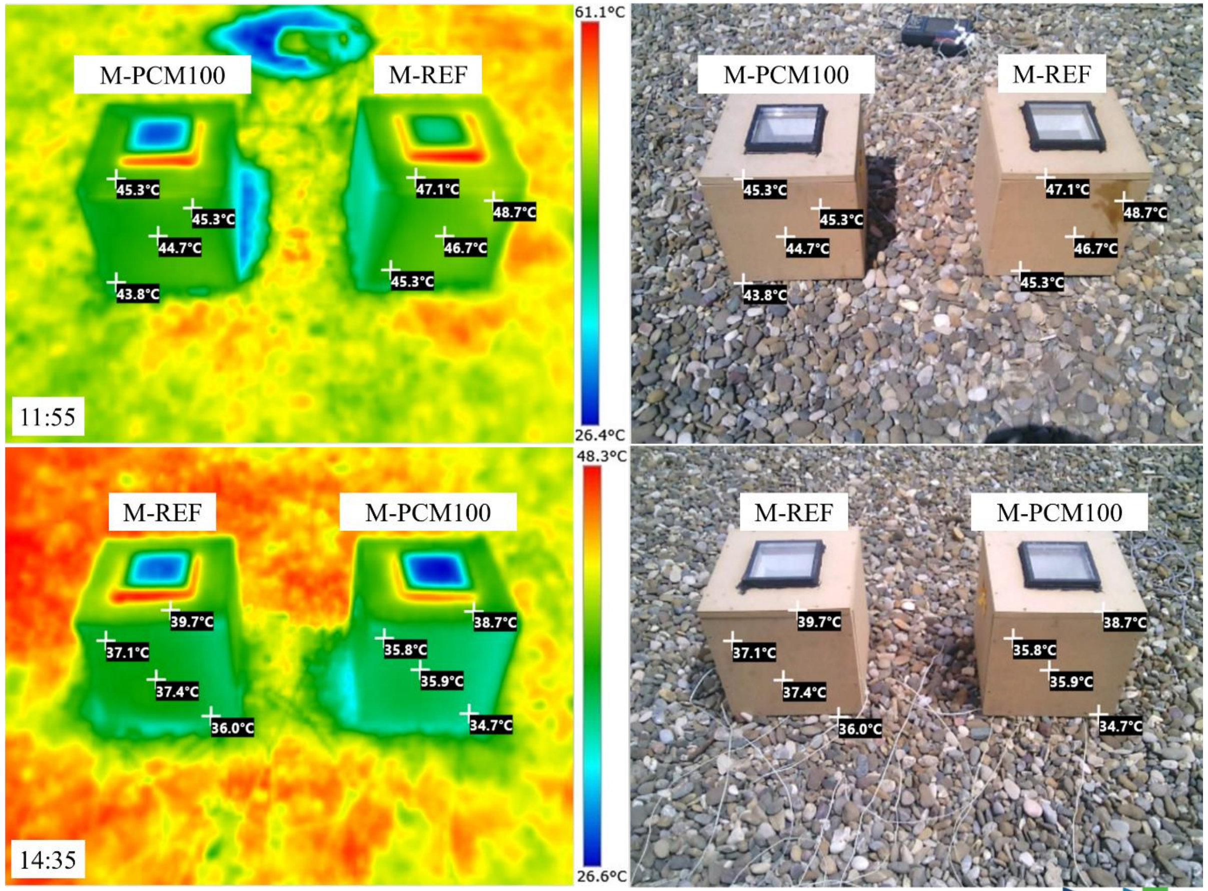
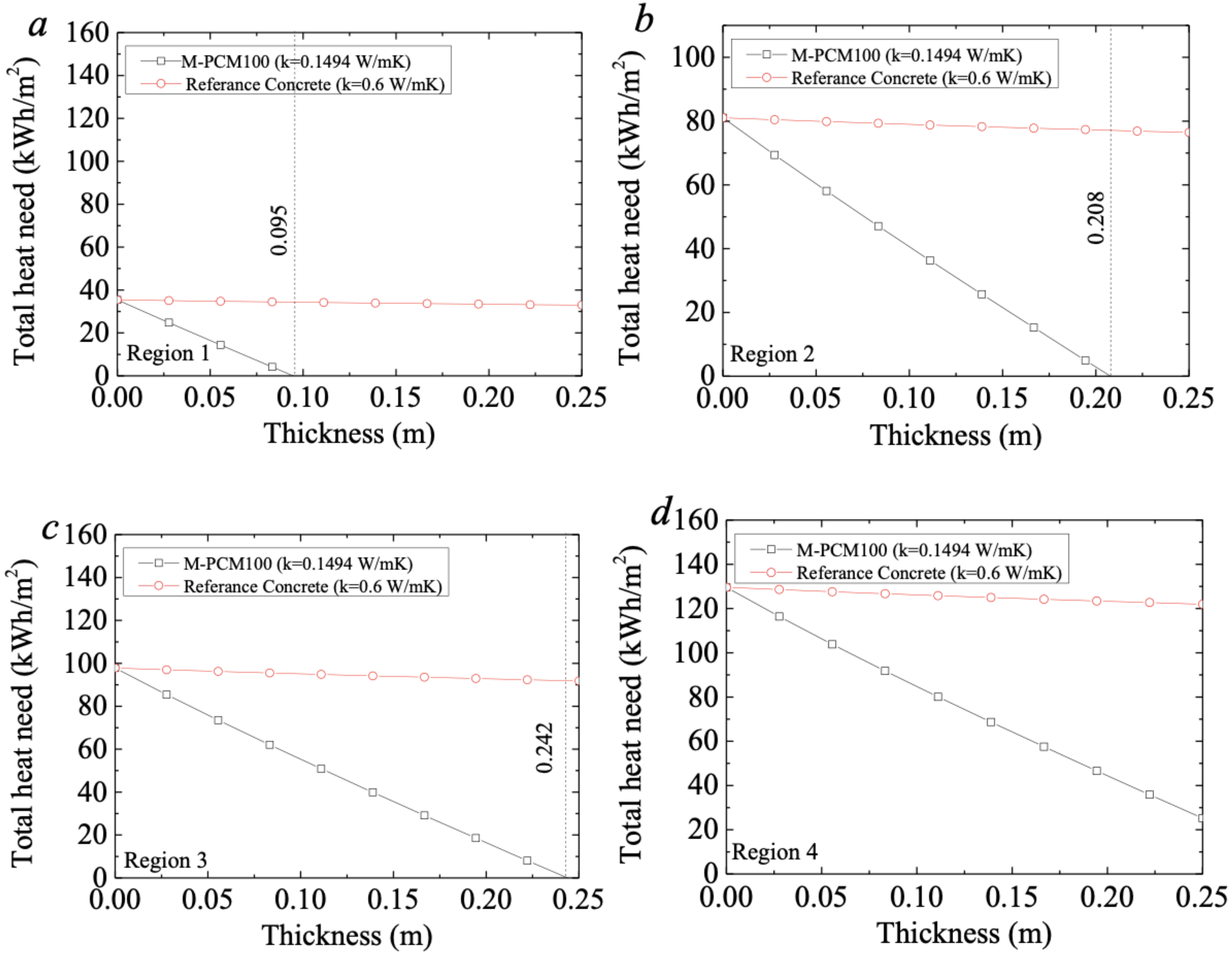


