END-SEMESTER REPORT

CP302

Capstone Project 01

Topic:

Designing of an Energy-efficient building using EnergyPlus

Under the guidance of -

Dr. Navaneeth K Marath & Dr. Devranjan Samanta Assistant Professors, Department of Mechanical Engineering, IIT Ropar

Submitted by

CHAHAT	2022MEB1046
MILI PRAJAPATI	2022MEB1325
PALAKPREET KAUR	2022MEB1327

CONTENT

1. Introduction

Buildings contribute significantly to global energy consumption, with heating and cooling demands playing a crucial role. Selecting appropriate building materials can enhance energy efficiency, especially in diverse climatic conditions (Figure 1). This study evaluates the thermal performance of buildings in four different climate zones using EnergyPlus, a powerful building energy simulation tool. The selected climates are:

- **Jaipur (Hot and Dry):** High temperatures with low humidity lead to excessive cooling requirements.
- **Delhi (Composite):** Experiences both extreme summers and winters, demanding balanced insulation.
- **Srinagar (Cold and Cloudy):** Predominantly low temperatures require effective heat retention.
- **Chennai (Warm and Humid):** High humidity and consistent warmth make ventilation and moisture control critical.

The primary objective is to identify materials that minimize cooling load while maintaining indoor comfort. The study begins with conventional materials like brick, concrete, and air gaps—widely used in construction—before shifting focus to advanced materials such as:

Phase Change Materials (PCM): These store and release latent heat during phase transitions, aiding temperature regulation.

To conduct a detailed and accurate thermal analysis, EnergyPlus is utilized. This software is well-suited for the study because it allows precise simulation of heat transfer, thermal mass, and material properties under different climatic conditions. By modeling buildings with different materials, EnergyPlus helps in quantifying cooling load variations, enabling data-driven selection of the most efficient materials. The insights gained will contribute to climate-responsive, energy-efficient building design, supporting sustainable urban development.

Type	Climate	Relative humidity (%)	Mean monthly temperature (°C)
I	Hot and dry	<55	>30
II	Warm and humid	>55	>30
III	Moderate	<75	25–30
IV	Cold and cloudy	>55	>25
V	Cold and sunny	<55	>25
VI	Composite	This applies when six months or more do not fall within any of the above categories	

Fig 1) Criteria for climatic zones in India

2. Objectives

The key objectives of this study are:

1. **Understanding EnergyPlus and Climate Impact** – Learning EnergyPlus software for thermal performance simulation and analyzing the influence of different climatic conditions on energy demand.
2. **Evaluating Construction Materials** – Comparing conventional (brick, concrete, air gap) and advanced (PCM) materials to determine their thermal efficiency.
3. **Optimizing Cooling Load and Material Selection** – Identifying the most efficient materials for each climate while exploring a common composition suitable for all four climates.
4. **Ensuring Sustainability and Cost-Effectiveness** – Assessing eco-friendly, durable, and economically viable insulation materials for large-scale construction.
5. **Promoting Energy-Efficient Building Design** – Providing insights for sustainable construction practices to reduce energy consumption and enhance thermal comfort.

3. Problem Description

With the increasing global emphasis on sustainable development, reducing the energy consumption of buildings has become a critical challenge. A significant portion of a building's energy demand comes from heating and cooling, which varies greatly depending on the climate, building materials, and insulation techniques used. In regions with extreme temperatures, inefficient building materials lead to high energy consumption, increased carbon footprint, and higher operational costs.

Traditional construction materials like brick, concrete, and air gaps offer some insulation but often fail to provide optimal thermal comfort in all climatic conditions. Conventional insulation materials such as Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS) are widely used in building envelopes due to their good thermal resistance and low cost. However, they come with certain limitations — they provide only passive insulation, lack thermal storage capacity, and often degrade over time due to moisture absorption or long-term exposure to temperature fluctuations. Moreover, they are petroleum-based and not environmentally sustainable in the long run.

In contrast, Phase Change Materials (PCMs) offer dynamic thermal management by absorbing and releasing latent heat during phase transitions, thereby actively regulating indoor temperatures. This not only improves thermal comfort but also reduces reliance on mechanical cooling and heating, making PCMs a more sustainable and efficient solution, especially for climates with high temperature variation, like that of Jaipur. Advanced materials such as Phase Change Materials (PCM) have shown potential in regulating indoor temperatures, yet their performance varies across different climates. Moreover, the economic feasibility and sustainability of these materials need further exploration.

This study aims to address these challenges by:

- Evaluating the thermal performance of buildings in four different climates (Jaipur, Delhi, Srinagar, Chennai).
- Identifying cost-effective and sustainable insulation materials to reduce cooling loads and improve thermal efficiency.
- Exploring whether a common material composition can work efficiently across all climate zones.

- Utilizing EnergyPlus to simulate and analyze heat transfer, cooling demand, and material properties for better decision-making in construction.

This study's findings will help design energy-efficient buildings that minimize cooling requirements, reduce environmental impact, and promote sustainable urban development.

4. Background and Literature Review

Paper 1:

Quantitative Assessment of Phase Change Material Utilization for Building Cooling Load Abatement in Composite Climatic Condition. Authors: Rajat Saxena, Kumar Biplab, Dibakar Rakshit. Objective: This study evaluates the potential of PCMs in reducing cooling loads in buildings under the climatic conditions of New Delhi.

Key Findings: Buildings account for 48% of total energy consumption, with a significant portion used for cooling. Three commercial PCMs were analyzed (HS29, HS34, and OM32) to determine their efficiency. HS34, with a melting/solidification temperature of 34°C, was found suitable based on mathematical modeling but exhibited supercooling issues, making it less effective in peak summers.

