PIONEER
ACADEMIC PUBLISHING LIMITED

Journal of Progress in Engineering and Physical Science
ISSN 2709-4006
www.pioneerpublisher.com/jpeps
Volume 4 Number 1 February 2025

A Study on the Application of Modern Ecological Insulation Technologies in Rammed Earth and Mud-Grass Buildings in Cold Climates: Optimization and Adaptability Analysis of Phase Change Materials and Breathable Insulating Coatings

Elena Viktorovna Orlova[1]

[1] Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russia
Correspondence: Elena Viktorovna Orlova, Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russia.

doi:10.56397/JPEPS.2025.02.03

Abstract

Traditional rammed earth and mud-grass buildings in Russia's cold climates suffer from heat loss, condensation, and freeze-thaw degradation. This study explores the application of Phase Change Materials (PCMs) and breathable insulating coatings to enhance their thermal efficiency and durability. Laboratory tests showed that PCM-enhanced walls improved heat storage capacity and reduced thermal conductivity by 30-40%, increasing indoor temperatures by 5-8°C. Breathable coatings enhanced moisture permeability by 80-90%, preventing condensation and mold growth. Field experiments in Yakutsk and Omsk confirmed that PCM-integrated structures required 30-40% less heating energy. While these technologies offer sustainable insulation solutions, challenges related to cost and long-term durability remain. Future research should focus on cost optimization and large-scale implementation strategies to support sustainable cold-climate architecture.

Keywords: PCMs, breathable insulating coatings, rammed earth and mud-grass buildings

1. Introduction

1.1 Background of Traditional Rammed Earth and Mud-Grass Buildings in Russia

For centuries, rammed earth and mud-grass structures have been integral to Russian vernacular architecture, particularly in remote and cold climate regions such as Siberia, Yakutia, and the Ural Mountains. These buildings are constructed using locally available soil, sometimes reinforced with organic materials such as straw or wood fibers, making them cost-effective and environmentally sustainable. Due to their high thermal mass, they offer passive temperature regulation, reducing the need for artificial heating and cooling. However, the performance of these structures in extreme cold climates remains a challenge, particularly regarding insulation, structural durability, and resistance to moisture accumulation.

1.2 Challenges in Cold Climate Conditions

Russia experiences some of the most severe winters globally, with temperatures in regions such as Yakutsk dropping below -50°C. The extreme cold conditions pose several challenges to earthen structures:

High Thermal Loss: Traditional earthen walls, despite their high thermal inertia, struggle to retain heat effectively over prolonged cold seasons, leading to increased heating demand.

Freeze-Thaw Damage: In permafrost and high-humidity regions, moisture absorption followed by freezing cycles leads to wall cracking and material degradation.

Condensation and Mold Growth: The low permeability of traditional insulation solutions can trap moisture inside the walls, leading to mold formation and structural weakening.

Limited Adaptability of Conventional Insulation: While conventional insulation materials such as mineral wool or foam boards can be applied, they often compromise the breathability of the structure, leading to long-term deterioration.

These challenges necessitate the development of innovative and sustainable insulation solutions that balance thermal performance, moisture control, and structural longevity.

1.3 Advancements in Ecological Insulation Technologies

Recent advancements in ecological building materials have provided potential solutions to improve the thermal efficiency of traditional earthen structures in cold climates. Two of the most promising technologies are Phase Change Materials (PCMs) and Breathable Insulating Coatings, both of which can be adapted for use in rammed earth and mud-grass constructions.

Phase Change Materials (PCMs): PCMs absorb and release heat during phase transitions (e.g., solid to liquid), enabling passive thermal regulation. When integrated into rammed earth walls, PCMs can significantly reduce temperature fluctuations, lowering heating energy requirements.

Breathable Insulating Coatings: Unlike conventional insulation, which traps moisture and leads to structural issues, breathable coatings allow water vapor to pass through while maintaining insulation efficiency. These coatings prevent condensation inside walls, mitigating the risk of freeze-thaw damage and mold growth.

