

Thermal Performance Enhancement of Phase Change Materials for Energy Efficient Building Applications

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ABSTRACT

Increasing cooling demands in buildings have encouraged the development of phase change materials (PCMs) with improved thermal performance. This study investigated four PCM formulations using 12 independently prepared samples combined with building thermal simulations. The evaluation covered thermal conductivity, latent heat capacity, thermal stability, indoor temperature, cooling load, and energy consumption. Statistical analysis involved descriptive methods, Shapiro-Wilk and Levene's tests, one-way ANOVA, and Tukey's HSD test. The medium-additive formulation achieved the best balance, with thermal conductivity of 0.281 W/m·K, latent heat capacity of 183.9 J/g, and heat retention of 99.1%. It reduced indoor temperature by 2.4°C, peak cooling load by 17.2%, and energy consumption by 14.3%.

INTRODUCTION

Reducing energy consumption in buildings has become an important challenge, particularly because thermal conditioning systems contribute substantially to operational energy use, especially in areas with high cooling requirements (Jha et al., 2024). This issue becomes more critical in hot and humid regions, where increasing ambient temperatures, continuous urban development, and higher demands for indoor thermal comfort lead to greater reliance on mechanical cooling technologies. In Indonesia, the demand for cooling energy is expected to grow by approximately 10 kWh/m² annually by 2030 and could reach an increase of 51–68 kWh/m² annually in several areas by 2100 (Veanti et al., 2022). Such conditions indicate the importance of developing passive thermal management strategies that can store and release heat without causing additional electricity consumption. Among various thermal storage approaches, phase change materials (PCMs) have attracted considerable attention due to their ability to store large amounts of latent heat and maintain thermal energy exchange within a defined temperature interval (Cabeza, 2020).

From a theoretical perspective, phase change materials (PCMs) are thermal energy storage media that operate by utilizing reversible phase transitions. Through this mechanism, heat energy can be absorbed during the melting process and subsequently released when the material returns to its solid state. When surrounding temperatures increase, PCM captures thermal energy from the environment as part of its phase transformation process. In contrast, under decreasing temperature conditions, the stored energy is discharged through solidification. The application of PCMs in building components, including walls, roofs, ceilings, and floors, has been reported to minimize indoor temperature variations and postpone the occurrence of peak thermal loads (Faraj et al., 2021). Nevertheless, the overall performance of PCM systems is influenced by various thermophysical characteristics, such as phase transition temperature, latent heat storage capacity, thermal stability, compatibility with host materials, and heat transfer capability. One of the primary challenges in PCM applications is its limited thermal conductivity, which may restrict the rate at which thermal energy is absorbed and released during charging and discharging processes (Wu et al., 2020).

Previous studies have highlighted the effectiveness of phase change materials (PCMs) in improving the thermal performance of building systems. Gao et al. (2020) found that the integration of PCM into hollow brick structures contributed to better thermal regulation by limiting heat transfer and postponing the propagation of peak temperatures through the building envelope. The study further emphasized that PCM performance is highly dependent on several design parameters, including material content, installation location, and phase transition temperature. Experimental investigations conducted by Al-Yasiri and Szabó (2022) under severe hot climate conditions showed that PCM application in building components could decrease roof surface temperature by up to 3.75°C and reduce thermal discomfort duration by 11.2%. In addition, Aghoei et al. (2024) reported through simulation analysis that PCM implementation in building envelopes reduced energy consumption by approximately 6% and

lowered energy use intensity by 5.6%. Collectively, these studies indicate that PCM provides promising benefits for improving building energy performance; however, its effectiveness depends on the interaction between climatic conditions, building characteristics, PCM placement strategy, layer thickness, and thermophysical properties.

Despite the growing number of studies on the application of phase change materials in buildings, previous research continues to reveal several limitations that constitute an important scientific gap. Podara et al. (2021) explained that increasing thermal conductivity through conductive additives does not necessarily improve latent heat capacity, indicating that material composition must be optimized carefully. Kurdi et al. (2021) found that only a limited number of phase change materials are suitable for wall construction because of leakage, thermal stability, and compatibility issues. Jha et al. (2024) further emphasized the need for continued research on formulation optimization, integration techniques, long-term durability, material compatibility, and economic feasibility. Consequently, studies integrating laboratory testing of multiple formulations, independent replications, statistical analysis, and building thermal simulation within a unified research design remain limited.

Based on this research gap, the present study aims to analyze the enhancement of phase change material thermal performance through formulation variations and to evaluate their effects on building energy efficiency. Specifically, the study compares one baseline formulation with three modified formulations containing thermal conductivity-enhancing additives to assess thermal conductivity, latent heat capacity, indoor temperature, cooling load, and building energy consumption. The research employs 12 samples comprising four formulations with three independent replications for each formulation. Laboratory characterization data are subsequently used as input parameters in a thermal simulation to compare a building without phase change materials with buildings incorporating each formulation into envelope components. The analysis is directed toward identifying the optimal formulation that can accelerate heat transfer, maintain thermal energy storage capacity, and improve overall building energy efficiency.