The study highlights the importance of proper PCM selection for effective thermal energy storage.

Paper 2:

Phase Change Materials (PCM) for Cooling Applications in Buildings: A Review Authors: Sarah Souayfane, Farouk Fardoun, Pascal-Henry Biwole Objective: To provide an overview of PCM applications in building cooling and factors affecting their efficiency.

Key Findings: PCMs help minimize peak cooling loads and stabilize indoor temperatures. Common challenges include incomplete solidification at night, limiting daytime effectiveness. Solutions involve optimized PCM selection, encapsulation methods, and integration techniques. Discusses various PCM applications such as free cooling and ventilated facades. Highlights the importance of choosing the right PCM based on climate and application type.

Paper 3:

Energy Performance of Phase Change Materials Integrated into Brick Masonry Walls for Cooling Load Management.Author: Aakash C. Rai.Objective: To analyze PCM integration in residential buildings’ brick masonry walls for cooling load management.

Key Findings:

PCM reduces cooling load fluctuations but is ineffective in overall cooling load reduction. Proper PCM positioning (on the inner side of walls with insulation shielding) is critical for efficiency. The melting temperature should align with indoor set-point temperature for maximum benefit. Numerical simulations indicate that PCM-based solutions should be compared with conventional insulation techniques for cost-effectiveness.

So overall what we conclude from these research paper and also tried to apply in our simulations is

- The study highlights that *maximum heat gain* occurs through the *roof*, and PCMs are most effective in reducing indoor temperature fluctuations during summer. When the ambient temperature aligns with the PCM’s phase change point, significant latent heat storage occurs.

- PCM-enhanced insulation can effectively reduce and *shift peak thermal loads*, especially when installed as *inner wallboards*. Night ventilation and proper placement of PCM improve performance, but selecting the right melting temperature is critical for comfort.
- The study explored six wall configurations using a *10 mm PCM layer*, as it's considered optimal**. *Positioning PCM on the inner side*** with insulation on the outer side significantly reduces heat gain and maximizes latent heat utilization, especially for *west-facing walls* exposed to peak solar radiation.

Other Common Materials and Their Limitations

- **Polystyrene Foam and Its Limitations**

Polystyrene Foam is a lightweight, synthetic polymer commonly used for insulation and packaging (source).

Limitations:

- Environmental Concerns: Polystyrene foam is non-biodegradable and can persist in the environment for hundreds of years (source).
- Health Risks: Polystyrene contains styrene, a chemical linked to health issues such as cancer and neurological effects (source).
- Flammability: Polystyrene is highly flammable and can pose fire hazards if not properly managed (source).
- Brittleness: Polystyrene foam is prone to cracking and breaking under stress, limiting its durability (source).
- Poor Heat Resistance: Polystyrene has a low maximum service temperature, making it unsuitable for high-temperature applications (source).

- **Fiberglass Insulation:**

- Health Concerns: Inhalation of fiberglass particles can cause respiratory issues and skin irritation (source).
- Moisture Sensitivity: Fiberglass can absorb moisture, reducing its insulating effectiveness over time (source).
- Compression Over Time: Fiberglass can settle or compress, leading to decreased insulation performance (source).

- **Polyurethane Foam:**

- Cost: Polyurethane foam is generally more expensive than traditional insulation materials (source).
- Chemical Emissions**:** It can emit volatile organic compounds (VOCs), affecting indoor air quality (source).
- Flammability: Requires additional fire-resistant coatings to meet safety standards (source).

- **Aerogel:**

- High Cost: Aerogel production is expensive, limiting its widespread use (source).
- Fragility: Aerogel is brittle and can break under mechanical stress (source).
- Handling Challenges: Requires careful handling and installation due to its delicate nature (source).

5. Terminology

1. EnergyPlus – EnergyPlus is a building energy simulation software developed by the U.S. Department of Energy (DOE) to analyze thermal performance, heating/cooling loads, and energy consumption in buildings. It integrates real-world weather data and material properties to provide accurate simulations.

Key Features

- Thermal Load Calculation – Determines heating and cooling requirements.
- Material and Construction Analysis – Evaluates insulation effectiveness.
- Weather Data Integration – Simulates real climatic conditions.
- Ideal Loads Air System – Estimates cooling loads without full HVAC modeling.

Application in This Study

EnergyPlus was used to simulate cooling loads for a standard building model (BESTEST Case 600) across Jaipur, Delhi, Srinagar, and Chennai. It provided insights into:

- Cooling demand variations across climates.
- Impact of material properties on energy efficiency.
- Annual and peak cooling energy consumption.

The results help in selecting optimal materials for climate-responsive, energy-efficient buildings.

2. Phase Change Materials (PCM)

Phase Change Materials (PCMs) are substances that store and release thermal energy during phase transitions (solid to liquid and vice versa). When the temperature rises, they absorb excess heat, and when the temperature drops, they release stored heat, helping maintain stable indoor temperatures (Figure 4). PCMs are used in building materials like wallboards, plaster, and insulation panels (Figure 2) to reduce cooling and heating loads, making buildings more energy-efficient.