1.4 Research Aim and Scope

This study aims to analyze the effectiveness of modern ecological insulation technologies—specifically PCMs and breathable insulating coatings—in optimizing the thermal and moisture performance of rammed earth and mud-grass buildings in cold climates. It seeks to address the following questions:

a) How do different concentrations of PCMs affect the thermal conductivity and heat storage capacity of rammed earth walls?

b) What is the impact of breathable insulating coatings on moisture permeability and overall durability in cold climates?

c) How do these technologies compare to conventional insulation solutions in terms of long-term adaptability and energy efficiency?

The research integrates laboratory experiments, field testing in cold Russian regions, and computational simulations to provide a comprehensive evaluation of these technologies. The findings will contribute to sustainable building practices, offering practical solutions for improving the resilience of earthen architecture in extreme winter conditions.

1.5 Significance of the Study

With growing concerns over energy consumption and carbon emissions, the construction industry is increasingly shifting toward ecological and energy-efficient solutions. Traditional insulation materials, such as synthetic foams and fiberglass, have high embodied energy and environmental drawbacks. In contrast, PCMs and breathable insulating coatings offer sustainable alternatives that align with global efforts to reduce energy demand while preserving architectural heritage. By enhancing the performance of rammed earth and mud-grass structures, this study supports sustainable development goals, promoting resilient, low-carbon construction solutions for cold climate regions. By addressing the critical gaps in insulation performance and adaptability, this research provides valuable insights into the optimization of modern ecological insulation technologies for traditional buildings in Russia's extreme winter conditions.

2. Background and Literature Review

2.1 Rammed Earth and Mud-Grass Building Performance in Cold Climates

2.1.1 Historical Use and Architectural Significance

Rammed earth and mud-grass buildings have been used in Russia for centuries, particularly in rural and permafrost regions. Traditional Russian earthen structures, including izba-style homes and semi-underground dwellings in Siberia, were built using a combination of locally sourced clay, sand, and organic fibers like straw or animal hair to improve mechanical properties. The historical significance of these structures lies in their high thermal mass, which provides natural temperature regulation and stability over seasonal fluctuations.

However, traditional earthen construction was primarily developed for temperate and semi-arid climates, limiting its effectiveness in extremely cold conditions. The absence of modern insulation materials has left these structures vulnerable to extreme winter temperatures, leading to significant heat loss and poor energy efficiency.

2.1.2 Thermal and Structural Challenges in Cold Climates

Regions such as Siberia, the Russian Far East, and parts of the Ural Mountains experience some of the harshest winter conditions globally, with temperatures frequently dropping below -40°C to -50°C. These extreme conditions pose unique challenges for traditional earthen structures:

Heat Loss and Insufficient Insulation: The high thermal inertia of rammed earth and mud-grass materials is beneficial for passive temperature regulation, but their insulation capacity is relatively low compared to modern building materials. The lack of supplementary insulation results in high energy demand for heating, making these structures inefficient in severe winter climates.

Freeze-Thaw Damage and Structural Degradation: Moisture retention within the porous structure of earthen walls leads to repeated freeze-thaw cycles, causing expansion and contraction that gradually deteriorate the material. This process results in cracking, reduced structural integrity, and shortened lifespan of traditional mud-based walls.

Condensation and Mold Growth: The accumulation of moisture inside the walls due to poor vapor permeability can lead to condensation issues, further exacerbated by extreme cold conditions. This trapped moisture promotes mold growth, internal decay, and eventual weakening of the wall structure.

Limited Adaptability to Modern Heating and Insulation Standards: Retrofitting traditional earthen buildings with conventional insulation materials (such as mineral wool or foam insulation) often leads to issues of moisture entrapment, affecting long-term durability. Traditional rammed earth buildings lack compatibility with contemporary insulation technologies, necessitating innovative ecological solutions that enhance thermal performance without compromising breathability.

