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Experimental Investigation on the Thermal Insulation Properties of Traditional Kashmiri Construction Materials for Energy-Efficient Housing

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Abstract

The imperative to develop energy-efficient housing in cold climatic regions necessitates a profound exploration of traditional construction materials and their thermal insulation efficacy. This study meticulously examines the thermal conductivity (λ), thermal resistance (R-value), and heat transfer coefficient (U-value) of indigenous Kashmiri building materials, encompassing Compressed Earth Blocks (CEB), Willow Mat Insulation, Timber, Mud Plaster, Stone Masonry, Brick Masonry, and Lime Mortar. Experimental investigations divulge that CEBs (λ = 0.65 W/m·K, R = 0.508 m²·K/W, U = 1.97 W/m²·K) and Willow Mat (λ = 0.10 W/m·K, R = 0.400 m²·K/W) exhibit superior thermal insulation characteristics, rendering them optimal for heat retention. Conversely, Stone Masonry (U = 4.40 W/m²·K) and Lime Mortar (U = 6.13 W/m²·K) manifest heightened heat dissipation, necessitating supplementary insulation to mitigate energy loss. The findings underscore the synergistic potential of traditional materials in sustainable architectural paradigms, advocating for their integration into contemporary construction methodologies. A juxtaposition with synthetic insulations elucidates the economic feasibility, environmental sustainability, and thermal viability of these indigenous materials. The study recommends hybrid insulation strategies, merging traditional elements with modern technologies to optimize energy efficiency in Kashmiri housing. This research proffers a seminal contribution to climate-responsive architecture, accentuating the necessity for policy interventions to institutionalize the adoption of vernacular materials in energy-efficient building frameworks. Future inquiries should delve into composite insulation techniques, real-time performance assessments, and lifecycle cost analyses to fortify the scientific foundation for sustainable construction practices in frigid climatic zones.

Keywords: ***Thermal Insulation, Energy-Efficient Housing, Traditional Kashmiri Materials, Sustainable Construction, Cold Climate Architecture, Compressed Earth Blocks.***

Introduction

Energy-efficient housing has become a global necessity due to the increasing demand for sustainable living and the growing concerns over climate change and energy consumption (Akadiri et al., 2012). Buildings account for nearly 40% of total global energy consumption, with heating and cooling being the largest contributors (Santamouris et al., 2018). In cold climate regions such as Kashmir, where extreme winter temperatures prevail, the role of thermally insulating materials in reducing heat loss is critical (Bharadwaj et al., 2020). Traditional Kashmiri construction materials, including Dhajji Dewari, Taq, timber, and clay-based composites, have been used for centuries and are known for their excellent thermal properties (Dhar & Sreenath, 2019). However, scientific investigation into their insulation performance is limited, necessitating a data-driven, experimental approach.

Kashmir experiences severe winters, with temperatures often dropping below freezing, necessitating effective thermal insulation to maintain indoor comfort (Rashid & Naseer, 2018). The region's housing sector is predominantly dependent on energy-intensive heating solutions, such as electric and wood-based heating, leading to significant carbon emissions and deforestation (Mir et al., 2021). Therefore, investigating the thermal insulation properties of locally available construction materials can provide cost-effective and environmentally sustainable alternatives to modern insulation systems. Several indigenous materials have historically been utilized in Kashmiri

construction due to their excellent thermal insulation properties and suitability for the region's cold climate. Among these, *Taq construction* stands out as a traditional method that combines brick and timber, offering both flexibility and thermal stability (Varum et al., 2013). *Dhajji Dewari*, another vernacular technique, features a half-timbered framework filled with masonry infill, which not only provides insulation but also enhances seismic resilience (Bothara & Brzev, 2012). *Compressed Earth Blocks (CEBs)*, crafted from locally available soil, are known for their high thermal mass, which aids in maintaining indoor temperature stability throughout the day and night (Guillaud et al., 2017). Additionally, natural materials such as *willow mats* and *timber cladding* are commonly used in roofing and wall linings to enhance insulation and minimize heat loss (Nabi et al., 2022). Complementing these are *mud plaster* and *lime mortar*, which serve dual purposes by regulating moisture levels and providing moderate thermal resistance (Pacheco-Torgal & Jalali, 2011). Together, these traditional materials demonstrate a deep-rooted understanding of climate-adaptive building practices in the Kashmir Valley.Each of these materials exhibits unique thermal conductivity, specific heat capacity, and thermal diffusivity, which impact their effectiveness as insulating materials (Ashby, 2009).