Fig. 17. Thermal camera images of test cabins

Test Results

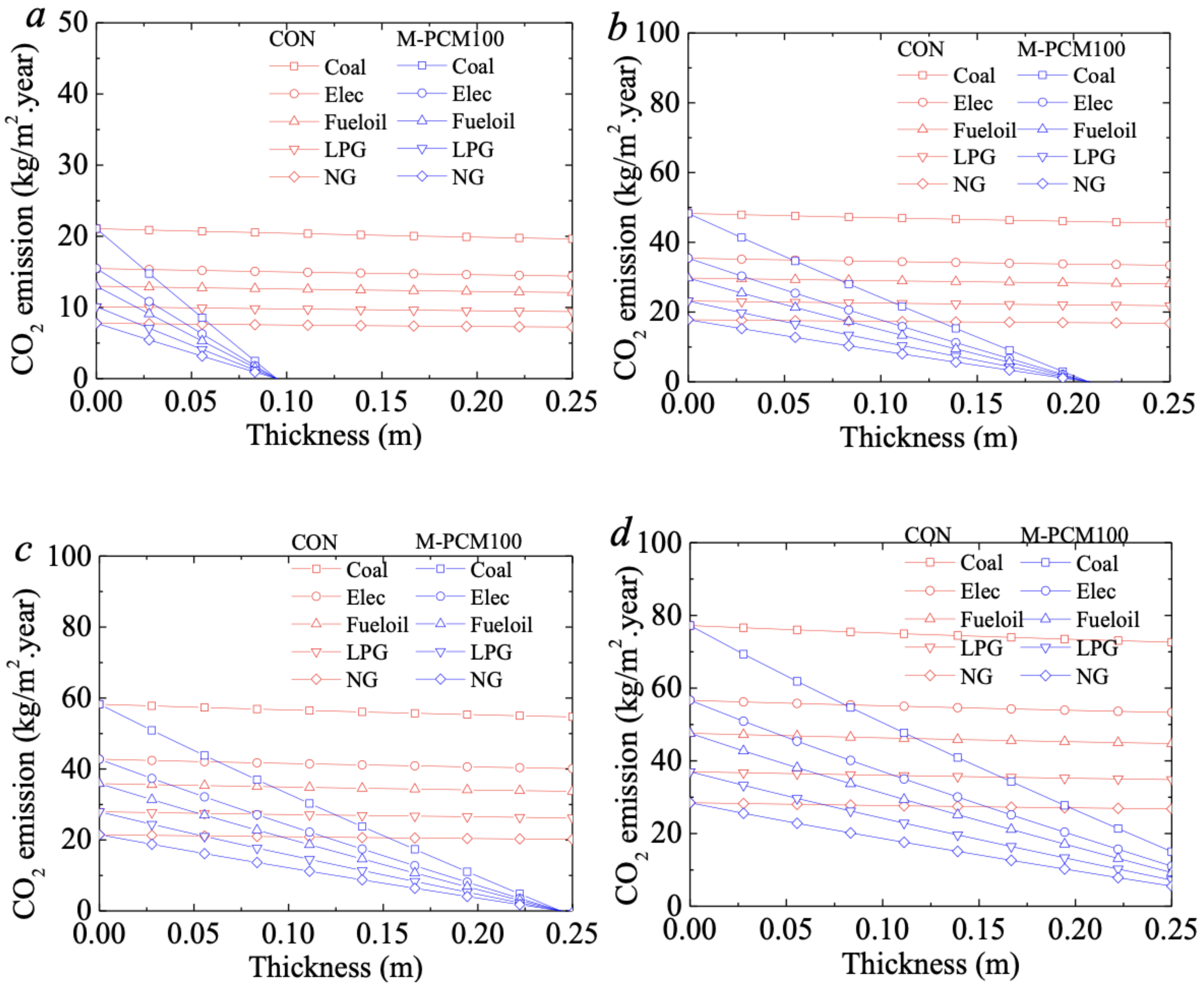
Fig. 18. Total heat needs a building in four different climate regions having proposed concrete and reference concrete.