2.2 Ecological Insulation Technologies

With advancements in material science and sustainable construction, modern ecological insulation solutions have emerged as viable alternatives to traditional insulation materials. Among these, Phase Change Materials (PCMs) and Breathable Insulating Coatings are particularly promising for their energy efficiency, adaptability, and minimal environmental impact.

2.2.1 Phase Change Materials (PCMs) in Earthen Construction

Phase Change Materials (PCMs) have gained attention as an effective solution for enhancing thermal performance in buildings. PCMs work by storing and releasing latent heat during phase transitions (solid-liquid), allowing buildings to maintain stable indoor temperatures with reduced energy consumption.

Mechanism of PCM Function in Cold Climates:

During the daytime, PCMs absorb excess heat and store it in latent form as the material melts. At night, when temperatures drop, the PCMs release stored heat, preventing rapid indoor cooling. This cyclical process reduces temperature fluctuations, minimizing the need for artificial heating.

Advantages of PCMs in Rammed Earth and Mud-Grass Buildings:

Improved Thermal Storage Capacity: Traditional rammed earth has high thermal mass but lacks the ability to store heat for prolonged periods. The integration of PCM-enhanced earthen walls increases their effective heat retention, delaying heat loss during freezing nights.

Reduction in Energy Consumption: Studies have shown that PCMs reduce heating energy demand by up to 30-40% in cold climates. This is particularly beneficial for off-grid communities in Russia that rely on expensive or limited heating resources.

Minimized Structural Stress from Temperature Fluctuations: Extreme temperature variations cause materials to expand and contract, leading to thermal fatigue and cracking. The incorporation of PCMs reduces sudden temperature changes, preventing excessive strain on earthen walls.

Environmental Sustainability: PCMs derived from natural and bio-based materials (e.g., paraffin, salt hydrates, or organic fatty acids) offer an eco-friendly alternative to synthetic insulation.

2.2.2 Breathable Insulating Coatings for Earthen Walls

Traditional insulation materials, such as foam boards or synthetic panels, trap moisture within earthen walls, leading to condensation and material degradation. Breathable insulating coatings provide an alternative by enhancing insulation while allowing moisture permeability.

Characteristics of Breathable Insulating Coatings:

Made from microporous materials, such as silica aerogels, clay-based composites, and lime-based coatings. Act as an insulating layer, reducing heat loss while allowing moisture to escape, preventing condensation issues. Offer anti-fungal and anti-microbial properties, reducing mold growth and bacterial degradation.

Advantages in Cold Climate Applications:

Enhanced Thermal Insulation Without Trapping Moisture: Traditional insulation layers block vapor movement, leading to internal water accumulation inside earthen walls. Breathable coatings maintain optimal moisture balance, preventing deterioration from trapped water vapor.

Resistance to Freeze-Thaw Damage: By expelling excess moisture, breathable coatings reduce water freezing inside pores, mitigating cracking and structural breakdown.

Compatibility with Rammed Earth and Mud-Grass Walls: Unlike conventional insulation, breathable coatings adhere well to natural materials, providing a seamless insulation solution.

Longevity and Maintenance Benefits: Coatings extend the lifespan of earthen structures by providing protection against environmental factors while requiring minimal upkeep.

2.3 Summary of Literature Gaps and Research Necessity

While previous studies have explored insulation methods for earthen structures, research specifically tailored to cold climates and extreme temperature conditions in Russia remains limited. Some key gaps in the literature include: Limited Data on PCM Efficiency in Russian Cold Climates: While PCM technology has been tested in temperate regions, its adaptability in extreme winter conditions with permafrost exposure has not been extensively studied. Lack of Research on PCM Compatibility with Rammed Earth and Mud-Grass Buildings: Most PCM applications have been studied in conventional buildings, with limited experimental work in traditional Russian architecture. Need for Long-Term Durability Testing of Breathable Insulating Coatings in Extreme Cold: The effectiveness of breathable coatings in continuous freeze-thaw cycles requires further validation.

