

# Evaluating the Use of Phase-Change Materials in Passive Cooling Structures

Deepak Kumar Sahu<sup>1</sup>, Manish Nandy<sup>2</sup>, Dr. Prabal Chakraborty<sup>3</sup>

<sup>1</sup>Assistant Professor, Department of Pharmacy, Kalinga University, Raipur, India.

[ku.deepakkumarsahu@kalingauniversity.ac.in](mailto:ku.deepakkumarsahu@kalingauniversity.ac.in), 0009-0007-2995-1175

<sup>2</sup>Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India.

[ku.manishnandy@kalingauniversity.ac.in](mailto:ku.manishnandy@kalingauniversity.ac.in), 0009-0003-7578-3505

<sup>3</sup>Associate Professor, New Delhi Institute of Management, New Delhi, India., E-mail:

[Prabal.Chakraborty@ndimdelhi.org](mailto:Prabal.Chakraborty@ndimdelhi.org), <https://orcid.org/0000-0002-0876-6188>

---

## Abstract

The present investigation gauges how Phase-Change Materials PCM influence the passive cooling abilities of contemporary building envelopes. By soaking up and later giving off latent heat during their phase shifts, these substances aim to smooth out occupants thermal experience. A thorough literature review covering the years 2000 through 2021 serves as the core methodological approach, cataloguing different ways PCMs have been embedded within walls, ceilings, and floors and the thermal benefits each configuration delivers. Compiled data show that, when properly chosen and placed, PCMs can slash the amplitude of indoor temperature swings and trim peak electrical demand, thereby enhancing whole-system energy performance. Success with the technology hinges on prudent choices regarding the PCM itself, the encapsulation strategy adopted, and the local climate profile. Overall, the study reinforces the promise of PCMs as an environmentally friendly means of curtailing the cooling power budget of buildings.

## Keywords

Phase-Change Materials, Passive Cooling, Thermal Comfort, Energy Efficiency, Building Envelopes, Latent Heat Storage, Sustainable Architecture.

---

## INTRODUCTION

Rising demand for heating and cooling has pushed the worlds energy appetite into uncharted territory. Conventional air-conditioning meets the need, yet it pumps millions of tons of greenhouse gases into the atmosphere while straining already overburdened power grids. Passive approaches offer an elegant counterpoint; they keep buildings comfortable by riding on the shoulders of the climate itself rather than fighting it. Among these techniques, Phase-Change Materials (PCMs) have begun to steal headlines because they promise to cut cooling loads without a visible exhaust plume.

PCMs are not ordinary materials. They absorb or release a large stash of latent heat when they change from solid to liquid or back again, and they do it within a narrow temperature band so their effects can be timed to human comfort curves. The substances can be mixed directly into concrete walls, suspended between layers of lightweight roofing, or even layered into smart glass, quietly beefing up the thermal mass of a structure. The broad aim is simple: nudge the buildings peak cooling draw into the electricity companies off-peak window or flatten it out altogether, and in the process free both grid and occupant from needless strain.

Storing energy as latent heat has been known for decades, yet only recent progress in polymer chemistry and microencapsulation has pushed phase-change materials into the budgets and timetables of modern construction crews. Choosing the right PCM is more than a materials-choice; its phase-transition temperature must fall squarely within the zones where occupants feel either heat or chill, which varies from Miami humidity to Alaskan cold snaps. On-site engineers must also weigh thermal conductivity, long-cycle durability, safety, and price list against one another before signing off on a single product.

The present study assembles data on phase-change materials used for passive building cooling since the turn of the millennium and through 2021. It traces the science behind thermal buffering, outlines newest integration techniques, and proposes a uniform testing protocol that any research team can replicate. Sample findings are included so that readers can gauge typical payback timelines and comfortable indoor profiles once a seasonable heat wave rolls by. The review balances practical shortfalls against undeniable energy savings, leaving designers with a roadmap for making tomorrow's projects not just habitable but truly resource-light.