Fig.2) PCM Board

Below there is classification of PCMs:

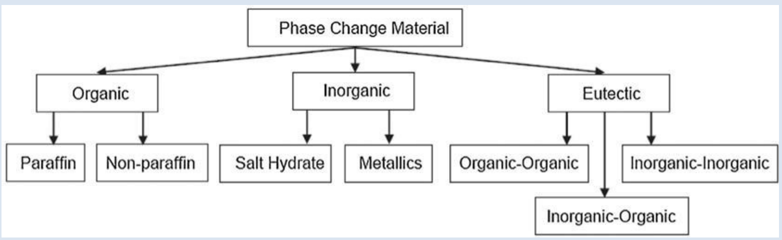


Fig. 3) PCM Classification

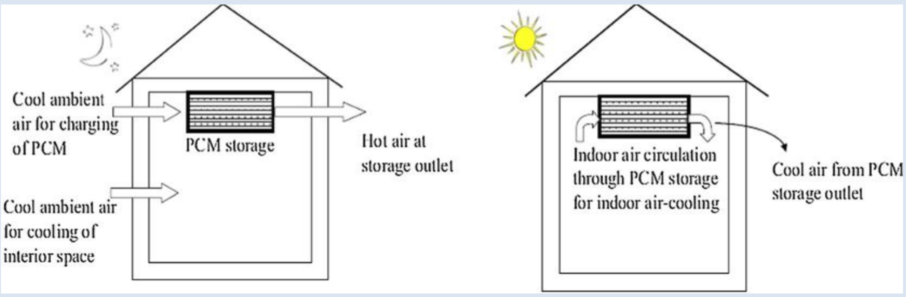


Fig. 4) Principal function of PCM "free cooling system"

3. Cooling Load – The amount of heat energy that must be removed from a space to maintain a desired indoor temperature.

4. Ideal Load HVAC System

In EnergyPlus, the Ideal Loads Air System represents a theoretical HVAC system with unlimited heating and cooling capacity. It delivers the exact amount of energy required to maintain the set indoor conditions without considering real-world constraints like system efficiency, duct losses, or equipment limitations. This system is primarily used for building energy analysis, allowing designers to evaluate heating and cooling loads without specifying an actual HVAC system. It helps in:

- Assessing thermal performance of different building materials and passive design strategies.
- Estimating baseline HVAC loads for selecting an appropriate real-world system.
- Comparing energy-efficient designs by analyzing the impact of insulation, shading, glazing, and ventilation.
- For this study, the Ideal Loads Air System serves as a reference to determine the heating and cooling demand of the proposed building model in Jaipur's climate, facilitating a better understanding of energy-efficient material performance.

5. Thermal Mass – The ability of a material to absorb, store, and release heat over time, affecting indoor temperature stability.

   Thermal mass ($J/m^2.K$) : density x specific heat x thickness (related to sensible heat)

   So, for PCMs, HS22P = 54480, HS24 = 59437, and OM29 = 34612.5 in J/m^2-K
6. U-Factor (Thermal Transmittance) – A measure of how well a material conducts heat; lower values indicate better insulation.
7. Solar Heat Gain Coefficient (SHGC) – The fraction of solar radiation admitted through a window, affecting cooling demand.
8. Latent Heat Storage – The process where energy is absorbed or released during a phase change without changing temperature.
9. Air Gap Insulation – The use of trapped air layers within walls to improve thermal resistance and reduce heat transfer.
10. Sustainable Insulation Materials – Materials designed to improve thermal efficiency while being eco-friendly, such as PCM, bio-based composites, and aerogels.

6. Methodology

To analyze the thermal performance of different construction materials across multiple climatic conditions, we used EnergyPlus to simulate the cooling loads of a standard house model. The methodology involves defining a baseline model, applying different material configurations, and conducting simulations using *climate-specific weather data*.

1. House Model Geometry

A standard building model was created in EnergyPlus with predefined dimensions and structural elements. The model specifications are (Figure 5):

- Dimensions: 8m (length) × 6m (width) × 2.7m (height)
- Windows: Two windows (3m × 2m each) on the front wall
- Window Positioning: 0.2m from the bottom, 0.5m from the sides, and 1m apart from each other.
- Baseline Wall Materials: Brick, concrete, and air gaps.

This configuration provides a controlled setup for evaluating the impact of different insulation materials on cooling loads.

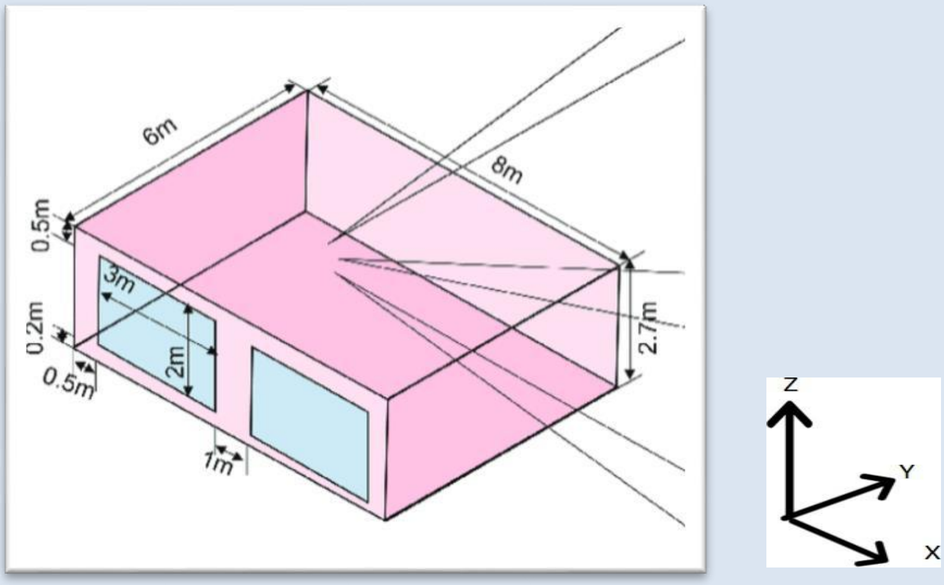


Fig.5) Geometry of BESTEST case 600 in the EnergyPlus simulation.