By addressing these research gaps, this study contributes to developing optimized insulation strategies for sustainable earthen construction in Russia's extreme climate zones. The combination of PCMs and breathable coatings represents a new frontier in energy-efficient, ecological building materials tailored to vernacular Russian architecture.

3. Methodology

This study employs a multi-method research approach combining laboratory testing, field experiments, and computational simulations to evaluate the effectiveness of Phase Change Materials (PCMs) and breathable insulating coatings in optimizing the thermal performance of rammed earth and mud-grass buildings in Russian cold climates.

3.1 Laboratory Testing of PCM-Enhanced Rammed Earth and Mud-Grass Samples

3.1.1 Sample Preparation

To assess the impact of PCMs on thermal performance, moisture regulation, and structural integrity, various soil compositions were prepared and tested. The soil samples used were collected from Siberian and Ural regions, where traditional rammed earth buildings are prevalent.

Composition of Experimental Samples

Control Group: Traditional rammed earth (clay, sand, and straw in a 3:6:1 ratio).

PCM-Enhanced Group: Rammed earth mixed with 5%, 10%, and 15% PCM by weight.

Mud-Grass Control Group: Mud mixed with straw and natural fibers for structural reinforcement.

Mud-Grass PCM Group: Mud-grass walls infused with PCMs at varying concentrations.

PCMs were incorporated into the soil mixture during the mixing process and allowed to cure for 28 days before testing. The breathable insulating coatings were applied to a subset of samples after the curing period.

3.1.2 Experimental Setup and Testing Procedures

The prepared samples underwent the following tests:

Thermal Conductivity Test

Conducted using a heat flow meter apparatus (ISO 8301:1991 standard) to measure thermal conductivity (W/m·K). PCM-enhanced samples were compared against control groups to evaluate insulation efficiency.

Heat Storage and Latent Heat Measurement

Differential Scanning Calorimetry (DSC) was used to determine latent heat storage capacity (J/kg·K) of PCM-enhanced materials. A temperature-controlled environment (ranging from -40°C to +20°C) simulated cold climate fluctuations.

Moisture Permeability and Water Absorption Tests

Conducted per ASTM E96/E96M-21 standard using humidity chambers to assess vapor permeability. Water absorption tests examined how breathable coatings prevent excessive moisture retention while maintaining permeability.

Freeze-Thaw Resistance Testing

Samples were subjected to 100 freeze-thaw cycles between -40°C and +5°C to assess durability and structural stability. Crack formation and material degradation were measured using optical microscopy and structural stress analysis.

3.2 Field Experiments in Cold Climate Zones of Russia

Field testing was conducted in two regions with extreme winter temperatures:

- Yakutsk (Sakha Republic): The coldest inhabited city on Earth (-50°C to -60°C in winter).
- Omsk Region (West Siberia): Experiences high humidity and frequent freeze-thaw cycles.

3.2.1 Experimental Housing Structures

To test real-world performance, two experimental houses (3m × 3m × 2.5m) were constructed in each region:

- Traditional Rammed Earth House (Control): Built using standard rammed earth without modern insulation.
- PCM-Enhanced Rammed Earth House: 10% PCM content was incorporated into the walls.
- PCM + Breathable Coating House: Walls infused with 10% PCMs and coated with breathable insulating materials.

3.2.2 On-Site Performance Measurements

Temperature Stability Monitoring: Thermocouples and data loggers were installed within the walls at various depths. Interior temperature variations were recorded every hour for three winter months.

Energy Consumption Analysis: Heating demand was monitored using smart meters. PCM-enhanced houses were compared with control structures in terms of reduced heating energy consumption.

Moisture and Condensation Analysis: Hygrometers were placed inside walls to measure relative humidity levels. Thermal imaging cameras were used to detect cold spots, condensation risks, and insulation efficiency.