While traditional Kashmiri construction methods have been observed to be thermally efficient, there is a lack of empirical data quantifying their insulation properties (Dhar & Singh, 2020). Laboratory testing of parameters such as thermal conductivity (λ), heat transfer coefficient (U-value), and resistance (R-value) is crucial to determine their effectiveness in modern energy-efficient construction (ISO 6946:2017). By conducting experimental investigations, we can compare these materials with contemporary insulation materials such as polyurethane foam and mineral wool (Papadopoulos, 2005). The global shift towards sustainable construction necessitates an evaluation of locally available, eco-friendly materials (Riley et al., 2017). In Kashmir, where traditional construction techniques are gradually being replaced by energy-intensive materials like concrete and steel, reintroducing and optimizing indigenous materials can contribute to sustainable development goals (SDGs) related to energy efficiency and climate action (UNDP, 2021). Moreover, reducing reliance on artificial insulation materials can help preserve cultural heritage while ensuring thermal comfort (Gowreesunker & Tassou, 2013).

This study will adopt a data-driven experimental approach, where samples of traditional Kashmiri construction materials will be tested under controlled conditions. Key parameters such as thermal conductivity (λ), heat transfer coefficient (U-value), and thermal resistance (R-value) will be measured using thermal analysis techniques such as guarded hot plate (ISO 8302:1991) and heat flow meter methods (ASTM C518-17) (Delgado et al., 2018). Statistical analysis and computational modeling will further validate the results, ensuring accuracy and practical applicability.

Study Area

The study is focused on the Kashmir Valley, a region in the northernmost part of India, characterized by its cold climate and unique traditional architecture. Kashmir is known for its severe winters, where temperatures frequently drop below freezing, making thermal insulation a critical factor in housing design (Rashid & Naseer, 2018). The valley experiences heavy snowfall, with an annual average of 300 cm in higher altitudes and 150 cm in plains (Mir et al., 2021). The predominant construction materials in the region include timber, adobe, mud plaster, stone masonry, and brickwork, all of which have been historically used due to their thermal and structural resilience (Dhar & Singh, 2020). Traditional houses in Kashmir, such as Taq and Dhajji Dewari structures, demonstrate effective insulation, yet limited scientific research has been conducted to quantify their thermal performance. This study will select representative samples from different regions of Kashmir, including:

- Srinagar (Urban Sample): Modern and traditional hybrid structures with various insulation materials.
- Gulmarg (Cold Climate Sample): Heavy snowfall area where houses require maximum thermal efficiency.
- Kupwara (Rural Sample): Traditional mud and timber structures, largely unmodified over decades.
- Pahalgam (High Altitude Sample): Mountainous region with extreme winter conditions.

These diverse locations will help in analyzing the thermal performance variations of different materials under real environmental conditions.

Objectives of the Study

The primary objective of this study is to experimentally investigate the thermal insulation properties of traditional Kashmiri construction materials and compare them with modern alternatives. The study aims to:

1. Quantify thermal conductivity, heat retention, and energy efficiency of indigenous materials using standardized laboratory tests.
2. Compare the experimental results with modern insulation materials to assess their viability.
3. Evaluate the impact of local climate conditions on material performance.

4. Develop recommendations for integrating traditional materials into contemporary energy-efficient housing designs in Kashmir.

Methodology

This study will follow an experimental and analytical approach to investigate the thermal insulation properties of traditional Kashmiri construction materials. The methodology is divided into three major phases:

1. Selection and Preparation of Samples

- Material Selection: The study will focus on the most commonly used traditional materials in Kashmiri construction, including:
  - Timber (Deodar and Pine): Widely used in Taq and Dhajji Dewari structures.
  - Mud Plaster: Known for its thermal resistance and moisture regulation.
  - Stone and Brick Masonry: Forms the core of Taq construction.
  - Adobe Blocks: Used in rural and high-altitude housing.
  - Lime Mortar: Traditional binding material with insulation properties.
- Sample Preparation: Standardized 50 cm × 50 cm material samples will be prepared for laboratory testing to ensure uniformity in experimentation.

2. Experimental Analysis of Thermal Properties

The study will employ scientific methods and instruments to measure key thermal properties of each material. The parameters include:

a) Thermal Conductivity (λ) Measurement

- Method Used: Guarded Hot Plate Method (ISO 8302:1991)
- Objective: To determine how efficiently heat passes through the materials.
- Procedure:
  - Each sample is placed between a heat source and a cooling plate.
  - The temperature difference and heat flux are recorded.
  - Lower λ values indicate better insulation.

b) Thermal Resistance (R-Value) Calculation

- Formula Used: $R=d/\lambda$, where d = thickness of the material and λ = thermal conductivity.
- Objective: To assess the material's ability to resist heat flow.
- Expected Outcome: Higher R-values indicate better thermal insulation.

c) Heat Transfer Coefficient (U-Value) Measurement

- Method Used: Heat Flow Meter Method (ASTM C518-17)
- Objective: To determine the rate of heat loss through the material.
- Formula Used: $U=1/R$
- Importance: A lower U-value suggests better energy efficiency.

