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CONFERENCE PAPER · LOW-CARBON BUILDINGS

Experimental Characterization and Seasonal Thermal Assessment of a Diatomite-Based Phase-Change Gypsum Wallboard

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ABSTRACT

This study investigates the thermal performance and energy-saving potential of a diatomite/microencapsulated phase-change material/gypsum (D-MPCM/G) composite wallboard. Four composite formulations containing 10 - 40 wt.% microencapsulated phase-change material (MPCM) were prepared and experimentally characterized. A three-dimensional transient heat-transfer model was developed to investigate the effects of PCM layer position, phase-transition temperature, transition range, and layer thickness on wall thermal performance. The results show that the composite containing 20 wt.% MPCM achieved a melting enthalpy of 25.98 J g-1 and a moisture uptake of approximately 0.45 g g-1 at 97.42% relative humidity while maintaining good visual integrity after three months of ambient storage. Numerical simulations indicate that a phase-transition temperature of 27 °C, a transition range of 2 K, and an interior PCM layer thickness of 10 mm provided the best thermal performance among the investigated configurations. These findings indicate that diatomite-based PCM gypsum wallboards have the potential to mitigate indoor-side wall temperature fluctuations and reduce heat gains through building envelopes.

KEYWORDS Diatomite, Microencapsulated phase-change material, Gypsum wallboard, Apparent heat capacity, Building envelope

1. Introduction

Building envelopes are exposed to strongly time-varying ambient temperature and solar radiation. Conventional gypsum finishes provide mainly sensible thermal storage, whereas phase-change materials (PCMs) can absorb and release latent heat within a selected temperature interval. Their capacity to moderate inward heat gains depends on climate, layer location, transition range, and regeneration during cooler periods (Yang *et al.* 2022). Therefore, nominal latent heat alone is insufficient to predict seasonal performance.

Diatomite offers a porous mineral framework with substantial water-sorption capacity. Together with gypsum and polymer-shell PCM microcapsules (MPCM), it can form an interior finishing material with both latent-heat storage and possible moisture-buffering functions (Abden *et al.* 2020; Yu *et al.* 2020). However, increasing MPCM content also reduces the fraction of the continuous mineral matrix. A formulation with the highest measured enthalpy may not remain visually intact or be suitable for a building panel.

This study evaluates a diatomite/MPCM/gypsum (D-MPCM/G) board through material measurements followed by three-dimensional, transient wall simulations under Taiyuan summer weather. The work first screens four MPCM loadings, then examines PCM-layer placement and idealized transition properties, and finally compares a representative summer day with June–August

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conditions. The target quantity is wall-level thermal response, not measured indoor comfort or whole-building air-conditioning electricity use.

2. Materials and methods

2.1. Composite preparation

The purchased MPCM contained an n-octadecane core and a poly(methyl methacrylate) (PMMA) shell. Diatomite served as porous mineral filler and high-strength gypsum as the binder. Dry ingredients were blended, combined with deionized water, cast, cured at ambient conditions, demolded, and dried to constant mass. Four nominal 20 g dry batches contained 10, 20, 30, or 40 wt.% MPCM; the remaining dry mass was divided equally between diatomite and gypsum (Table 1).

Table 1. Dry formulations (g per 20 g batch).

MPCM (wt.%)	MPCM	Diatomite	Gypsum
10	2	9	9
20	4	8	8
30	6	7	7
40	8	6	6

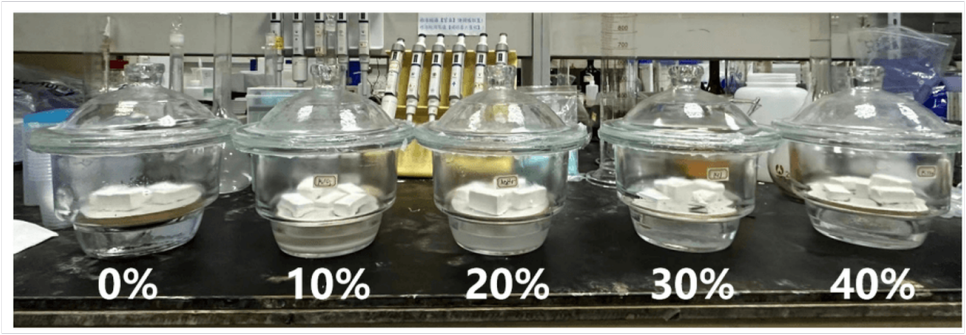

Figure 1. Moisture absorption experiment under constant humidity environment.