Theoretically, this study is expected to strengthen current understanding of the relationships among phase change material composition, thermal conductivity, latent heat capacity, and building thermal response. Methodologically, the study integrates material characterization, statistical testing, and building thermal simulation, allowing performance enhancement to be evaluated both experimentally and practically. From a practical perspective, the findings may provide a basis for selecting suitable phase change material formulations to reduce indoor temperature fluctuations, cooling loads, and energy consumption. The results may also serve as an initial reference for developing walls, roofs, or ceilings with enhanced thermal energy storage capability. Therefore, this study contributes to the advancement of thermal engineering materials and supports the implementation of passive technologies for energy-efficient building applications.

LITERATURE REVIEW

Phase Change Materials for Thermal Energy Storage

Phase change materials (PCMs) are thermal storage materials that utilize reversible phase transitions to absorb and release heat energy within a specific operating temperature range. During the melting process, PCM stores thermal energy in the form of latent heat with minimal temperature variation. Conversely, the stored energy is discharged when the material undergoes solidification. This thermal storage mechanism allows PCM to enhance the effective thermal capacity of lightweight building components and reduce fluctuations in indoor temperature conditions. The applicability of PCM in building systems depends on several important characteristics, including phase transition temperature, latent heat capacity, thermal conductivity, chemical stability, safety considerations, and compatibility with surrounding construction materials. PCM formulations with transition temperatures approaching the human thermal comfort range are considered more appropriate for passive temperature regulation in energy-efficient buildings (Duraković, 2020).

Thermal Performance Enhancement

Despite its potential as a thermal storage medium, the application of PCM is frequently limited by its relatively low thermal conductivity, which restricts the rate of heat absorption and release. Various enhancement techniques have therefore been investigated, particularly through the addition of conductive materials such as expanded graphite, carbon-based additives, metallic particles, and porous conductive structures. These additives improve internal heat transfer by providing additional conduction pathways, thereby accelerating the melting and solidification processes. However, increasing additive content beyond an optimal level may negatively affect latent heat storage capacity because the proportion of active PCM decreases. Consequently, the design of PCM composites requires an appropriate balance between improved thermal conductivity, sufficient energy storage capability, thermal stability, and long-term cycling performance (Ali, 2024).

Integration into Building Envelope Components

The incorporation of PCM into building envelope components represents a potential strategy for improving thermal energy storage and controlling heat exchange between outdoor and indoor environments. Under high ambient temperatures, PCM absorbs heat entering through the building envelope and delays its transfer into occupied spaces. When environmental temperatures decline, the stored thermal energy is gradually released as the PCM returns to its solid phase. The effectiveness of PCM integration is strongly affected by several factors, including phase transition temperature, material thickness, installation position within the envelope system, thermal conductivity, and external climatic conditions. Proper design and placement of PCM-based systems can minimize heat transmission, maintain more stable indoor temperatures, and reduce the energy demand associated with building thermal conditioning (Pirasaci, 2020).

Experimental Characterization and Building Simulation

Comprehensive assessment of PCM performance requires experimental characterization of key thermophysical properties, including thermal conductivity, melting and solidification temperatures, latent heat capacity, and thermal stability. Multiple measurements are necessary to confirm that observed differences between formulations are caused by material modifications rather than experimental variability. The obtained laboratory parameters can subsequently be integrated into building simulation models to predict their influence on indoor temperature behavior, peak cooling demand, and overall energy consumption under controlled conditions. This combination of material-level testing and building-scale simulation provides a more complete understanding of PCM effectiveness in practical applications. Furthermore, building energy performance is determined not only by material characteristics but also by factors such as envelope configuration, operational conditions, internal heat sources, and environmental parameters (Fathi, 2024).

METHODOLOGY

Research Approach and Experimental Design

This study employed a quantitative experimental approach combined with building thermal simulation. A completely randomized single-factor design was used to examine the effect of phase change material formulation on thermal conductivity, phase transition temperature, latent heat storage capacity, and thermal stability. Four formulations were evaluated, consisting of one baseline formulation and three modified formulations containing low, medium, and high concentrations of a thermal conductivity-enhancing additive. Each formulation was independently prepared three times, resulting in 12 experimental samples. Sample preparation and testing order were randomized to minimize systematic and batch-related errors (Montgomery, 2020).

Experimental Units and Sampling

The experimental units were phase change material specimens, and no human participants were involved. Purposive non-probability sampling was applied because the formulations were intentionally selected to represent one control and three additive concentration levels. The study used 12 specimens comprising four formulations with three independent replications. Each replication was prepared as a separate batch to estimate within-formulation variation and improve experimental reliability.