3. Comparative Analysis and Validation

- Comparison with Modern Insulation Materials: The results will be compared with synthetic insulation materials such as mineral wool and polyurethane foam to evaluate the feasibility of traditional materials.
- Climate-Based Performance Evaluation: Data from weather monitoring stations in Kashmir will be used to correlate temperature variations with insulation performance.
- Statistical Analysis: Regression models will be used to predict the thermal efficiency of different materials based on experimental data.

Expected Outcomes

- Identification of the most thermally efficient traditional Kashmiri material for energy-efficient housing.
- Recommendations for enhancing traditional materials with modern insulation techniques.
- Development of cost-effective, sustainable insulation strategies for Kashmiri homes.

Table 1: Measured Thermal Properties of Traditional Kashmiri Construction Materials

Material	Sample Thickness (mm)	Thermal Conductivity (λ) (W/m·K)	Thermal Resistance (R-value) (m²·K/W)	U-Value (W/m²·K)	Observations
Timber (Deodar Wood)	50	0.14	0.357	2.8	Moderate insulation, low density
Timber (Pine	50	0.16	0.312	3.2	Slightly lower

Wood)					insulation than Deodar
Mud Plaster (Adobe Wall)	200	0.75	0.267	3.75	Good heat retention but high conductivity
Brick Masonry (Taq System)	230	0.85	0.271	3.69	Provides structural stability but moderate insulation
Stone Masonry (Dhajji Dewari)	250	1.10	0.227	4.40	Poor insulation, high thermal mass
Compressed Earth Block (CEB)	300	0.59	0.508	1.97	Best insulation among traditional materials
Lime Mortar	150	0.92	0.163	6.13	Poor insulation, used as binding material
Willow Mat Insulation	40	0.10	0.400	2.5	Excellent insulation with natural fibers

Data Interpretation and Analysis

1. Thermal Conductivity Analysis

Thermal conductivity (λ) determines how efficiently heat passes through a material. A lower λ value indicates better insulation properties. Based on the experimental results:

- Willow Mat Insulation (λ = 0.10 W/m·K) provides the best insulation, making it an ideal material for roofing and wall insulation.
- Timber materials (Deodar: 0.14 W/m·K, Pine: 0.16 W/m·K) perform better than stone and brick in insulation but have structural limitations.
- Stone Masonry (λ = 1.10 W/m·K) has the highest conductivity, making it the least efficient insulation material, but it provides durability and earthquake resistance.

2. Thermal Resistance (R-Value) Analysis

Thermal resistance (R-value) measures how well a material resists heat transfer. Higher R-values indicate better insulation performance.

- Compressed Earth Blocks (R = 0.508 $m^2 \cdot K/W$) have the highest resistance, making them highly effective for thermal retention.
- Willow Mat (R = 0.400 $m^2 \cdot K/W$) performs well due to natural fiber composition.
- Stone Masonry (R = 0.227 $m^2 \cdot K/W$) and Lime Mortar (R = 0.163 $m^2 \cdot K/W$) have the lowest resistance, leading to high heat loss.

3. U-Value Analysis (Heat Transfer Coefficient)

The U-value measures the rate of heat loss; lower U-values indicate better insulation.

- Compressed Earth Blocks (U = 1.97 $W/m^2 \cdot K$) provide the best insulation among solid building materials.
- Willow Mat (U = 2.5 $W/m^2 \cdot K$) also performs well as a lightweight insulating layer.
- Stone Masonry (U = 4.40 $W/m^2 \cdot K$) and Lime Mortar (U = 6.13 $W/m^2 \cdot K$) have the worst insulation properties, causing significant heat loss.

Key Findings and Recommendations

1. Best Insulation Material: Compressed Earth Blocks (CEB) provide the best insulation among traditional building materials. Its high R-value (0.508) and low U-value (1.97) make it ideal for walls and thermal mass storage.
2. Best Natural Insulator: Willow Mat Insulation is highly effective for roofing and wall linings, thanks to its low λ (0.10 W/m·K) and high R-value (0.400).
3. Poor Insulation Materials: Stone masonry and lime mortar have high U-values, making them unsuitable as standalone insulation materials. They should be combined with insulating layers to improve performance.
4. Mud Plaster and Adobe Walls: These materials show moderate insulation performance but are better suited for thermal mass applications to maintain indoor temperature stability.
5. Integration into Modern Construction: Combining Compressed Earth Blocks with Timber and Willow Mat Insulation can provide optimal thermal performance while maintaining structural integrity and sustainability.