2. Climate Zones Considered

The study covers four distinct climatic regions in India:

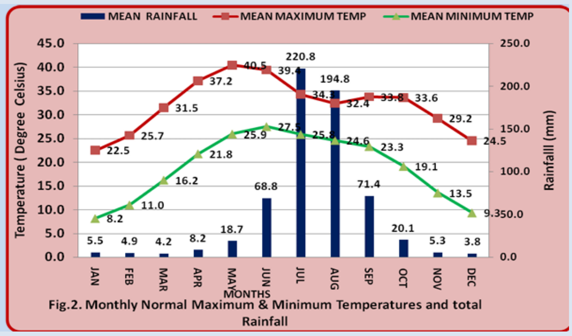
- Jaipur (Hot and Dry) – High temperatures, low humidity, and strong solar radiation
- Delhi (Composite) – Experiences extreme summer and winter conditions
- Srinagar (Cold and Cloudy) – Cold temperatures with significant heating demand
- Chennai (Warm and Humid) – High humidity and consistent warm weather

Weather data files were used in EnergyPlus to ensure realistic environmental conditions for each region.

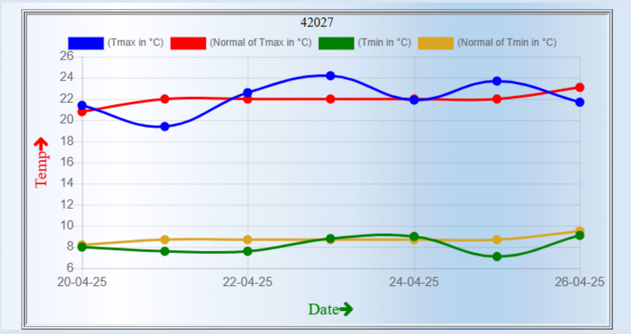
Table 1: Coordinates and elevation of the locations.

Site Location	Jaipur	Srinagar	New Delhi	Chennai
Latitude	26.92	34.08	28.58	13
Longitude	75.82	74.83	77.2	80.18
Time zone	5.5	5.5	5.5	5.5
Elevation	390	1587	216	16

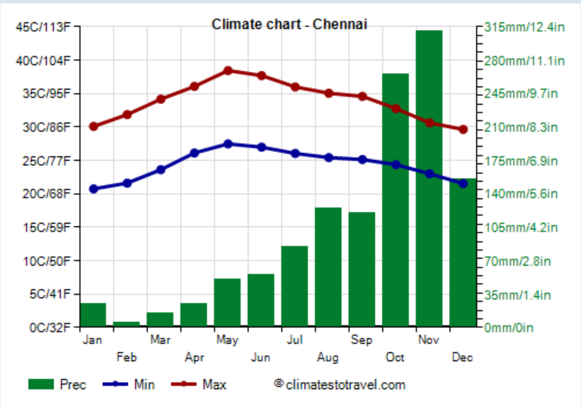
We can observe the Temperature variation with the climate data that is available on official *meteorological and climate data websites* as follow:



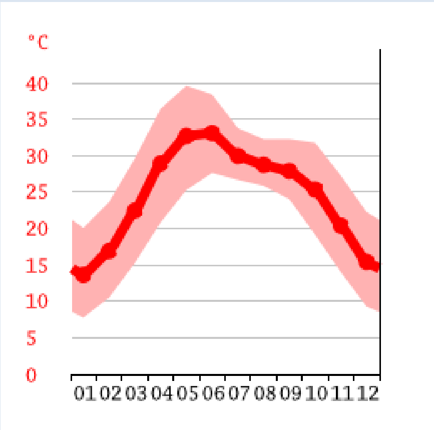
(a)



(b)



(c)



(d)

Fig. 6) meteorological and climate data websites

3. Simulation Setups

The following wall configurations will be simulated to compare the impact of conventional and advanced materials on thermal performance:

a) **Material:** Table 2 provides the required thermophysical properties of the material used in construction.

Table 2:

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7
Name		Concrete	RoofMetalSteel	Mortar	PlasterCement	CeramicBrick	PlasterGypsum	Tedlar
Roughness		MediumRough	Smooth	Rough	MediumRough	Rough	MediumSmooth	Smooth
Thickness	m	0.2	0.1	0.025	0.01	0.2	0.015	0.00002
Conductivity	W/m-K	1.75	55	1.15	1.15	0.9	0.6	0.2
Density	kg/m3	2200	7800	2000	2000	1600	850	1000
Specific Heat	J/kg-K	1000	460	1000	1000	920	1100	2000
Thermal Absorptance		0.9	0.25	0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.8	0.25	0.5	0.7	0.7	0.4	0.7
Visible Absorptance		0.8	0.25	0.5	0.7	0.7	0.4	0.7

Field	Units	Obj8	Obj9	Obj10	Obj11	Obj12	Obj13
Name		Fiber Cement	Polystyrene Foam	Concrete Blocks	HS22P	HS24	OM29
Roughness		MediumRough	Smooth	MediumRough	MediumSmooth	MediumSmooth	MediumSmooth
Thickness	m	0.015	0.07	0.15	0.015	0.015	0.015
Conductivity	W/m-K	0.75	0.03	1.8	1	0.7	0.2
Density	kg/m3	1750	30	2400	1600	1585	923
Specific Heat	J/kg-K	900	1100	900	2270	2500	2500
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.7	0.7	0.7	0.7	0.7	0.7
Visible Absorptance		0.7	0.7	0.7	0.7	0.7	0.7

b) Extra Requirements:

Air Gap: Thermal resistance = 0.5 m2-K/W Window

Material:

U-factor: 3

Solar Heat Gain Coefficient: 0.8 Visible

Transmittance: 0.5

The material configuration was applied to all four climates, and their cooling loads were analyzed.

c) Construction:

Table 3 provides the information about the material

layering used.