Material Preparation

The baseline formulation contained only the selected phase change material, whereas the modified formulations contained predetermined additive concentrations expressed as mass percentages. All components were weighed using a calibrated analytical balance and mixed under controlled temperature and stirring conditions. The mixtures were placed in identical molds, sealed when necessary, and conditioned under uniform conditions. Sample mass, dimensions, preparation temperature, mixing duration, and conditioning time were kept constant across all formulations.

Data Collection and Instruments

Laboratory data were collected through direct thermophysical measurements. Phase transition temperatures, melting and solidification enthalpies, and latent heat storage capacity were measured using Differential Scanning Calorimetry under identical testing conditions (Kahwaji et al., 2021). Thermal conductivity was measured using a calibrated transient plane source, heat-flow meter, or guarded hot plate apparatus, while density was determined from specimen mass and volume. Temperature and heat-flow responses were recorded using calibrated thermocouples connected to a digital data-acquisition system (Toifane et al., 2022).

Thermal Stability and Quality Control

Thermal stability was assessed through thermogravimetric analysis and repeated melting–solidification cycles. After cycling, the specimens were reassessed for phase transition temperature, latent heat capacity, leakage, and physical changes because repeated thermal exposure may affect material performance (Anand et al., 2021). Instrument accuracy was maintained through calibration, zero correction, standardized procedures, and consistent testing conditions. Measurement reliability was evaluated using the mean, standard deviation, coefficient of variation, and measurement uncertainty from the three independent replications.

Building Thermal Simulation

The experimentally measured thermophysical properties were incorporated into a building thermal model developed using EnergyPlus version 23.2. Five scenarios were simulated: a reference building without phase change material, a building using the baseline formulation, and buildings using each modified formulation. Building geometry, envelope configuration, orientation, ventilation, internal heat gains, cooling settings, and operating schedules were kept constant. A standardized hot and humid weather dataset was used, while the conduction finite-difference and phase-change hysteresis models represented the melting and solidification behavior of the materials (Feng et al., 2022).

Research Procedure

The research stages included literature assessment, material selection, formulation preparation, laboratory characterization, thermal-cycle testing, statistical analysis, building-model development, and simulation comparison. Each sample was coded, and the testing sequence was randomized. Laboratory data were screened for completeness, measurement errors, and physically implausible values before analysis. Valid thermophysical data were then entered into the simulation model to evaluate indoor temperature, heat flux, cooling load, and energy consumption (Farulla et al., 2023).

Data Analysis

The experimental results obtained from laboratory measurements were processed using descriptive statistical approaches, including calculation of mean values, standard deviations, coefficients of variation, percentage differences, and

95% confidence intervals. Prior to hypothesis testing, the dataset was examined using the Shapiro–Wilk test for distribution normality and Levene’s test to verify variance equality among groups. Differences between material formulations were evaluated through one-way analysis of variance (ANOVA), followed by Tukey’s honestly significant difference (HSD) procedure when significant effects were identified. The effect magnitude of formulation variations was quantified using eta-squared values. All statistical procedures were performed using IBM SPSS Statistics version 29. Meanwhile, simulation outputs were interpreted through comparative evaluation by examining variations in indoor temperature, cooling requirements, and total energy consumption compared with the reference building condition.

RESEARCH RESULT

Thermophysical Properties of the Phase Change Material Formulations

A total of 12 specimens were successfully prepared, consisting of one baseline formulation and three modified formulations with low, medium, and high additive concentrations. Each formulation was independently prepared in three replications. The measured variables included thermal conductivity, latent heat storage capacity, phase transition temperature, and latent heat retention after thermal cycling. The complete experimental dataset is presented in Table 1.

Table 1. Experimental thermophysical data for the four formulations

Formulation	Replication	Thermal conductivity (W/m ·K)	Latent heat capacity (J/g)	Phase transition temperature (°C)	Latent heat retention (%)
F0 – Baseline	1	0.205	175.3	25.8	98.4
F0 – Baseline	2	0.216	174.1	25.6	98.7
F0 – Baseline	3	0.210	175.7	25.7	98.5
F1 – Low additive	1	0.232	180.8	25.7	98.8
F1 – Low additive	2	0.249	178.2	25.5	99.0
F1 – Low additive	3	0.241	178.8	25.6	98.9
F2 – Medium additive	1	0.269	184.1	25.6	99.1
F2 – Medium additive	2	0.292	183.7	25.4	99.2
F2 – Medium additive	3	0.281	184.0	25.5	99.0
F3 – High additive	1	0.298	176.2	25.5	98.7

Formulation	Replication	Thermal conductivity (W/m ·K)	Latent heat capacity (J/g)	Phase transition temperature (°C)	Latent heat retention (%)
F3 – High additive	2	0.322	177.8	25.3	98.9
F3 – High additive	3	0.311	177.7	25.4	98.8

The descriptive results showed a progressive increase in thermal conductivity as the additive concentration increased. The mean thermal conductivity increased from 0.210 W/m ·K in the baseline formulation to 0.241 W/m ·K in F1, 0.281 W/m ·K in F2, and 0.310 W/m ·K in F3. These values represented increases of 14.4%, 33.4%, and 47.5%, respectively, relative to the baseline formulation. The highest latent heat storage capacity was recorded for F2 at 183.9 J/g, corresponding to an increase of 5.1% compared with the baseline formulation.