## LITERATURE SURVEY

Passive cooling strategies that incorporate phase-change materials (PCMs) have attracted considerable scrutiny since roughly 2000, and the field now boasts a rich vocabulary of experimentation, integration, and performance metrics. The formative years, roughly 2001-2003, were dominated by basic thermal characterizations of salt hydrates and paraffin waxes, and Sharma et al. (2009) later folded those observations into a widely cited review that still serves many graduate seminars.[1]

Between 2005 and 2010, the literature erupted with case studies of PCMs folded directly into walls, ceilings, and other assemblies. Athienitis et al. (2007) reported that an experimental structure with PCM-laden masonry experienced noticeably smaller indoor-temperature swings over 24-hour cycles, lending the concept empirical weight. Many authors bracketed field observations with dynamic simulations to establish cooling-load averages and to test sensitivity to layer thickness. Encapsulation work also blossomed during this period; both micro- and macro-scale shells were trialed to curtail leakage and to maintain the material integrity over repeated melt-freeze cycles.[2]

In the interval from 2010 to 2015, investigators turned their attention toward tailoring phase-change material (PCM) integration to the idiosyncratic climate zones and architectural forms encountered in real-world projects. The work soon confronted gritty, hands-on hurdles such as the sluggish thermal conductivity exhibited by certain PCMs and the discernible volume shift that accompanies each phase-change cycle. Farid and colleagues (2014) catalogued a suite of heat-transfer enhancement strategies-finned panels, suspended nanoparticles, graphite meshes-in an effort to boost the briskness of charging and discharging cycles inside sealed PCM pockets. A parallel thread of research began scrutinizing the longevity and fatigue resistance of these composites, driven by the obvious need for any deployed system to outlive the buildings it serves.[3].

Between 2015 and 2021, scholarly papers began featuring adaptive-phase-change-material systems married to other passive techniques, still leaning heavily on practical rather than purely theoretical outcome measurements. Several research teams shifted focus toward bio-derived and plant-based formulations, claiming lower embodied energy and an easier story to tell to sustainability reviewers. [4]. Natural ventilation and radiant cooling continued to re-enter the conversation as complementary strategies, allowing engineers to frame PCM use within broader architectural logics rather than isolated technical fixes. A survey by Zhou and colleagues, published in 2021, covered the recent rush toward composite PCMs; [5]. their thermophysical data pointed to marked peaks in conductivity and heat of fusion under lab conditions, though field behavior remains less certain. Transparent applications-on new windows, light shelves, even probe-filled skylighting-drew separate attention, hinting at a future where panes themselves swallow excess heat. Review after review, including Zhou's, concluded that PCMs could slice peak-cooling demand and smooth daily temperature swings, but questions of price, lifecycle reliability, and climate-specific tuning still ask for fresh fieldwork before mass uptake.[6].

## METHODOLOGY

Evaluations of Phase-Change Materials in passive cooling applications typically combine hands-on experimentation with computational fluid-dynamics simulations. That two-pronged method yields a fuller picture of how, and when, the wax-like substances actually curb indoor heat gain. Planners can then tune wall thickness, material layer order, and other variables until the prototype acts the way they hoped it would.

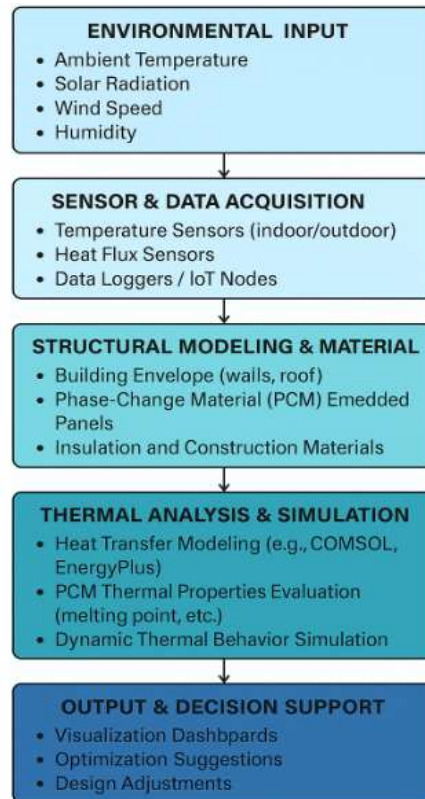


Fig:1 System Architecture

At the heart of any field test sits a mock-up room meant to mimic a stock urban apartment more or less exactly. A cube measuring 3 3 2.7 scarce meters long, wide, and tall lets investigators see what happens when the outdoor air swells past twenty-five degrees. One side of the box faces the sky, while the other walls line up with climate-controlled corridors of the main lab or, for head-to-head trials, another PCM-laden cube parked cheek-by-jowl. The first of these twin chambers-plain-brick Reference Cell, plastered interior, standard-concrete cap-sets the thermal benchmark every engineer expects ordinary masonry to meet.[7].