Table 3: For Baseline:

Field	Obj1	Obj2	Obj3	Obj4
Name	RoofConstruction	FloorConstruction	WallConstruction	WindowSimpleGlazi
Outside Layer	RoofMetalSteel	Concrete	Fiber Cement	WindowSimpleGlazi
Layer 2	PlasterGypsum		Concrete Blocks	
Layer 3			PlasterGypsum	
Layer 4				
Layer 5				
Layer 6				
Layer 7				
Layer 8				
Layer 9				
Layer 10				

Table 4: For PCMs:

Field	Obj1	Obj2	Obj3	Obj4
Name	RoofConstruction	FloorConstruction	WallConstruction	WindowSimpleGlazingConstruction
Outside Layer	RoofMetalSteel	Concrete	Fiber Cement	WindowSimpleGlazing
Layer 2	PlasterGypsum		Concrete Blocks	
Layer 3			Tedlar	
Layer 4			HS22P	
Layer 5			AirGap	
Layer 6			Tedlar	
Layer 7			PlasterGypsum	
Layer 8				
Layer 9				
Layer 10				

d) Enthalpy–temperature relationship:

(i) PCM: OM29 (Organic):

OM29 PCM has a melting temperature range of 28.5 - 29.5°C, making it suitable for thermal energy storage applications.

The enthalpy-temperature data can be used in EnergyPlus simulations to model OM29 PCM's thermal performance accurately.

The enthalpy variation over the temperature range is tabulated below for precise energy modeling:

Temperature (°C)	Enthalpy (kJ/kg)
20.0	0.0
25.0	11.6
28.0	18.5
28.5	19.6
29.0	116.6
29.5	194.0
30.0	196.7
35.0	210.2

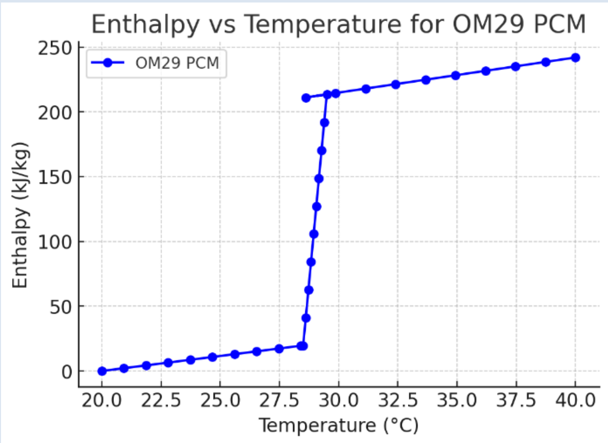


Fig. 7): Enthalpy and temperature relationship for OM29 PCM

(ii) PCM-HS22P:

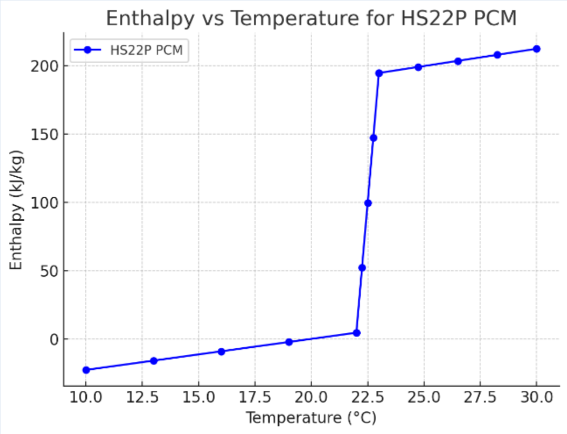


Fig. 8) Enthalpy and temperature relationship for HS22P PCM

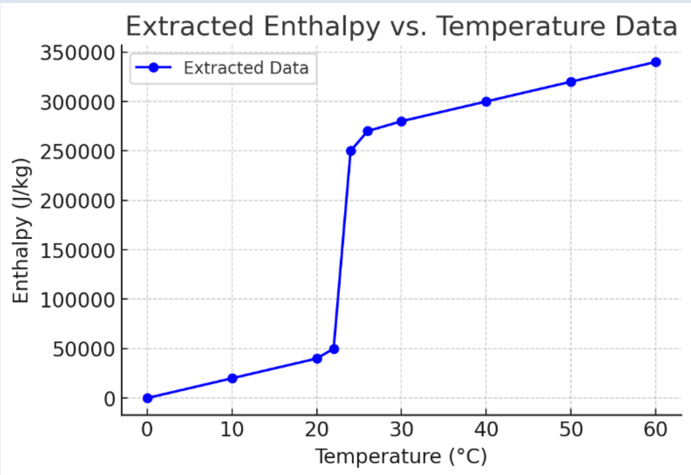
Temp.	enthalpy (KJ/Kg)
10°C →	-22.70
13°C →	-15.89
16°C →	-9.08
19°C →	-2.27
22°C →	4.54
22.25°C →	52.04
22.50°C →	99.54
22.75°C →	147.04
23°C →	194.54
24.75°C →	198.97
26.50°C →	203.40
28.25°C →	207.82

These PCM layers we are going to insert in the Baseline modal between the Structural Layer and the Interior Layer (Finish).

(iii) PCM-HS24:

The enthalpy-temperature graph of HS24 PCM demonstrates its thermal storage characteristics effectively:

- Phase Change Temperature: The material undergoes a phase transition at approximately 24°C.
- Latent Heat Storage: A sharp increase in enthalpy at this temperature corresponds to the latent heat storage capacity, which plays a crucial role in thermal regulation.
- Thermal Behavior: Before and after the phase transition, the material stores sensible heat, indicated by the gradual change in enthalpy outside the phase change region.