Table 2. Descriptive statistics of the thermophysical properties

Formulation	Thermal conductivity (W/m ·K)	Change from baseline (%)	Latent heat capacity (J/g)	Change from baseline (%)	Transition temperature (°C)	Heat retention (%)
F0 – Baseline	0.210 ± 0.006	—	175.0 ± 0.8	—	25.7 ± 0.1	98.5 ± 0.2
F1 – Low additive	0.241 ± 0.009	14.4	179.3 ± 1.4	2.4	25.6 ± 0.1	98.9 ± 0.1
F2 – Medium additive	0.281 ± 0.012	33.4	183.9 ± 0.2	5.1	25.5 ± 0.1	99.1 ± 0.1
F3 – High additive	0.310 ± 0.012	47.5	177.2 ± 0.9	1.3	25.4 ± 0.1	98.8 ± 0.1

Note. Values are presented as mean ± standard deviation based on three independent replications ($n = 3$). F0 = baseline formulation; F1 = low additive concentration; F2 = medium additive concentration; F3 = high additive concentration..

Statistical Analysis of Thermal Conductivity and Latent Heat Capacity

The residuals of the thermal conductivity data satisfied the normality assumption based on the Shapiro–Wilk test, with a test statistic of 0.934 and a probability value of 0.421. The latent heat capacity residuals were also normally distributed, with a test statistic of 0.949 and a probability value of 0.625. Levene’s test showed that the variance was homogeneous for both thermal conductivity and latent heat capacity, with probability values of 0.772 and 0.692, respectively. Therefore, the assumptions required for one-way analysis of variance were satisfied.

Table 3. Assumption testing and one-way analysis of variance results

Variable	Shapiro-Wilk statistic	Probability value	Levene statistic	Probability value	Analysis of variance	Probability value	Eta-squared
Thermal conductivity	0.934	0.421	0.378	0.772	$F(3,8) = 61.161$	< 0.001	0.958
Latent heat capacity	0.949	0.625	0.502	0.692	$F(3,8) = 50.916$	< 0.001	0.950

One-way analysis of variance showed a statistically significant difference in thermal conductivity among the four formulations, $F(3,8) = 61.161$, probability value < 0.001 . The eta-squared value of 0.958 indicated that 95.8% of the observed variation in thermal conductivity was associated with formulation differences. Tukey's honestly significant difference test showed significant differences between all formulation pairs, with probability values below 0.05.

A statistically significant difference was also identified in latent heat storage capacity, $F(3,8) = 50.916$, probability value < 0.001 . The formulation factor accounted for 95.0% of the observed variation in latent heat capacity. Pairwise comparisons showed that F1 and F2 had significantly higher latent heat capacities than F0, whereas the difference between F0 and F3 was not statistically significant.

Table 4. Tukey's honestly significant difference results

Variable	Comparison	Mean difference	Probability value	Result
Thermal conductivity	F0-F1	0.030 W/m · K	0.021	Significant
Thermal conductivity	F0-F2	0.070 W/m · K	< 0.001	Significant
Thermal conductivity	F0-F3	0.100 W/m · K	< 0.001	Significant
Thermal conductivity	F1-F2	0.040 W/m · K	0.005	Significant
Thermal conductivity	F1-F3	0.070 W/m · K	< 0.001	Significant
Thermal conductivity	F2-F3	0.030 W/m · K	0.024	Significant
Latent heat capacity	F0-F1	4.23 J/g	0.002	Significant
Latent heat capacity	F0-F2	8.90 J/g	< 0.001	Significant
Latent heat capacity	F0-F3	2.20 J/g	0.074	Not significant

Variable	Comparison	Mean difference	Probability value	Result
Latent heat capacity	F1-F2	4.67 J/g	0.001	Significant
Latent heat capacity	F1-F3	2.03 J/g	0.101	Not significant
Latent heat capacity	F2-F3	6.70 J/g	< 0.001	Significant

Phase Transition and Thermal Stability Results

The mean phase transition temperatures ranged from 25.4°C to 25.7°C. The baseline formulation exhibited a mean transition temperature of 25.7°C, while F1, F2, and F3 exhibited mean values of 25.6°C, 25.5°C, and 25.4°C, respectively. The maximum difference among formulations was 0.3°C, indicating that all formulations remained within a comparable phase transition range. After repeated melting and solidification cycles, all formulations retained more than 98% of their initial latent heat capacity. F2 recorded the highest heat retention at 99.1%, followed by F1 at 98.9%, F3 at 98.8%, and F0 at 98.5%. No visible leakage, substantial phase separation, or structural deterioration was recorded during the cycling test. The mass loss recorded during thermogravimetric analysis remained below 1.5% within the intended building operating-temperature range.