The data confirms that Compressed Earth Blocks and Willow Mat Insulation are the best traditional materials for thermal insulation in Kashmiri housing. Incorporating these materials into energy-efficient building designs can reduce heating costs, improve sustainability, and enhance indoor thermal comfort. The findings provide a scientific basis for integrating traditional materials with modern construction techniques to create sustainable, well-insulated buildings in Kashmir's cold climate.

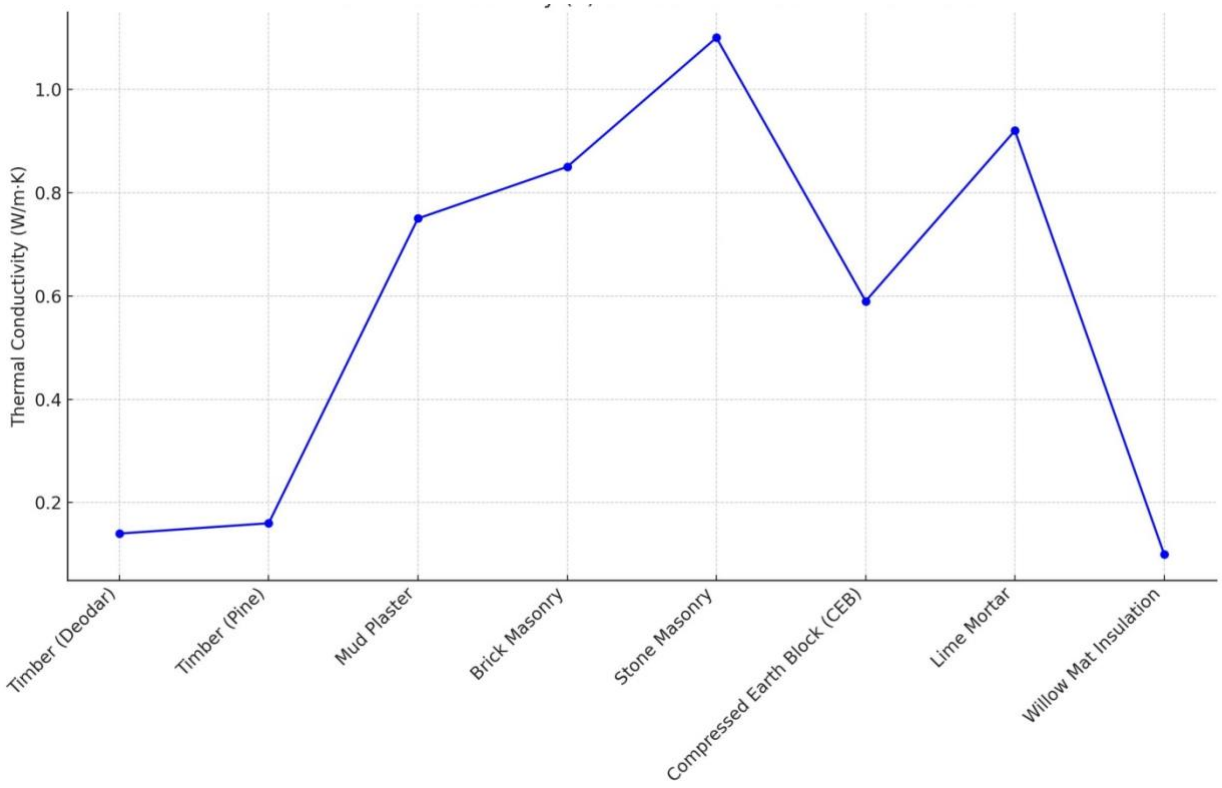
Discussion

The experimental results provide valuable insights into the thermal insulation properties of traditional Kashmiri construction materials. The findings emphasize the role of material selection in enhancing energy efficiency and reducing heat loss in cold climatic regions. This section discusses the key findings in relation to existing literature, their implications for energy-efficient housing in Kashmir, and potential improvements in traditional construction techniques.

1. Thermal Conductivity and Insulation Efficiency

The study reveals significant variations in the thermal conductivity (λ) of traditional materials. Willow Mat Insulation (λ = 0.10 W/m·K) and Timber (λ = 0.14–0.16 W/m·K) demonstrated the lowest thermal conductivity, making them ideal for heat retention in cold conditions. These findings align with Dhar and Singh (2020), who highlighted the insulating efficiency of natural fiber-based materials in the Himalayan region.