2.2. Material characterization

Differential scanning calorimetry (DSC) used approximately 5 mg per specimen, nitrogen protection, a 5 °C min^{-1} scan, and a 0–100 °C temperature range. A preliminary thermal cycle preceded the reported heating and cooling data. Thermogravimetric analysis (TGA) examined mass loss on heating, and a transient plane-source method was used to measure thermal conductivity. Specimens were also inspected visually after three months at approximately 26 ± 1 °C and 50 ± 5% relative humidity (RH).

Water-sorption tests used saturated-salt environments in accordance with ISO 12571 (International Organization for Standardization 2013), after specimens had been dried to constant mass. Uptake was recorded over seven days, including a high-RH condition of approximately 97.42%. The reported sorption is a material-level uptake measurement; it is not a measurement of moisture buffering in an occupied room. Likewise, three-month visual observations do not establish bending strength, fire classification, leakage resistance under repeated thermal cycling, or long-term durability.

2.3. Transient heat transfer wall model

COMSOL Multiphysics was employed for transient conduction in a multilayer wall, with latent heat represented by temperature-dependent apparent heat capacity. In the composite domain, the governing relation was $\rho c_{app}(T)\ \partial T/\partial t = \nabla\cdot[k\nabla T]$. The wall comprised 15 mm concrete, 175 mm

masonry mortar, and a PCM-containing interior finish varied from 5 to 10 mm. The composite was treated as homogeneous and isotropic; microcapsule-scale heat transfer, moisture transport, and lateral fluxes were not explicitly resolved.

The measured 20 wt.% composite supplied baseline density (381 kg m^{-3}), conductivity (0.213 W $m^{-1}K^{-1}$), and sensible heat capacity (2078 J kg^{-1} K^{-1}). Parametric sweeps independently altered the assumed transition center and width, without demonstrating that those changes could be obtained in the fabricated sample. Taiyuan hourly weather and solar data were used to derive an outdoor sol-air boundary temperature. Indoor air was held at 26 °C; external and internal heat-transfer coefficients were 19 and 3.7 W $m^{-2}K^{-1}$. Initial temperature was 24 °C, with insulated lateral faces and a nominal 6 s time step.