Building Thermal Simulation Results

Five building scenarios were evaluated using identical geometry, envelope configuration, operating schedules, internal heat gains, and weather conditions. The reference scenario did not contain phase change material, while the remaining four scenarios incorporated F0, F1, F2, and F3 into the building envelope. Simulation outputs included maximum indoor temperature, indoor temperature fluctuation, peak cooling load, cumulative cooling demand, and building energy consumption.

Table 5. Building thermal simulation results

Scenario	Maximum indoor temperature (°C)	Temperature fluctuation (°C)	Peak cooling load (kW)	Cooling demand (kWh/day)	Energy consumption (kWh/day)
Reference building	33.8	8.1	5.80	42.6	39.8
Building with F0	32.7	6.8	5.35	39.7	37.3
Building with F1	32.1	6.2	5.12	38.3	35.9
Building with F2	31.4	5.5	4.80	36.7	34.1
Building with F3	31.7	5.8	4.92	37.4	34.8

All phase change material scenarios produced lower indoor temperatures, cooling loads, and energy consumption than the reference building. The F2 scenario recorded the lowest maximum indoor temperature at 31.4°C, representing a reduction of 2.4°C relative to the reference scenario. It also reduced indoor temperature fluctuation by 32.1%, peak cooling load by 17.2%, cumulative cooling demand by 13.8%, and energy consumption by 14.3%.

Table 6. Percentage improvement relative to the reference building

Scenario	Maximum temperature reduction (%)	Temperature fluctuation reduction (%)	Peak cooling-load reduction (%)	Cooling-demand reduction (%)	Energy-consumption reduction (%)
F0	3.3	16.0	7.8	6.8	6.3
F1	5.0	23.5	11.7	10.1	9.8
F2	7.1	32.1	17.2	13.8	14.3
F3	6.2	28.4	15.2	12.2	12.6

Identification of the Best-Performing Formulation

Although F3 achieved the highest thermal conductivity value of 0.310 W/m·K, this formulation did not provide the maximum latent heat storage capacity compared with F2. The F2 formulation demonstrated a more balanced thermophysical performance, with a thermal conductivity of 0.281 W/m·K, latent heat capacity of 183.9 J/g, and latent heat retention of 99.1%. Furthermore, the simulation analysis indicated that the building incorporating F2 achieved the most favorable improvements, including lower indoor temperature variations, reduced peak cooling demand, decreased cumulative cooling requirements, and lower energy consumption. Considering both experimental measurements and simulation outcomes, F2 was selected as the optimal formulation due to its balanced contribution to material performance and building energy efficiency.

Summary of Principal Results

The incorporation of additives into PCM formulations resulted in an improvement in thermal conductivity, with increases ranging from 14.4% to 47.5% compared with the baseline formulation. Among the evaluated formulations, F2 exhibited the highest latent heat storage capacity, whereas F3 showed the greatest enhancement in thermal conductivity. Statistical evaluation confirmed that the differences among formulations significantly affected both thermal conductivity and latent heat capacity. Despite variations in composition, all formulations maintained latent heat retention above 98% after thermal cycling, indicating good thermal stability. At the building scale, the simulation results revealed that the F2-based system provided the most effective performance, reducing the maximum indoor temperature by 2.4°C, peak cooling load by 17.2%, and overall energy consumption by 14.3% compared with the reference building.

DISCUSSION

The results demonstrate that variation in the phase change material formulation substantially influenced its thermophysical performance. Thermal conductivity increased by 14.4 percent, 33.4 percent, and 47.5 percent in the low-, medium-, and high-additive formulations, respectively, compared with the baseline formulation. This progressive increase supports the heat-transfer theory that conductive additives form additional pathways within the material matrix, thereby reducing internal thermal resistance during melting and solidification. The large eta-squared value of 0.958 further indicates that formulation differences accounted for most of the observed variation in thermal conductivity rather than random experimental variation. This finding is consistent with Bhamare et al. (2021), who emphasized that the thermal response of a building-integrated phase change material depends on the combined effects of its thermophysical properties and effective utilization of the phase transition process. Tripathi and Shukla (2024) similarly concluded that improving heat-transfer characteristics can increase the effectiveness of latent thermal storage within building-envelope components.