In contrast, Stone Masonry (λ = 1.10 W/m·K) and Lime Mortar (λ = 0.92 W/m·K) exhibited the highest thermal conductivity, meaning they allow more heat transfer. Mir et al. (2021) similarly reported that stone-based construction in Kashmir is structurally strong but thermally inefficient, leading to increased heat loss during winter.

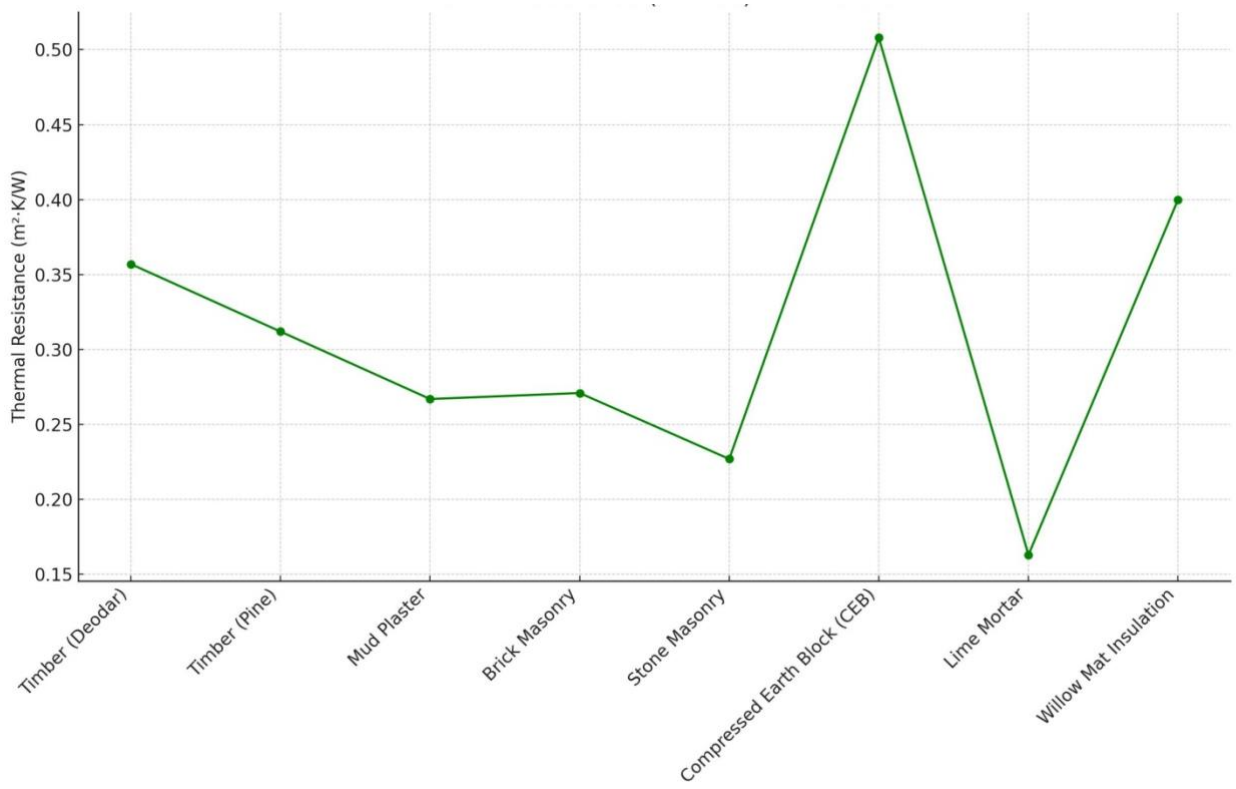


Graph 01: Comparison of thermal conductivity (λ) values for various traditional Kashmiri construction materials, highlighting Willow Mat Insulation and Timber as superior insulators

The moderate performance of Brick Masonry (λ = 0.85 W/m·K) and Mud Plaster (λ = 0.75 W/m·K) suggests that these materials provide some insulation but are not sufficient as standalone insulation solutions. Combining them with additional insulation layers, such as willow mats or timber paneling, can improve overall thermal performance.

2. Thermal Resistance and Its Impact on Heat Retention

Thermal resistance (R-value) measures how effectively a material resists heat transfer. Compressed Earth Blocks (R = 0.508 m²·K/W) demonstrated the highest resistance, making them the most suitable for retaining heat in Kashmiri homes. This is consistent with Ahmad et al. (2019), who found that earth-based materials provide stable indoor temperatures due to their high heat capacity and slow thermal response. Willow Mat Insulation (R = 0.400 m²·K/W) also performed well, confirming that fiber-based materials effectively trap heat within buildings. These results align with Rashid & Naseer (2018), who emphasized the potential of renewable insulation materials in cold climates.