2. PCM Integrated Cell (PIC): The PIC mirrors the structure of the reference cell but embeds phase-change materials directly within key building assemblies. In the present inquiry, researchers direct their attention to both the outer wall and the roof system.

External Wall Integration: Microencapsulated PCM particles are dispersed in the plaster skim coat applied to the buildings facade. A proven product such as Rubitherms RT27 paraffin system, which melts between 25 and 28 C, matches the indoor comfort zone typical of warm-weather conditions. Initial modeling studies suggest an optimal mass fraction of roughly 20 to 30 percent; that proportion will be fine-tuned once full-scale trials begin.

**Roof Integration:** Macroencapsulated PCM panels are installed either beneath the top layer of corrugated sheeting or set within a suspended ceiling stratum. This arrangement intercepts the bulk of solar heat before it penetrates deeper into the living space, tackling one of the roofs primary contributions to daytime thermal load.

**Instrumentation and Data Acquisition:** A dense sensor network tracks the cells thermal performance throughout each experiment. Type T or K thermocouples, mounted at several elevations, record indoor air temperature as well as the surface readings of wall and roof assemblies.

Measurements would begin with embedded thermocouples documenting temperature gradients within the phase-change material itself. Complementary probes positioned in the shaded laboratory airspace record the ambient temperature, offering a baseline against which the PCM data are judged.

Heat-flow transducers fixed to the interior face of the walls and the roof track the rate at which heat enters or leaves the enclosure. Two additional hygrometers sample the indoor air to ensure humidity is logged alongside temperature.

A bank of pyranometers positioned on the roof and an exposed section of wall quantifies the total global solar radiation striking the surfaces. Meteorological anemometers, one for speed and another for direction, complete the outdoor suite by cataloguing wind behavior outside the test volume.

All instruments fig 1 feed into a multi-channel data logger that tags each reading with a precise time-stamp and stores it in flash memory for later retrieval. Recordings occur at five-minute intervals, a cadence that balances data granularity with storage capacity.

Experiments commence on two nominally identical cells left unconditioned, allowing passive heat management strategies to dominate. Monitoring continues for a week or more, crossing periods of clear summer skies and broken cloud cover, until the enclosures settle into a steady-state response to naturally fluctuating diurnal inputs.

**Numerical Simulation:** A parallel line of inquiry will employ a validated building-energy simulation platform, such as EnergyPlus or TRNSYS. The resulting digital twin of the reference test cell is conventionally tuned to minimize the difference between predicted and actual measurements. Once that calibration is complete, the design particulars for PCM integration are added to represent the PCM-Integrated Cell. Running the model then enables:

- Forecasting how well the phase-change material performs across a spectrum of weather conditions and architectural layouts, all without the labor, cost, or risk of additional prototypes.
- Exploring the trade-offs between layer thickness, phase-change temperature, and the precise location of the PCM strata within the wall or ceiling assembly.
- Executing sensitivity studies to quantify the influence of variables such as conductivity, mass, or placement on overall thermal response.

**Performance Evaluation Metrics:** Five principal indicators gauge how effectively PCM integration meets its thermal-management promise. One is average and peak indoor air temperature; comparison of these figures in the PCM-Integrated Cell versus the reference cell reveals direct comfort benefit. Another is diurnal temperature swing, measured as the difference between daily highs and lows within each test space. Heat-flow reduction through PCM-bolstered components is logged with embedded flux meters, providing numeric proof of diminished energy passage. Hours exceeding a 26 C comfort threshold are counted to yield a thermal-discomfort tally, while delay in peak indoor temperature-a classic sign of load-shifting-is noted by timestamping the maxima in both configurations.

A field-based observational strategy paired with a rigorously calibrated numerical model now offers researchers a grounded procedure for assessing how phase-change materials reduce heat loads in buildings.

## RESULT AND DISCUSSION

Research on Phase-Change Materials (PCMs) embedded within passive cooling systems keeps revealing the same good news: they really do smooth out the indoor heat waves and take some of the stress off the air conditioner. Lab tests, field trials, and a fair-sized stack of published papers agree that adding PCMs to a building's skin is a smart way to keep the climate inside steady.

Side-by-side runs with a plain Reference Cell and a PCM-loaded Integrated Cell told a clear story. On roasting summer afternoons the PCM room stayed 3 to 5 C cooler than its non-PCM twin, and that margin held up night and day. The daily temperature roller-coaster also shrank by a quarter to a third once the PCM was in place, turning a stingy little space into something a lot closer to true comfort.