The medium-additive formulation produced the most balanced performance, with a thermal conductivity of 0.281 watts per meter-kelvin and a latent heat capacity of 183.9 joules per gram. Although the high-additive formulation achieved the highest conductivity of 0.310 watts per meter-kelvin, its latent heat capacity declined to 177.2 joules per gram and its building-level energy performance remained below that of the medium-additive formulation. This result indicates that maximizing conductivity does not necessarily produce the most effective thermal energy storage material because a non-phase-changing additive replaces part of the active storage component. Excessive additive content may also promote particle agglomeration or alter the continuity of the phase change process, thereby limiting the amount of energy stored per unit mass. The finding differs from the simple assumption that higher conductivity always improves building performance, but it agrees with Tunçbilek et al. (2022), who found that nanoparticle addition could reduce energy-saving performance when losses in latent heat capacity and thermal resistance exceeded the benefit of faster heat transfer. The medium-additive formulation therefore represents an optimum balance rather than the maximum value of a single thermophysical property.

The phase transition temperatures remained within a narrow range of 25.4–25.7 degrees Celsius, indicating that the conductive additive changed the heat-transfer rate without substantially shifting the thermal activation range. This condition is important because a phase change material must repeatedly cross its melting and solidification range to absorb and release useful latent heat under building operating conditions. Kishore et al. (2022) explained that fixed transition temperatures may restrict annual storage utilization when indoor settings and outdoor temperatures vary across seasons. The simulated hot and humid conditions in the present study apparently enabled sufficient thermal activation, as all material scenarios reduced indoor temperature fluctuations and cooling demand. Nevertheless, Kalbasi (2022) found that the same phase change

material can produce different or even opposing seasonal effects depending on climate, transition temperature, and the period used to evaluate energy savings. Consequently, the transition range identified in this study should be interpreted as suitable for the selected simulation conditions rather than universally optimal for all buildings and climates.

All formulations retained more than 98 percent of their initial latent heat capacity after repeated melting and solidification cycles, while the medium-additive formulation achieved the highest retention of 99.1 percent. The limited change in transition temperature, absence of visible leakage, and low mass loss suggest that the modifying process did not cause immediate thermochemical deterioration. These results support the potential use of the material in building envelopes, where repeated daily temperature changes require stable melting and solidification behavior. Katish et al. (2024) reported that selected organic phase change materials maintained stable transition temperatures and latent heat properties after as many as 10,000 accelerated thermal cycles. The similarity between these findings supports the theoretical expectation that a chemically compatible formulation can retain its thermal-storage function under repeated operation. However, the present cycling results remain preliminary because short-term laboratory stability does not directly establish durability over the full service life of a building component.

The building simulation showed that all phase change material formulations improved thermal performance relative to the reference building, but the medium-additive formulation produced the largest overall benefit. This formulation reduced maximum indoor temperature by 2.4 degrees Celsius, temperature fluctuation by 32.1 percent, peak cooling load by 17.2 percent, cumulative cooling demand by 13.8 percent, and energy consumption by 14.3 percent. These reductions indicate that the material increased the effective thermal inertia of the envelope by absorbing part of the incoming heat and delaying its transfer to the indoor space. Masood et al. (2023) similarly identified latent heat storage as an effective mechanism for shifting cooling demand and reducing unwanted temperature variations in cooling-dominated buildings. The results also demonstrate that building performance was determined by the combined effects of conductivity, latent heat capacity, transition temperature, and storage regeneration rather than by conductivity alone. The reported energy reduction should nevertheless be treated as scenario-specific because building geometry, weather conditions, envelope configuration, cooling settings, occupancy, and internal heat gains were held constant in the simulation.

The principal novelty of this study lies in the integration of material formulation, independently replicated thermophysical testing, inferential statistical analysis, and building thermal simulation within a single evaluation framework. Previous studies have often examined material enhancement or building-envelope performance separately, making it difficult to determine whether improvements measured at the material scale produce meaningful building-level energy benefits. The present approach demonstrates that the formulation with the highest conductivity was not the formulation that generated the greatest cooling-load and energy reductions. This finding

contributes theoretically by establishing that phase change material optimization is a multi-property problem involving heat-transfer rate, storage capacity, activation temperature, and cycling stability. Zhao et al. (2024) likewise identified formulation optimization, integration configuration, environmental compatibility, durability, and cost as interconnected factors affecting the effectiveness of phase change materials in buildings. Practically, the findings provide an initial basis for selecting a medium-additive formulation for walls, roofs, or ceilings when both thermal storage and building energy performance are considered.

Several limitations require critical consideration before the findings can be generalized or applied in construction. The use of only three independent replications per formulation limits statistical power, while the deterministic simulation was not validated against temperature, heat-flow, or electricity measurements from a physical test room. The type, particle size, precise concentration, dispersion quality, fire behavior, mechanical compatibility, toxicity, and economic cost of the conductive additive also require further evaluation. Future research should increase the number of independently prepared specimens, conduct several hundred to several thousand thermal cycles, and use microscopic and chemical analyses to detect agglomeration, degradation, or phase separation. Physical validation should be performed using instrumented building cells, followed by sensitivity analyses involving different climates, envelope positions, material thicknesses, orientations, ventilation rates, and cooling set points. Life-cycle cost and environmental assessments should ultimately be combined with thermophysical and energy analyses to determine whether the medium-additive formulation remains optimal when technical, economic, safety, and sustainability criteria are evaluated simultaneously.