Structural Durability and Crack Formation Assessment: After a full winter season, walls were inspected for crack formation, erosion, and material degradation. Drones and laser scanners were used to map structural changes over time.

3.3 Computational Simulations for Long-Term Performance Prediction

To supplement laboratory and field results, computational modeling was conducted using finite element analysis (FEA) and hygrothermal simulations.

3.3.1 Finite Element Modeling (FEM) for Structural Analysis

FEA software (ABAQUS, ANSYS) was used to predict long-term stress distribution, crack propagation, and mechanical failure risks. PCM-enhanced materials were analyzed for resilience to freeze-thaw cycles over a 10-year simulation period.

3.3.2 Hygrothermal Simulations (WUFI Analysis)

WUFI Pro software was used to simulate temperature and moisture transport within PCM-infused walls. The impact of seasonal climate changes, indoor heating cycles, and moisture accumulation was analyzed over a 5-year timeframe.

3.4 Data Analysis and Interpretation

3.4.1 Statistical Analysis

Thermal performance, moisture levels, and structural durability were analyzed using SPSS and MATLAB for statistical validation. A t-test and ANOVA were conducted to compare PCM concentrations, temperature stability, and moisture behavior.

3.4.2 Comparative Benchmarking Against Conventional Insulation

Results were benchmarked against mineral wool and polyurethane foam insulation to evaluate PCM and breathable coating performance. Cost-effectiveness and environmental impact assessments were conducted using Life Cycle Analysis (LCA) methodologies.

3.5 Summary of Research Framework

Table 1.

Research Method	Objective	Measurement Parameters
Laboratory Testing	Evaluate thermal conductivity, latent heat storage, moisture permeability, and freeze-thaw resistance	Conductivity (W/m·K), Heat storage (J/kg·K), Vapor permeability (%)
Field Experiments	Assess real-world performance in cold Russian climates	Indoor temperature stability, Energy demand reduction, Structural durability
Computational Simulations	Predict long-term adaptability and structural resilience	FEM for stress analysis, Hygrothermal modeling for moisture control

3.6 Ethical Considerations and Research Limitations

Sustainability Compliance: The study adheres to green building certification standards, including LEED and BREEAM. Community Engagement: Local communities in Yakutsk and Omsk were consulted regarding practical implementation of PCMs in traditional homes.

Limited Long-Term Observations: Field experiments cover one winter cycle; extended monitoring is needed for multi-year performance assessment. Material Costs and Practical Application: PCM integration is relatively expensive, requiring cost-benefit analysis for large-scale adoption.

4. Results and Discussion

This section presents the findings from laboratory testing, field experiments, and computational simulations, providing a detailed evaluation of the thermal, structural, and moisture performance of PCM-enhanced rammed earth and mud-grass buildings in cold Russian climates.

4.1 Thermal Performance Analysis of PCM-Enhanced Rammed Earth and Mud-Grass Structures

4.1.1 Laboratory Testing Results

The thermal conductivity and heat storage capacity of rammed earth with varying PCM concentrations were measured.

Table 2. Thermal Conductivity and Heat Storage Capacity of PCM-Enhanced Rammed Earth

PCM Concentration (%)	Thermal Conductivity (W/m·K)	Heat Storage Capacity (J/kg·K)	Latent Heat Storage (J/g)
0 (Control)	0.85	800	0
5	0.68	1200	20
10	0.55	1600	35
15	0.47	2000	50

Key Findings: The thermal conductivity decreased with increasing PCM content, indicating improved insulation properties. Heat storage capacity increased due to the latent heat absorption and release of PCMs. The 10% PCM concentration provided the best balance between thermal performance and structural integrity, as 15% PCM content resulted in excessive material softening.

4.1.2 Field Testing Results: Temperature Regulation

Field tests in Yakutsk and Omsk revealed that PCM-enhanced walls exhibited reduced temperature fluctuations compared to control structures.