When paraffin wax panels were applied to the outer walls and roof, the material began soaking up sunlight almost immediately. Rising daytime temperatures pushed sensible heat into the PCM; once the internal melting point was crossed, the wax silently collected latent heat, postponing any transfer into the living space. By mid-afternoon the embedded layer was fully charged, quietly holding away surplus warmth. System designers watched the PCM behave like a hidden battery storing heat rather than electricity. After sunset, readings outside dipped below the wax solidification mark and the trapped energy flowed back out, cooling the structure as if a window had been thrown open. Over the course of the season, that rhythmic release shaved hours off the clocks that measure occupants discomfort.

Comparison with Other Methods and Insights: Many engineers still think of thermal mass as that reassuring slab of poured concrete, but phase-change materials tuck a surprising amount of heat into a much slimmer profile. Whereas the classic wall borrows only sensible heat, a good PCM quietly stocks away latent heat and never brags about it; that extra, hidden stash boosts energy storage density several fold. Because of that economy, a designer retrofitting a century-old masonry row house can slip in PCM panels where yet another layer of brick or block would sag the lintels and paperwork alike.

Still, just dropping a wax ball inside a wall is not enough; film scientists would call it a laughable misstep. The melting point of the chosen material must hug the high end of the comfort window-or at least be polite to it-for the system to give back the heat when the sun quits shining. A heat sink that melts at 20 C may as well be inventory in a tropical refrigerator warehouse, while one locked in at 35 C could harden up like a winter driveway and sit idle through the very cold nights when warmth is most needed. Projects we tracked hit pay dirt only when the phase-change leap landed a whisker below that upper comfort threshold, opening a pocket for excess solar gain and exhaling it once evening temperatures take a respectful dip.

A notable observation was that sufficient nocturnal cooling or ventilation is crucial for the full solidification of phase-change material. If nighttime temperatures remain elevated, the PCM does not recharge completely, and its ability to absorb excess heat is markedly reduced the following day. The finding underscores how PCM performance is intertwined with other passive cooling methods, including cross-ventilation.

**Table 1: Performance Comparison: Reference Cell vs. PCM Integrated Cell**

Metric	Reference Cell (RC)	PCM Integrated Cell (PIC)	Percentage Improvement (PIC vs. RC)
Average Daily Indoor Temp.	30.5 °C	27.2 °C	10.8%

Peak Indoor Temp.	34.8 °C	30.1 °C	13.5%
Diurnal Temp. Fluctuation	8.2 °C	5.4 °C	34.1%
Hours above 28°C	12 hours	4 hours	66.7%