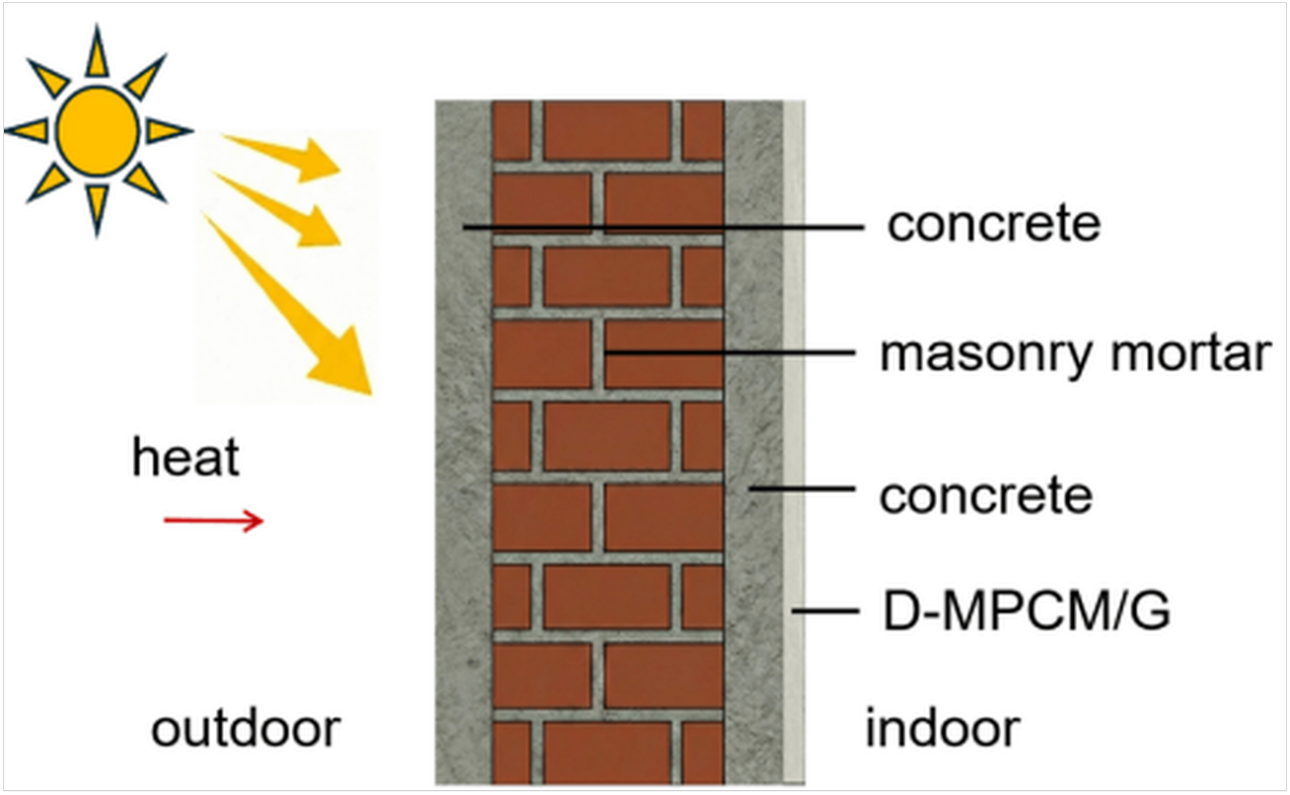

Figure 2. Physic model of heat transfer of a wall.

Table 2. Selected numerical model inputs.

Quantity	Specification
Wall construction	15 mm concrete + 175 mm masonry mortar + PCM finish
Interior reference	26 °C
Surface coefficients	19 / 3.7 W m^{-2} K^{-1}(outer / inner)
PCM layer thickness	5, 8, 10 mm
Simulation period	Typical day; June–August
Mesh, time step	3.5 mm; 6 s

2.4. Mesh and external-model checks

Characteristic mesh sizes of 4.5, 4.0, 3.5, and 3.0 mm were compared. The adopted 3.5 mm mesh contained approximately 1.29 million elements. Model response was also compared against published wall-temperature data for a different PCM system (Ye *et al.* 2017): R^2 = 0.92, RMSE = 1.64 °C, and MAPE = 4.66%. However, the predicted peak exceeded the reference by about 2.49 °C and

occurred 3 h earlier. This comparison supports qualitative trend agreement but does not directly validate the D-MPCM/G wallboard or establish peak-attenuation accuracy.

2.5. Performance metrics and boundaries

The outdoor sol-air formulation used a solar absorptance of 0.6, ground reflectance of 0.1, and a 1.8 °C sky-radiation correction. The indoor surface was coupled convectively to the 26 °C air set point. Instantaneous inward wall heat flux can be expressed as $q''_{in}(t) = h_{i\ max}[T_{si}(t) - T_{a,\ 0}]$ (W m^{-2}), with a time integral giving area-normalized heat gain (e.g., Wh m^{-2} if time is in hours). This is a physically explicit reporting convention, not an independently confirmed reconstruction of the thesis post-processing.

Outputs were inner-surface temperature extrema and swing, liquid-fraction history, and the relative cumulative cooling-load comparison reported in the thesis. Because the source labels integrated totals in W and does not fully document the sign and time-integration convention, its 20.07% and 7.76% differences are retained here as reported relative comparison indices, without asserting verified absolute energy savings. The model excludes occupancy, infiltration, HVAC equipment, and whole-building interactions.

3. Results and discussion

3.1. Experimental properties and material choice

DSC showed increasing enthalpy with MPCM fraction (Fig. 3). At 10, 20, 30, and 40 wt.%, the measured melting enthalpies were 13.77, 25.98, 39.28, and 51.49 J g^{-1}; corresponding solidification values were 13.32, 21.59, 31.92, and 41.43 J g^{-1}. Reported transition widths were 3.0, 3.5, 4.4, and 4.8 K, respectively. Thus, the fabricated 20 wt.% specimen did not possess the 2 K transition width used in the preferred numerical scenario.