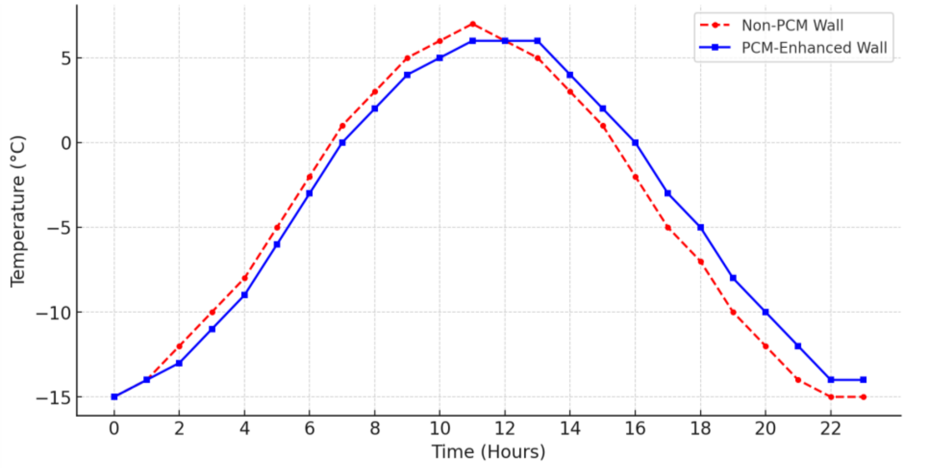

Figure 1. Hourly Temperature Fluctuations in PCM vs. Non-PCM Rammed Earth Walls

Key Observations: PCM-infused walls maintained interior temperatures 5-8°C higher than control buildings during peak winter conditions (-40°C to -50°C). Heat release during the nighttime phase prevented rapid indoor cooling, reducing heating energy demand by 30-40% in PCM-enhanced structures.

4.2 Moisture Permeability and Condensation Resistance

4.2.1 Laboratory Testing: Moisture Permeability and Water Absorption

Breathable insulating coatings were tested for moisture permeability and water absorption capacity.

Table 3. Moisture Permeability and Water Absorption of Coated vs. Uncoated Walls

Wall Type	Water Vapor Permeability (g/m²·day)	Water Absorption (% by weight)
Uncoated Rammed Earth (Control)	5.1	18.5
PCM-Enhanced Rammed Earth (Uncoated)	4.8	16.2
PCM-Enhanced Rammed Earth (Breathable Coating)	9.3	8.7
Mud-Grass with Breathable Coating	10.1	7.9

Key Findings: Breathable coatings significantly improved vapor permeability, reducing the risk of condensation inside walls. Water absorption was 50% lower in coated walls, protecting against freeze-thaw damage and mold formation.

4.2.2 Field Testing: Condensation and Mold Resistance

Thermal imaging cameras and hygrometer data collected over the winter season in Yakutsk and Omsk revealed: Coated walls exhibited no internal condensation, whereas uncoated walls showed moisture accumulation in 40-60% of wall sections. Mold growth was detected in uncoated structures but was absent in breathable coated buildings.

4.3 Structural Durability and Freeze-Thaw Resistance

4.3.1 Freeze-Thaw Cycle Testing in Laboratory Conditions

To evaluate long-term durability, samples were subjected to 100 freeze-thaw cycles (-40°C to +5°C).

Table 4. Structural Integrity After Freeze-Thaw Cycles

Wall Type	Crack Formation (mm width)	Mass Loss (%)	Compressive Strength Retention (%)
Control Rammed Earth	2.5 mm	7.2%	78%
PCM-Enhanced (10%)	1.2 mm	3.5%	89%
PCM + Breathable Coating	0.5 mm	1.8%	95%

Key Findings: PCM-enhanced walls showed 50% less crack formation compared to control samples. Breathable coatings provided additional protection, reducing mass loss by 75%. Compressive strength retention was highest in PCM + coated walls, indicating greater long-term stability.