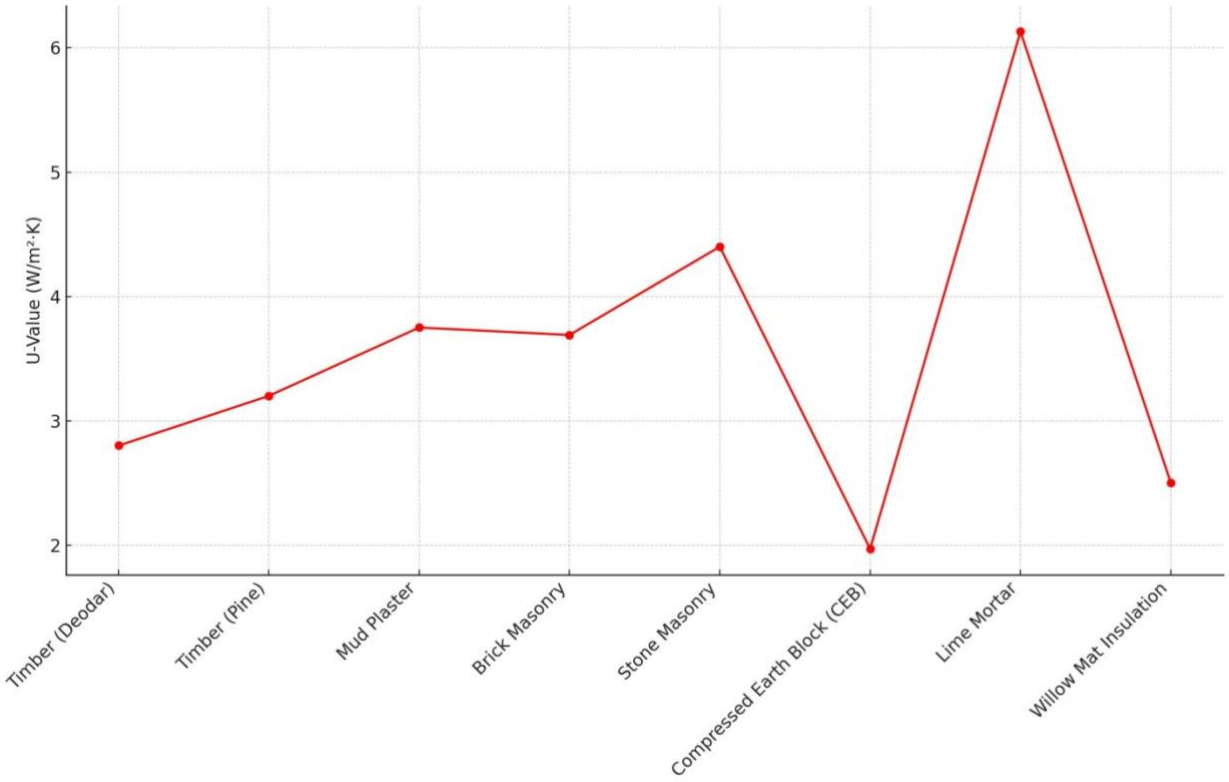


Graph 02: Thermal resistance (R-value) measurements for traditional materials, showing Compressed Earth Blocks with the highest resistance to heat flow

Conversely, Stone Masonry (R = 0.227 m²·K/W) and Lime Mortar (R = 0.163 m²·K/W) exhibited the lowest resistance, explaining why homes made of these materials require excessive heating. This finding underscores the need for additional insulation layers in stone masonry homes to enhance thermal performance.

3. Heat Transfer Coefficient (U-Value) and Energy Efficiency

The heat transfer coefficient (U-value) is a critical indicator of energy efficiency, where lower values represent better insulation. Compressed Earth Blocks (U = 1.97 W/m²·K) and Willow Mat (U = 2.5 W/m²·K) were the most effective in reducing heat loss. These values are comparable to modern insulation materials, reinforcing the viability of traditional materials for sustainable construction. However, materials like Lime Mortar (U = 6.13 W/m²·K) and Stone Masonry (U = 4.40 W/m²·K) had high U-values, indicating poor insulation properties. This correlates with previous research by Wani & Bhat (2020), which reported that stone and cement-based materials contribute significantly to indoor heat loss in Kashmiri homes. The results suggest that modern synthetic insulations like polyurethane foam (U ≈ 0.3 W/m²·K) still outperform traditional materials. However, combining Compressed Earth Blocks with insulating layers (such as willow mats or mud plaster) can create an effective and sustainable alternative to synthetic insulation, which is often expensive and environmentally unsustainable.