- Region 1: Mediterranean climate - hot, dry summers and cool, wet winters.
- Region 2: Oceanic climate - warm, humid summers and cold, damp winters.
- Region 3: Continental climate - snowy, cold winters and hot, arid summers.
- Region 4: Varied climate - significant fluctuations, snowy winters and dry summers.

Test Results

Fig. 19. CO_2 emissions resulting from heating a building in four distinct climate regions, using both proposed concrete and reference concrete.



- Region 1 showed significant reductions with increased PCM wall thickness, especially with coal.
- PCM walls eliminated emissions in some regions like Region 2, suggesting substantial environmental impact.
- Coal led to highest emissions reduction, followed by electricity, fuel oil, LPG, and natural gas, showcasing varied CO_2 savings with PCM.

Key Learnings

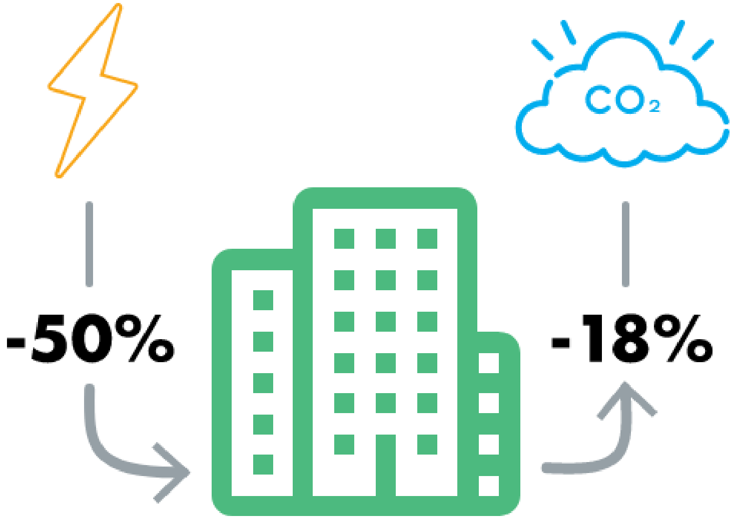
- Testing and simulations demonstrated that PCM in building materials/composites significantly improves thermal and energy efficiency.

- PCM composites effectively control room temperature, providing higher temperatures in colder hours and lower temperatures during warmer periods, mitigating temperature fluctuations.

- Thermo-regulation tests confirmed PCM's ability to stabilize temperatures.

- Customized PCM-integrated walls showed significant energy savings across different climates.

- PCM-infused concrete led to notable reductions in carbon emissions, especially with high-emission fuel types, contributing to environmental sustainability.



Future directions

- Utilizing Waste-Based Materials: Exploring waste-based porous materials for stabilizing PCM composites, enhancing sustainability.
- Improving Mechanical-Thermal Performance: Optimizing PCM composites through advanced engineering for better mechanical and thermal properties.
- 3D Printing Integration: Investigating PCM integration into 3D printing for customized, energy-efficient building components.
- Climate-Adaptive Analysis: Conducting comprehensive studies to adapt PCM composites to diverse climates.
- Lifecycle Assessment and Circular Economy: Assessing PCM composites' lifecycle and integrating them into circular economy practices.

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