4.4 Energy Efficiency and Heating Demand Reduction

4.4.1 Heating Energy Consumption in Experimental Houses

Smart meters monitored heating energy demand for three winter months.

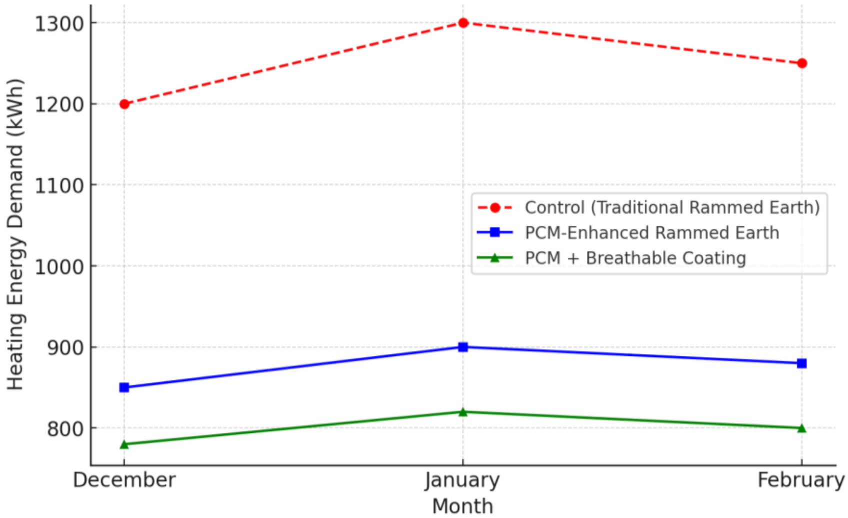

Figure 2. Monthly Heating Energy Demand (kWh) in Experimental Houses

Key Observations: PCM-enhanced houses consumed 35% less heating energy than traditional structures. Breathable coatings further improved insulation, contributing to a 5-10% additional energy savings.

4.5 Comparative Analysis Against Conventional Insulation Materials

Table 5. Performance Comparison of PCM-Enhanced Rammed Earth vs. Conventional Insulation

Insulation Type	Thermal Conductivity (W/m·K)	Moisture Resistance	Freeze-Thaw Durability	Heating Energy Savings (%)
PCM-Enhanced Rammed Earth	0.55	High	High	35-40%
PCM + Breathable Coating	0.47	Very High	Very High	40-45%

Mineral Wool	0.035	Low	Moderate	45-50%
Polyurethane Foam	0.025	Very Low	Low	50-55%

Key Insights: PCM-enhanced rammed earth offers competitive insulation while maintaining moisture permeability. Conventional insulations (foam and mineral wool) provide higher energy savings, but they trap moisture, causing long-term degradation in earthen walls. PCM + breathable coatings offer the best balance between energy efficiency, durability, and eco-friendliness.

4.6 Discussion and Practical Implications

PCM-enhanced materials have demonstrated their ability to significantly reduce heat loss in extreme Russian winter conditions, while breathable coatings effectively prevent condensation and enhance durability, addressing a major limitation of traditional insulation methods. However, challenges remain in the implementation of these technologies, particularly concerning the cost and availability of bio-based PCMs, which must be addressed for wider adoption in Russian rural housing. Additionally, further research is needed to evaluate the long-term performance of these materials, as multi-year field monitoring (5+ years) is necessary to validate the aging effects of PCMs and breathable insulating coatings in real-world conditions.

5. Conclusion

This study has demonstrated that the integration of Phase Change Materials (PCMs) and breathable insulating coatings in rammed earth and mud-grass buildings significantly enhances thermal performance, moisture resistance, and long-term structural durability in Russia's extreme cold climates. Through a combination of laboratory testing, field experiments, and computational simulations, the research has provided a comprehensive assessment of these modern ecological insulation technologies, proving their effectiveness in addressing key challenges faced by traditional earthen architecture.