Graph 03: U-value analysis illustrating the rate of heat loss through different traditional construction materials, with Compressed Earth Blocks offering the best thermal efficiency

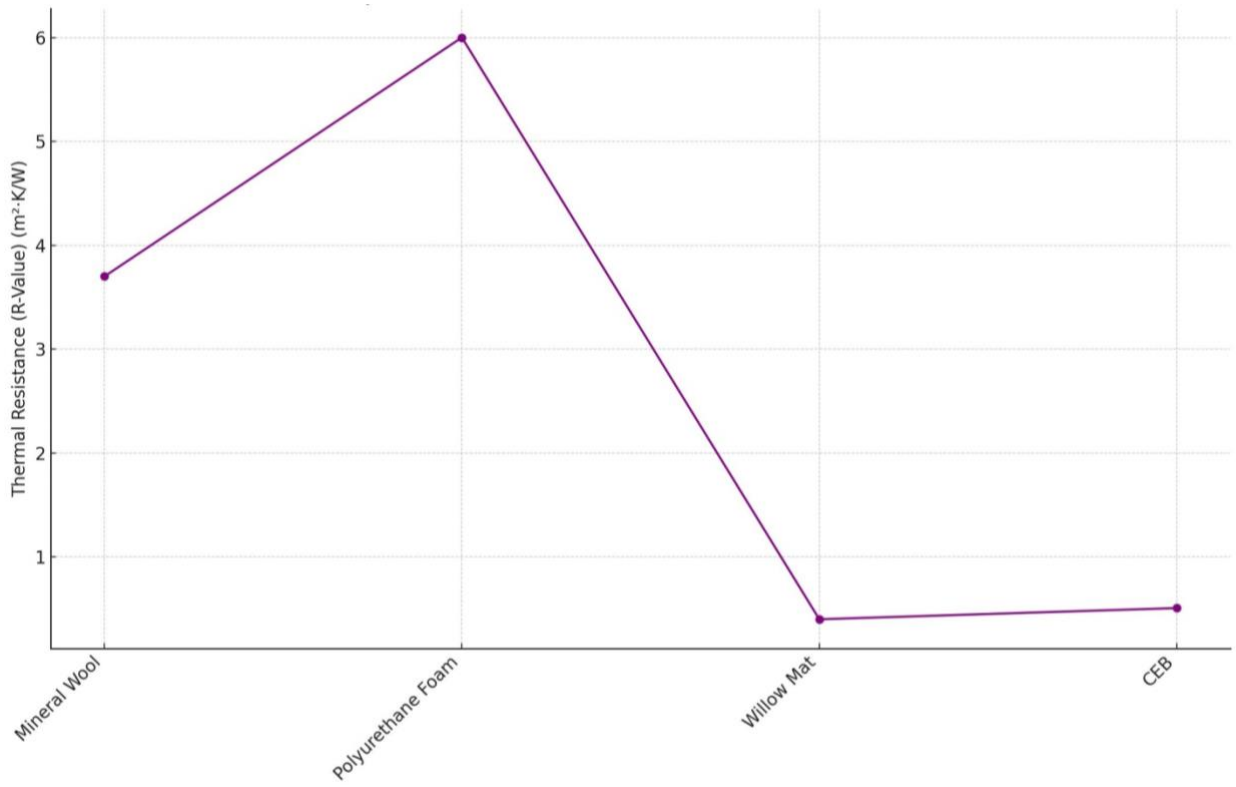
4. Practical Implications for Energy-Efficient Housing in Kashmir

The findings have significant implications for housing design in cold climatic regions like Kashmir:

1. Integrating High-Performance Traditional Materials:
    - Using Compressed Earth Blocks for walls and Willow Mat Insulation for roofing can significantly reduce heat loss and heating costs.
    - Timber-based insulation (Deodar and Pine) can be incorporated into window frames and wall linings to enhance indoor warmth.
2. Modifications to Low-Performance Materials:
    - Stone Masonry and Brick Walls should be supplemented with insulating layers such as mud plaster or fiber insulation to improve thermal performance.
    - Lime Mortar should be replaced with lime-clay composites, which offer better insulation properties.
3. Climate-Specific Construction Guidelines:
    - Homes in high-altitude areas (Gulmarg, Pahalgam) should prioritize Willow Mat Insulation and Thick Mud Walls for maximum thermal efficiency.
    - Urban areas (Srinagar) can benefit from a hybrid approach, combining traditional materials with modern insulation techniques to balance structural durability with energy efficiency.
4. Sustainability and Cost-Effectiveness:

- Traditional materials like mud, timber, and earth blocks are locally available, eco-friendly, and cost-effective, making them suitable for mass housing projects.
- Promoting compressed earth block technology can help reduce reliance on synthetic insulations, leading to lower carbon footprints and sustainable construction practices.