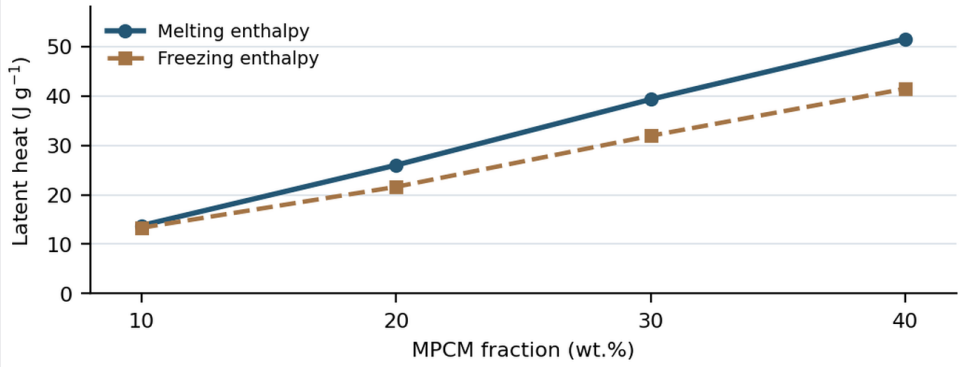

Figure 3. Measured melting and solidification enthalpies versus MPCM fraction.

All formulations exhibited less than 2% mass loss up to 100 °C in the reported TGA tests. After three months of ambient storage, the 10 and 20 wt.% specimens remained visually intact, whereas the 30 wt.% specimen showed edge shedding and the 40 wt.% specimen showed swelling and embrittlement. The 20 wt.% loading was therefore selected as a practical screening choice—not an experimentally established mechanical or lifetime optimum.

At approximately 97.42% RH, the 20 wt.% composite reached about 0.45 g g^{-1} water uptake after seven days, compared with roughly 0.005 g g^{-1} for ordinary gypsum. This marked difference indicates high sorption capacity, but the high-RH measurement does not quantify room humidity moderation, adsorption/desorption hysteresis, or vapor-transport response during typical indoor RH cycles.

3.2. Interpretation of the formulation trade-off

The 40 wt.% specimen had almost twice the 20 wt.% specimen's melting enthalpy per unit mass, yet its visibly deteriorated matrix made it a less attractive candidate for the next modeling stage. The observed compromise is therefore between calorimetric capacity and macroscopic condition after short-term ambient storage. It remains necessary to measure strength, dimensional change, and performance after repeated melting–solidification cycles before judging suitability for construction.

The discrepancy between melting and solidification enthalpy also highlights the importance of cyclic heat-storage performance. Furthermore, diatomite-mediated water uptake is an ancillary material property: the present heat-conduction model did not solve coupled heat and moisture transport. Hence neither the thermal calculation nor the sorption tests alone demonstrate improved indoor humidity or occupied-space thermal comfort.

3.3. Transition temperature, width, and thickness

The simulated phase-transition widths were 2, 3.5, 5, and 6.5 K, and transition centers covered approximately 25–29 °C. The 2 K case centered at 27 °C showed a more pronounced daily phase-fraction excursion than the broader-width cases under the tested Taiyuan conditions. Across June–August, it spent about 593 h in the modeled transition process with a mean liquid fraction of 0.41; the 28 °C case spent 607 h but had a mean fraction of 0.29. Average liquid fraction alone is not a measure of recovered latent heat; cycle amplitude and inward heat gain should be considered jointly.

For PCM finishing layers of 5, 8, and 10 mm, representative-day peak interior-surface temperatures were 30.57, 29.96, and 28.74 °C, respectively (Fig. 4). Corresponding reported daily swings were 4.98, 5.40, and 3.67 °C. Thus, 10 mm gave the lowest peak and swing among the three tested thicknesses; it was 1.83 °C cooler at peak than 5 mm. Summer-average daily peak reductions relative to the non-PCM baseline were 0.28, 0.42, and 0.47 °C. This is a bounded parametric comparison, not proof that no thickness above 10 mm would perform better.