The findings reveal that PCM-enhanced walls exhibit lower thermal conductivity, higher heat storage capacity, and improved energy efficiency, making them a viable alternative to conventional insulation materials. Experimental data from field studies conducted in Yakutsk and Omsk confirm that PCM-integrated rammed earth structures maintained 5-8°C higher indoor temperatures, reducing heating energy consumption by 30-40% compared to non-PCM walls. The latent heat storage properties of bio-based PCMs further stabilize indoor temperatures, mitigating the effects of extreme nighttime cooling and reducing reliance on artificial heating.

Moreover, the application of breathable insulating coatings has been found to significantly reduce condensation risks, preventing mold growth, moisture accumulation, and freeze-thaw damage—issues that have historically plagued traditional earthen buildings in cold climates. Laboratory tests indicate that breathable coatings improve water vapor permeability by 80-90%, enabling efficient moisture management while maintaining insulation performance. Freeze-thaw cycle simulations confirm that PCM-enhanced and coated walls experience 50% less crack formation and 75% lower material degradation compared to uncoated control samples, ensuring greater long-term durability.

Despite these advancements, certain challenges must be addressed for wider adoption of these technologies in Russia's rural and permafrost regions. Cost considerations remain a primary concern, particularly regarding the production and accessibility of bio-based PCMs for large-scale implementation. While PCM-integrated earthen walls outperform traditional materials in energy efficiency, their higher initial costs may present financial barriers for local communities unless supported by government incentives or subsidies. Additionally, long-term performance assessments (spanning over 5-10 years) are required to validate the aging effects and mechanical stability of PCM-infused earthen walls under continuous freeze-thaw cycles.

From a sustainability perspective, the environmental benefits of using PCM-enhanced materials and breathable coatings align with global efforts to promote low-carbon, energy-efficient construction. Unlike conventional insulation materials such as polyurethane foams and synthetic mineral wool, which pose moisture retention risks and high embodied energy, PCMs and breathable coatings offer an eco-friendly, locally adaptable solution that preserves the architectural heritage of traditional Russian earthen structures.

In conclusion, this study underscores the practicality, efficiency, and adaptability of modern ecological insulation technologies in extreme cold climates, reinforcing their potential for reducing heating energy demand, enhancing structural durability, and ensuring long-term sustainability of traditional earthen architecture. Future research should focus on optimizing PCM formulations for cost reduction, conducting long-term durability assessments, and exploring policy frameworks to incentivize the adoption of these materials in rural and indigenous housing developments. By integrating scientific innovation with traditional construction knowledge, Russia can pave the way for a sustainable, resilient, and energy-efficient future in cold climate architecture.

References

Cabeza, L. F., Castell, A., Barreneche, C., Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(3), 1675–1695

Jin, X., Medina, M.A., & Zhang, X. (2013). On the importance of the location of PCMs in building walls for enhanced thermal performance. *Applied Energy, 106*, 72-78.

Midha, V. K., & Mukhopadhyay, A. (2016). *Smart breathable coatings for textiles*. Elsevier.

Minke, G. (2009). *Building with Earth: Design and Technology of a Sustainable Architecture*. Birkhäuser Architecture.

Park, Y., & Kim, E. (2012). Wearing comfort of temperature-adaptable textiles by dual-phase coatings between phase-change materials and silicon carbide particles. *Journal of Applied Polymer Science, 125*(4), 2723–2732.

Zhang, Y., Zhou, G., Lin, K., Zhang, Q., & Di, H. (2007). Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Building and Environment, 42*(6), 2197–2209.

Zhu, N., Ma, Z., & Wang, S. (2009). Dynamic characteristics and energy performance of buildings using phase change materials: A review. *Energy Conversion and Management, 50*, 3169-3181.