Temperature (°C)	**Enthalpy (J/kg)**
0	0
10	20000
20	40000
22	50000
24	250000
26	270000
28	275000
30	280000
40	300000
50	320000
60	340000

Fig. 9) Enthalpy and temperature relationship for HS24 PCM

4. HVAC System for Load Calculation

An ideal HVAC system was modeled in EnergyPlus for accurate thermal performance evaluation to estimate the energy required to maintain a comfortable indoor temperature.

- Temperature Range: The indoor temperature was maintained between 21°C and 28°C, ensuring a realistic comparison of cooling loads.
- Outdoor and indoor temp variation.
- Cooling Load Extraction: The energy required to maintain comfort conditions was recorded for each simulation.

5. Simulation and Data Analysis

- The simulations were executed in EnergyPlus, and cooling loads were extracted in CSV format and HTML format for further analysis.
- Excel was used to generate comparative plots and analyse trends in energy consumption across different materials and climates.
- The study first examined how baseline materials (brick, concrete, and air gaps) performed across different climates, identifying variations in cooling loads due to temperature, humidity, and solar radiation differences. This provided a reference point for evaluating the impact of advanced insulation materials in later stages.

6. Expected Outcome

The study aims to determine:

- Cooling load and Heating load variations across different climates – Understanding how the baseline materials (brick, concrete, plaster gypsum etc.) perform in Jaipur, Delhi, Srinagar, and Chennai.
- Impact of climate conditions on material efficiency – Evaluating how factors like temperature, humidity, and solar radiation influence the cooling demand.
- Scope for material optimization – Establishing a reference point for selecting and testing advanced materials in future studies.
- Data-driven insights for energy-efficient construction – Providing a comparative analysis that can aid in designing thermally efficient buildings based on climatic requirements.

7. Simulation Results:

❖ Outdoor Temperature:

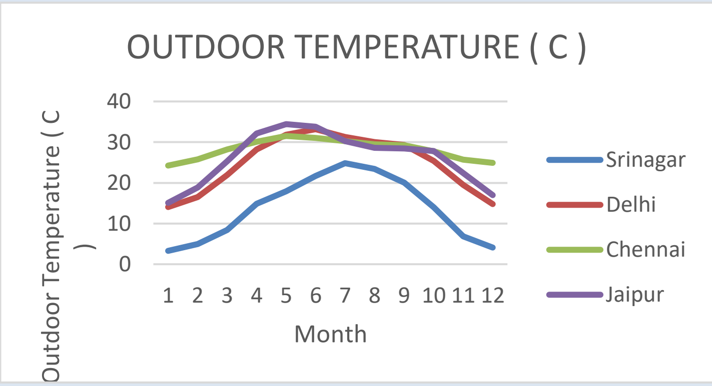
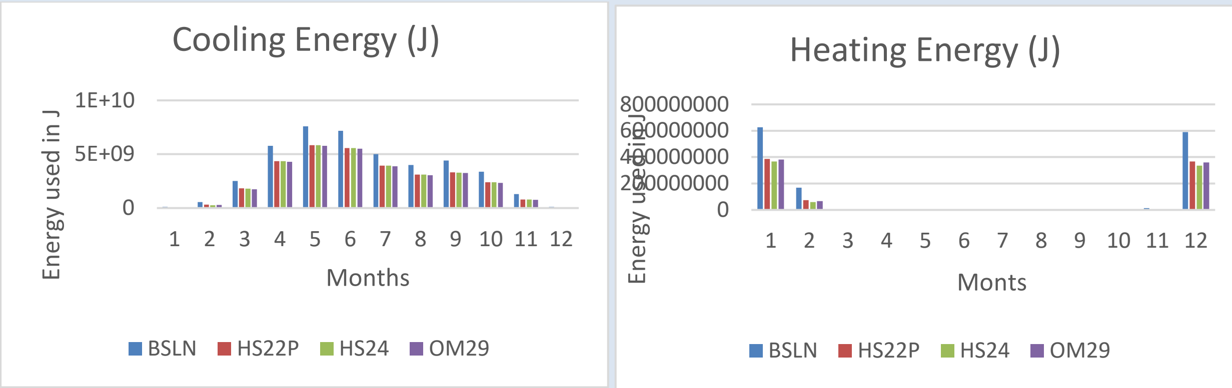


Fig. 10) Outdoor Temperature over a year

❖ Heating and Cooling energy distribution:

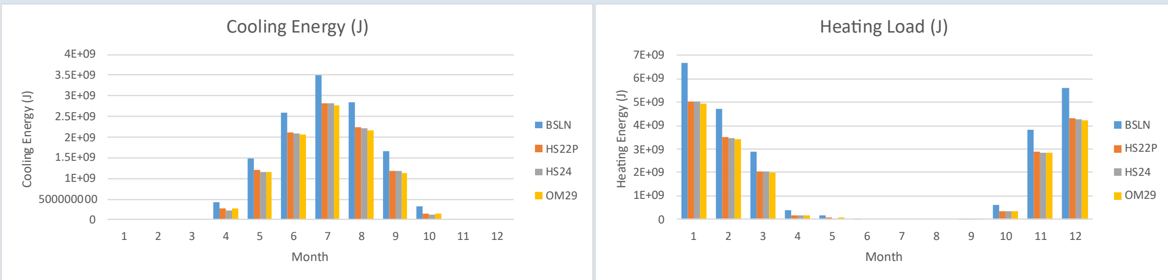
JAIPUR –



(a) **(b)**

Fig. 11) (a) cooling energy (in J) and (b) Heating energy (in J) distribution for a year