CONCLUSIONS AND RECOMMENDATIONS

The results confirm that phase change material formulation significantly influences thermal conductivity, latent heat storage capacity, thermal stability, and building energy performance. Among the four formulations, the medium-additive formulation provided the best overall performance by achieving a thermal conductivity of 0.281 watts per meter-kelvin, a latent heat capacity of 183.9 joules per gram, and a latent heat retention rate of 99.1 percent. Its application in the building thermal model reduced maximum indoor temperature by 2.4 degrees Celsius, peak cooling load by 17.2 percent, cumulative cooling demand by 13.8 percent, and energy consumption by 14.3 percent compared with the reference building. These findings demonstrate that the most effective formulation is not necessarily the one with the highest thermal conductivity, but the one that provides the best balance among heat-transfer capability, latent heat storage capacity, transition temperature, and cycling stability.

The medium-additive formulation is therefore recommended for preliminary implementation in building-envelope components such as walls, roofs, and ceilings, particularly in cooling-dominated buildings. Its application should be accompanied by appropriate encapsulation, uniform additive

dispersion, and placement within envelope layers that allow complete melting and solidification cycles. Before large-scale implementation, prototype testing should be conducted to evaluate leakage resistance, mechanical compatibility, fire safety, thermal durability, economic feasibility, and environmental performance. Building designers should also adjust the formulation, layer thickness, and phase transition range according to climatic conditions, cooling schedules, and envelope configuration rather than applying one universal design.

ADVANCED RESEARCH

This study was limited by the use of three independent replications for each formulation, short-term thermal cycling, one standardized hot and humid weather dataset, and deterministic simulation without validation using a physical test room. In addition, the effects of additive particle size, dispersion quality, encapsulation method, mechanical properties, toxicity, fire behavior, and production cost were not fully evaluated. Future research should increase the number of independently prepared specimens, perform several hundred to several thousand thermal cycles, and validate the simulation using measured temperature, heat flux, cooling demand, and electricity consumption from instrumented building cells. Further studies should also compare different additive concentrations, phase change material thicknesses, envelope positions, orientations, climates, ventilation conditions, and cooling set points, followed by life-cycle cost and environmental assessments. These steps are necessary to determine whether the medium-additive formulation remains optimal under broader technical, economic, safety, and sustainability criteria.

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REFERENCES

- Aghoei, M. M., Astanbous, A., Khaksar, R. Y., Moezzi, R., Behzadian, K., Annuk, A., & Gheibi, M. (2024). Phase change materials as a passive system in the opaque building envelope: A simulation-based analysis. *Journal of Energy Storage*, 101, Article 113625. <https://doi.org/10.1016/j.est.2024.113625>
- Al-Yasiri, Q., & Szabó, M. (2022). Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot climate: An experimental study. *Applied Energy*, 314, Article 118957. <https://doi.org/10.1016/j.apenergy.2022.118957>

- Ali, H. M. (Ed.). (2024). *Phase change materials for thermal energy management and storage: Fundamentals and applications*. CRC Press. <https://doi.org/10.1201/9781003331957>
- Anand, A., Shukla, A., Kumar, A., Buddhi, D., & Sharma, A. (2021). Cycle test stability and corrosion evaluation of phase change materials used in thermal energy storage systems. *Journal of Energy Storage*, 39, Article 102664. <https://doi.org/10.1016/j.est.2021.102664>
- Bhamare, D. K., Rathod, M. K., & Banerjee, J. (2021). Proposal of a unique index for selection of optimum phase change material for effective thermal performance of a building envelope. *Solar Energy*, 218, 129–141. <https://doi.org/10.1016/j.solener.2021.02.027>
- Cabeza, L. F. (Ed.). (2020). *Advances in thermal energy storage systems: Methods and applications* (2nd ed.). Woodhead Publishing. <https://shop.elsevier.com/books/advances-in-thermal-energy-storage-systems/cabeza/978-0-12-819885-8>
- Duraković, B. (2020). *PCM-based building envelope systems: Innovative energy solutions for passive design*. Springer. <https://doi.org/10.1007/978-3-030-38335-0>
- Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2021). A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. *Journal of Energy Storage*, 33, Article 101913. <https://doi.org/10.1016/j.est.2020.101913>
- Farulla, G. A., Brancato, V., Palomba, V., Zhang, Y., Dino, G. E., & Frazzica, A. (2023). Experiments and modeling of solid–solid phase change material-loaded plaster to enhance building energy efficiency. *Energies*, 16(5), Article 2384. <https://doi.org/10.3390/en16052384>
- Fathi, M. (2024). Sustainability and energy efficiency in buildings: A review. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 16(2), Article 03123002. <https://doi.org/10.1061/JLADAH.LADR-1110>
- Feng, F., Fu, Y., Yang, Z., & O'Neill, Z. (2022). Enhancement of phase change material hysteresis model: A case study of modeling building envelope in EnergyPlus. *Energy and Buildings*, 276, Article 112511. <https://doi.org/10.1016/j.enbuild.2022.112511>
- Gao, Y., He, F., Meng, X., Wang, Z., Zhang, M., Yu, H., & Gao, W. (2020). Thermal behavior analysis of hollow bricks filled with phase-change material. *Journal of Building Engineering*, 31, Article 101447. <https://doi.org/10.1016/j.jobbe.2020.101447>
- Jha, S. K., Sankar, A., Zhou, Y., & Ghosh, A. (2024). Incorporation of phase change materials in buildings. *Construction Materials*, 4(4), 676–703. <https://doi.org/10.3390/constrmater4040037>
- Kahwaji, S., Johnson, M. B., & White, M. A. (2021). Thermal property determination for phase change materials. *The Journal of Chemical Thermodynamics*, 160, Article 106439. <https://doi.org/10.1016/j.jct.2021.106439>
- Kalbasi, R. (2022). Usefulness of phase change material in building applications focusing on envelope heat exchange: Energy saving considering two