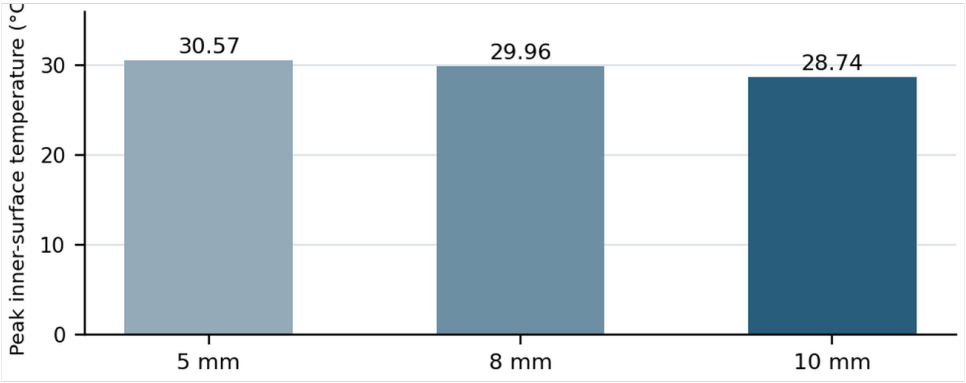

Figure 4. Simulated peak interior wall-surface temperatures at the three tested layer thicknesses.

3.4. Predicted wall heat-gain attenuation

In the representative-day comparison with the non-PCM wall, the modeled interior-surface peak decreased by 1.58 °C; the daily surface-temperature range declined from 5.71 to 3.80 °C (33.45%). The source thesis also reported a 20.07% reduction in its cumulative daily wall cooling-load comparison index and 7.76% over June–August (Fig. 5). These percentages describe the source model's reported wall response, not directly metered cooling energy or HVAC electricity consumption.

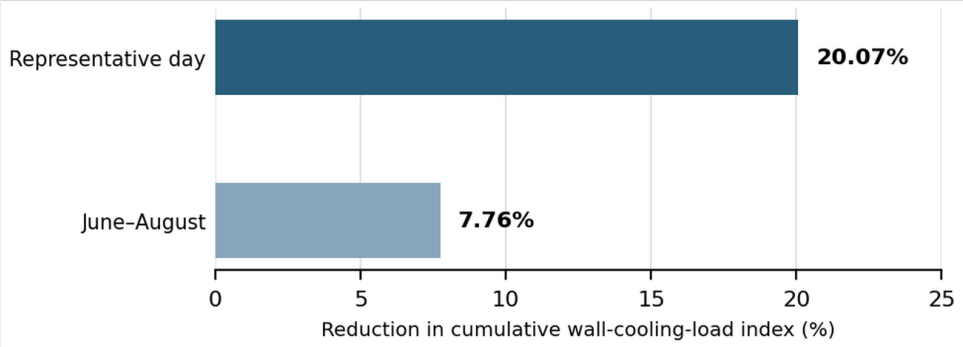

Figure 5. Relative reductions in the wall cooling-load comparison index; absolute integration units remain unverified.

3.5. Implications for climate-specific design

Phase-change activation and nighttime regeneration are as important as nominal latent heat. Wider transition intervals may prevent complete phase conversion under modest daily temperature excursions. Interior placement was retained for finishing-board integration and room-side response, although the external placement case in the initial screen showed stronger full-cycle phase conversion. The 10 mm, 27 °C, 2 K option is therefore a testable numerical design candidate for this climate and wall model, not a universally optimal product.

4. Conclusion

A diatomite/gypsum wallboard containing 20 wt.% MPCM had a measured melting enthalpy of 25.98 J g^{-1}, high moisture uptake at 97.42% RH, and no obvious visual degradation during three-month ambient storage. Within the investigated simulation cases, a 27 °C transition center, an idealized 2 K interval, and a 10 mm interior finishing layer gave favorable wall thermal attenuation. The predicted representative-day interior surface peak was 1.58 °C lower than for the non-PCM wall. The thesis reported relative reductions of 20.07% (representative day) and 7.76% (June–August) for its cumulative wall cooling-load index, subject to post-processing verification. Material realization of the 2 K interval, direct validation of the composite wall, dimensional auditing of integrated heat flux, and durability testing are required before drawing building-scale energy conclusions.

Declarations

Author contributions. Chen Mao: Writing (original draft), Data curation, Formal analysis, Investigation, Methodology, Conceptualization.

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Conflicts of interest. The authors declare no competing interests.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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