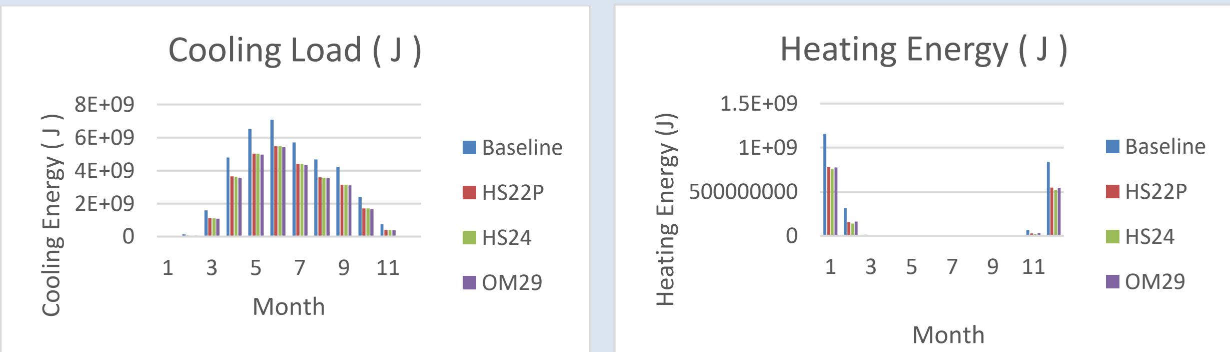
Srinagar –



(a) **(b)**

Fig. 12) (a) cooling energy (in J) and (b) Heating energy (in J) distribution for a year

New Delhi –



(a) **(b)**

Fig. 13) (a) cooling energy (in J) and (b) Heating energy (in J) distribution for a year

Chennai –

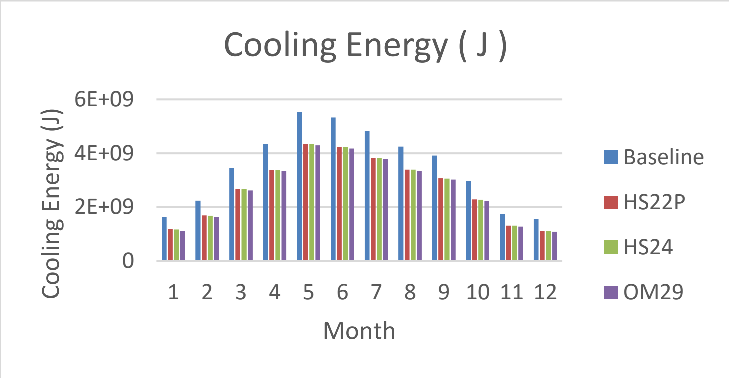


Fig. 14) cooling energy (in J) distribution for a year

Table 5: Total energy and Total energy ratio with respect to Baseline construction result for different climates and PCMs

	Material		Baseline		HS22P		HS24		OM29			
Location												
Delhi			11180.98		8357.5		8306.944		8215.278		Best PCM for Delhi is OM29	
			1		0.747475		0.742953		0.734755			
Jaipur			12014.46		8982.263		8932.302		8824.131		Best PCM for Jaipur is OM29	
			1		0.747621		0.743463		0.734459			
Chennai			11604		9032.862		9014.584		8868.255		Best PCM for Chennai is OM29	
			1		0.778427		0.776852		0.764241			
Srinagar			10490.27		7882.656		7799.67		7718.842		Best PCM for Srinagar is OM29	
			1		0.751425		0.743515		0.735809			
					Best climate for HS22P is of Delhi		Best climate for HS24 is of Delhi		Best climate for OM29 is of Jaipur			

The above table provide a knowledge about the effective PCM for a particular location and which PCM is best for which location.

Table 6 presents the cost analysis for various materials based on their impact on energy utilization. In our model, the total volume of PCM required for the walls is approximately 0.95 m.

Table 6:

PCM	Density (kg/m³)	Mass Required (kg)	Min. Price (₹/kg)	Min. Cost (₹)	Max. Price (₹/kg)	Max. Cost (₹)
HS22P	1600	1520	150	228,000	500	760,000
HS24	1585	1505	150	225,750	500	752,500
OM29	923	875	200	131,250	500	437,500

If we consider 8 ₹ per KWh then for OM29 (least mass (in Kg required)) the money saved

- New Delhi: cost = 23727 ₹
- Jaipur: cost = 25522 ₹
- Srinagar: cost = 21886 ₹
- Chennai: cost = 22171 ₹

The minimum/average years required to recover the money used to intergrate the PCMs in the walls according to that estimated saved money:

- New Delhi: 5.5/12 years
- Jaipur: 5.1/11 years
- Srinagar: 6/13 years
- Chennai: 5.9/12.8 years
- So, OM29 will be best for Jaipur as it is light weight, more energy saving and take least time for cost recovery than Other PCMs and locations.

8. Discussion and Analysis

1. Climate Impact on Thermal Performance

- Hot Climates (Jaipur, Chennai): Consistently high cooling demand throughout the year.
- Cold Climate (Srinagar): High heating demand in winters; cooling needed only during peak summer.
- Composite Climate (New Delhi): Requires both heating (winters) and cooling (summers).

2. PCM Performance Insights

- Melting Point Relevance: The melting range is crucial for effective thermal regulation.
    - *OM29:* 28.5–29.5°C
    - *HS24:* 24–25°C
    - *HS22P:* 22–23°C
- Simulation Findings:
    - OM29 showed the best performance across all climates, which was unexpected for Srinagar.
    - PCMs reduced cooling load by up to 20%, depending on climate and material properties.
    - OM29 is performing best for Jaipur both performance wise and cost recovery wise.
- Positioning Matters: PCM placed inside the wall (as per literature) significantly influences efficiency.
- Layer Thickness: Kept constant in this study; future work may explore thickness optimization.