- scenarios. *Sustainable Energy Technologies and Assessments*, 50, Article 101848. <https://doi.org/10.1016/j.seta.2021.101848>
- Katish, M., Allen, S., Squires, A., & Ferrandiz-Mas, V. (2024). Thermal stability of organic phase change materials by accelerated thermal cycling technique. *Thermochimica Acta*, 737, Article 179771. <https://doi.org/10.1016/j.tca.2024.179771>
- Kishore, R., Booten, C., Bianchi, M., Vidal, J., & Jackson, R. (2022). Evaluating cascaded and tunable phase change materials for enhanced thermal energy storage utilization and effectiveness in building envelopes. *Energy and Buildings*, 260, Article 111937. <https://doi.org/10.1016/j.enbuild.2022.111937>
- Kurdi, A., Almoatham, N., Mirza, M., Ballweg, T., & Alkahlan, B. (2021). Potential phase change materials in building wall construction – A review. *Materials*, 14(18), Article 5328. <https://doi.org/10.3390/ma14185328>
- Masood, U., Haggag, M., Hassan, A., & Laghari, M. (2023). A review of phase change materials as a heat storage medium for cooling applications in the built environment. *Buildings*, 13(7), Article 1595. <https://doi.org/10.3390/buildings13071595>
- Montgomery, D. C. (2020). *Design and analysis of experiments* (10th ed.). John Wiley & Sons. <https://books.google.com/books?id=kB7zDwAAQBAJ>
- Pirasaci, T. (2020). Investigation of phase state and heat storage form of the phase change material layer integrated into the exterior walls of the residential-apartment during heating season. *Energy*, 207, Article 118176. <https://doi.org/10.1016/j.energy.2020.118176>
- Podara, C. V., Kartsonakis, I. A., & Charitidis, C. A. (2021). Towards phase change materials for thermal energy storage: Classification, improvements and applications in the building sector. *Applied Sciences*, 11(4), Article 1490. <https://doi.org/10.3390/app11041490>
- Toifane, H., Tittlein, P., Cherif, Y., Zalewski, L., & Leuck, H. (2022). Thermophysical characterization of a thermoregulating interior coating containing a bio-sourced phase change material. *Applied Sciences*, 12(8), Article 3827. <https://doi.org/10.3390/app12083827>
- Tripathi, B. M., & Shukla, S. K. (2024). A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials. *Journal of Energy Storage*, 79, Article 110128. <https://doi.org/10.1016/j.est.2023.110128>
- Tunçbilek, E., Arıcı, M., Krajčík, M., Li, Y., Jurčević, M., & Nižetić, S. (2022). Impact of nano-enhanced phase change material on thermal performance of building envelope and energy consumption. *International Journal of Energy Research*, 46(14), 20249–20264. <https://doi.org/10.1002/er.8200>
- Veanti, D. P. O., Virgianto, R. H., & Astiduari, I. G. A. P. P. (2022). The impact of climate change on cooling energy demand in Indonesia based on representative concentration pathways scenarios. *Science and Technology Indonesia*, 7(1), 9–16. <https://doi.org/10.26554/sti.2022.7.1.9-16>

- Wu, S., Yan, T., Kuai, Z., & Pan, W. (2020). Thermal conductivity enhancement on phase change materials for thermal energy storage: A review. *Energy Storage Materials*, 25, 251–295. <https://doi.org/10.1016/j.ensm.2019.10.010>
- Zhao, S., Ming, T., Wu, Y., Cai, C., Yin, K., de Richter, R., Fang, Y., Chen, Y., & Zhou, N. (2024). Application research and effectiveness analysis of phase change materials in building envelope: A review. *Energy and Buildings*, 324, Article 114923. <https://doi.org/10.1016/j.enbuild.2024.114923>