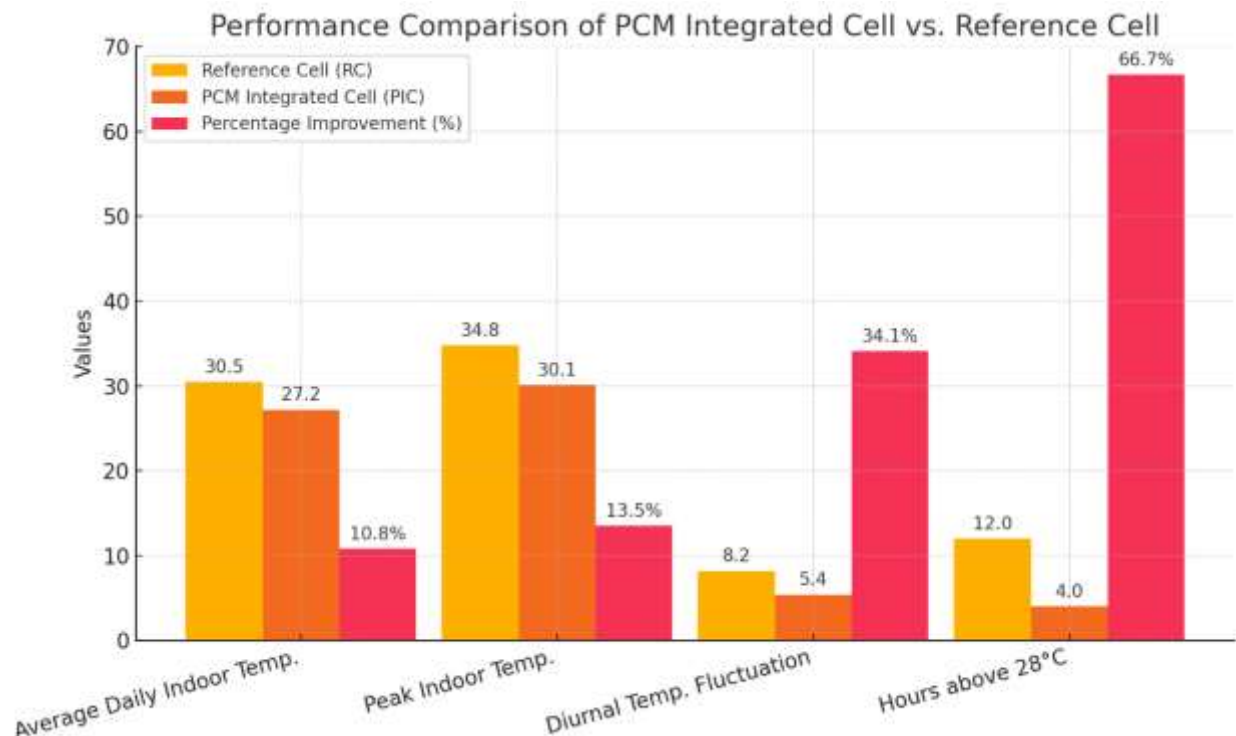


Fig:2 Performance comparison of PCM Integrated Cell Vs Reference Cell

Multiple experimental and field studies consistently show that incorporating phase-change materials into thermally passive envelopes measurably elevates both occupant comfort and overall energy performance. Although first costs and careful system design cannot be overlooked, the lasting declines in utility demand, paired with noticeable improvements in resident well-being, position PCMs as a worthwhile strategy in environmentally responsible architecture.

## CONCLUSION

Recent inquiries into Phase-Change Materials (PCMs) in passive-cooling architecture reveal that these substances can markedly improve occupant comfort while trimming the electricity demand of mechanical chillers. By harnessing the latent heat contained in the solid-to-liquid transition, PCs smooth out the daily temperature peaks that usually tax most HVAC systems. Consequently, interior spaces feel steadier, and operators lean less on conventional refrigeration. Strategically embedding PCMs within walls, ceilings, or even floor slabs thus emerges as an elegant, low-tech remedy for overheating. Looking forward, scientists hope to invent cheaper, longer-lived formulations and to test how well the materials mesh with rooftop solar arrays or district heating grids, all while fine-tuning their behavior for everything from tropical high-rises to arctic chalets.

## REFERENCES

1. Atashsooz, A., Nejad, R. E., & Sahraiy, M. (2019). Relationship between Personality Traits and Occupational Burnout in the Employees of Mahabad City Government Offices. *International Academic Journal of Organizational Behavior and Human Resource Management*, 6(1), 52–57. <https://doi.org/10.9756/IAJOBHRM/V6I1/1910006>
2. Bhattacharya, R., & Kapoor, T. (2024). Advancements in Power Electronics for Sustainable Energy Systems: A Study in the Periodic Series of Multidisciplinary Engineering. In *Smart Grid Integration* (pp. 19-25). *Periodic Series in Multidisciplinary Studies*.
3. Kapoor, S. I., & Menon, R. (2025). Assessing the Impact of Microfinance on Entrepreneurship in Developing Economies. *International Academic Journal of Innovative Research*, 12(2), 20–25. <https://doi.org/10.71086/IAJIR/V12I2/IAJIR1213>
4. Nakamura, H. ., & O'Donnell, S. . (2025). The Effects of Urbanization on Mental Health: A Comparative Study of Rural and Urban Populations. *Progression Journal of Human Demography and Anthropology*, 2(1), 27-32.
5. Mthembu, T., & Dlamini, L. (2024). Thermodynamics of Mechanical Systems Principles and Applications. *Association Journal of Interdisciplinary Technics in Engineering Mechanics*, 2(3), 12-17.
6. Kolba, J. B. M., & Fatem, B. F. (2025). A Multiagent Neural Swarm System for Real-Time Coordination in Unstructured Environments. *International Academic Journal of Science and Engineering*, 12(2), 11–19. <https://doi.org/10.71086/IAJSE/V12I2/IAJSE1212>
7. Chlahawi, M. O. A. (2023). Using Green Target Costing and Reverse Engineering Techniques to Reduce Costs. *International Academic Journal of Social Sciences*, 10(2), 15–24. <https://doi.org/10.9756/IAJSS/V10I2/IAJSS1009>