3. Simulation Methodology

- Ideal Loads Air System: Allowed for fair comparison between PCM types by eliminating HVAC system variability.
- Time Step Sensitivity: Smaller time steps are crucial for accurate PCM behavior simulation.
- Simplifications Used: The study includes assumptions that may differ from real-life scenarios.

4. PCM Selection by Climate

- Hot Climate (Jaipur, Chennai): *OM29* is most effective.
- Cold Climate (Srinagar): *HS22P* was expected to perform best, but *OM29* gave better results.
- Composite Climate (Delhi): *HS24* aligned best with climate needs, though *OM29* still performed strongly.

5. Comparative PCM Characteristics

- Wider Phase Transition (OM29): Offers better energy storage behavior than narrower range PCMs like HS22P.
- Latent Heat Storage: OM29's higher capacity contributed to better energy performance.
- Overall Verdict: OM29 outperformed in all climate cases due to its balanced properties.

6. Why OM29 Outperforms Others

- Stable Cycling: Organic, does not separate or supercool.
- Non-Corrosive & Lightweight: Ideal for integration into building envelopes.
- Higher Specific Heat & Flash Point: Absorbs more heat and safer at higher temperatures.
- Environment-Friendly: Non-toxic and safe for indoor use.

9. Conclusion

- The EnergyPlus simulation results provide compelling evidence that Phase Change Materials offer significant potential for reducing building cooling and heating loads across various Indian climate zones.
- The performance of PCMs is highly dependent on matching their thermophysical properties-particularly melting temperature range-to specific climatic conditions.
- ***For Srinagar:*** Given the city's temperature range of 3°C to 25°C, both HS22P and OM29 primarily utilize their sensible heat. With the same $\Delta T = 19°C$ and volume, we found OM29 to store less sensible heat than HS22P based on:

$$Q=V\cdot\rho\cdot Cp\cdot\Delta TQ$$

- Despite this, it is surprising — and worth analyzing — that OM29 appears to perform better in some simulations. Why? This could be due to ***factors*** like *faster thermal response, better match with peak indoor loads, or material behavior at specific operating conditions*, which influence real-world effectiveness beyond theoretical sensible heat capacity.
- OM29, on the other hand, is **more effective** in warmer climates, as demonstrated by its performance in cities like Delhi and Jaipur.

10. Future Work:

To make the study more practical and useful for real building design, the following future work is suggested. These points will help improve the accuracy of simulations and make buildings more energy-efficient in real-life situations.

- To enhance the practicality and accuracy of simulations for real-world building design, the following future directions are suggested:
- Ground & Soil Properties
  Include location-specific soil thermal properties (type, moisture, conductivity) to improve floor heat transfer accuracy.
- Window Operation Schedules and Air Infiltration
  Incorporate opening/closing schedules based on occupancy or weather to evaluate natural ventilation effects. Model realistic infiltration through windows, doors, and cracks to assess its impact on ideal HVAC loads.
- PCM Boards

We can use the PCM boards as they are *cheaper* and easily available than Raw PCMs.

- PCM on Roofs
  Explore PCM application on roofs, which receive more solar heat, to further reduce cooling demands.
- Multilayer PCM Systems
  Test multiple *PCM layers* with *different melting points* for extended thermal regulation.
- PCM Thickness Optimization
  Analyze how *varying PCM thickness* affects performance and cost-efficiency.

10. References:

1. https://www.sciencedirect.com/science/article/abs/pii/S0378778816302419?via%3Dihub
2. https://asmedigitalcollection.asme.org/solarenergyengineering/article-abstract/140/1/011001/473337/Quantitative-Assessment-of-Phase-Change-Material?redirectedFrom=fulltext
3. https://www.sciencedirect.com/science/article/abs/pii/S0360132321003346?via%3Dihub
4. https://drive.google.com/file/d/1w-DJGW9yqlCGt1eHA2rzmhpGvvKU-x2U/view?usp=sharing (our own presentation for reference).
5. https://www.researchgate.net/figure/Geometry-of-BESTEST-case-600-in-the-EnergyPlus-simulation_fig5_347587277
6. https://www.sciencedirect.com/science/article/abs/pii/S0378778819337946?via%3Dihub
7. https://pubs.acs.org/doi/10.1021/acsami.0c03897?ref=pdf

8. EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001 (BESTEST) EnergyPlus Version 1.2.0.029 June 2004, 1.2.1 Case 600 – Base Case Low Mass Building, page , EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001 (BESTEST)

9. Referencehttps://www.researchgate.net/figure/Geometry-of-BESTEST-case-600-in-the-EnergyPlus-simulation_fig5_347587277
10. https://www.perplexity.ai/search/is-it-okay-if-i-say-indian-wal-AfoYpseWTw2XkGjxI2gzjQ?2=d#2
11. https://www.perplexity.ai/search/is-it-okay-if-i-say-indian-wal-AfoYpseWTw2XkGjxI2gzjQ#4
12. https://www.perplexity.ai/search/is-it-okay-if-i-say-indian-wal-AfoYpseWTw2XkGjxI2gzjQ#5

13. Energy-saving potential of a passive cooling system for thermal energy management of a residential building in Jaipur City, India - ScienceDirect
14. A novel method to investigate the influence of phase change material orientation in reduction of car cabin temperature - ScienceDirect
15. Constructon of a PCM layer for a multi-layer wall: (a) polyethylene... | Download Scientific Diagram

16. Microsoft Word - 8_TDS-HS22P-P 060722
17. Jaipur: climate.pdf
18. Srinagar: Local Weather Report and Forecast
19. Delhi: New Delhi climate: Weather New Delhi & temperature by month
20. Chennai: Chennai climate: weather by month, temperature, rain - Climates to Travel

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