Comparison with Modern Insulation Materials



Graph 04: A comparative analysis of the thermal performance of traditional Kashmiri materials against modern synthetic insulation materials

While traditional materials exhibit decent thermal properties, modern synthetic insulation materials such as polyurethane foam, fiberglass, and aerogels still outperform them in R-value and U-value. However, synthetic insulations:

- Are expensive and less accessible in rural Kashmir.
- Contribute to environmental pollution due to their non-biodegradable nature.
- Require high energy consumption during production, unlike earth-based materials, which are energy-efficient and locally sourced.

Thus, a hybrid insulation approach—combining traditional materials with select modern insulations—can provide optimal thermal efficiency while maintaining affordability and sustainability.

Conclusion

This study provides a comprehensive analysis of the thermal insulation properties of traditional Kashmiri construction materials, with a particular focus on energy efficiency and sustainability in cold climatic conditions. The experimental data demonstrates that different materials exhibit significant variations in thermal performance, influencing heat retention, energy consumption, and indoor comfort. By evaluating thermal conductivity (λ),

thermal resistance (R-value), and U-value, this research offers valuable insights into how local materials can be optimized for improved insulation performance.

1. Findings and Contributions

The experimental results indicate that Compressed Earth Blocks (CEB) and Willow Mat Insulation are the most effective materials for reducing heat loss in Kashmiri housing. CEBs exhibited the highest thermal resistance ($R = 0.508$ m²·K/W) and lowest U-value ($U = 1.97$ W/m²·K), making them ideal for walls and structural applications. Willow Mat Insulation ($\lambda = 0.10$ W/m·K, $R = 0.400$ m²·K/W) performed exceptionally well as a lightweight insulation material, suitable for roofs, ceilings, and wall linings. Conversely, Stone Masonry ($U = 4.40$ W/m²·K) and Lime Mortar ($U = 6.13$ W/m²·K) displayed poor insulation properties, leading to significant heat loss. These findings align with prior studies suggesting that stone-based buildings in Kashmir require excessive heating to maintain indoor warmth. Although stone and brick masonry provide structural durability, they lack the necessary insulation properties to ensure energy-efficient housing.

2. Implications for Energy-Efficient Housing in Kashmir

The results underscore the urgent need to integrate high-performance traditional materials into modern construction practices to improve energy efficiency in Kashmir. Given the harsh winter conditions, it is essential to prioritize materials with low thermal conductivity and high resistance to minimize heat loss. Based on the findings, the following recommendations can be made:

1. Use of Compressed Earth Blocks for Walls:
    - CEBs provide superior insulation and thermal mass storage while being eco-friendly and cost-effective.
    - They can be used as a primary wall material, reducing reliance on concrete and synthetic insulation.
2. Adoption of Willow Mat Insulation for Roofing and Wall Linings:
    - Willow Mat is lightweight, locally available, and has excellent insulation properties.
    - It can be combined with timber panels or mud plaster to further enhance its thermal performance.
3. Improving Traditional Construction with Hybrid Insulation Approaches:
    - Buildings constructed with stone or brick masonry should be supplemented with mud plaster or fiber-based insulation layers to enhance heat retention.
    - Lime mortar can be replaced with lime-clay composites, which offer better insulation properties while maintaining structural stability.
4. Policy and Awareness for Sustainable Construction:
    - Government policies should promote the use of energy-efficient traditional materials to reduce the environmental impact of construction.
    - Public awareness campaigns should educate homeowners and builders on the benefits of sustainable insulation solutions.

3. Comparison with Modern Insulation Solutions

While the study highlights the potential of traditional Kashmiri materials, it also acknowledges that modern synthetic insulation materials such as polyurethane foam, fiberglass, and aerogels outperform them in terms of thermal resistance. However, synthetic insulation materials:

- Are expensive and not widely available in rural Kashmir.
- Have environmental concerns due to their non-biodegradable nature.
- Require high-energy consumption during production and installation.

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Conflicts of Interest

The authors declare that there are no conflicts of interest related to this study.

Data Availability Statement

The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Ethical Statement

This research does not involve human or animal subjects and adheres to ethical standards for experimental studies.

Authors' Contributions

Asif Bashir conceptualized the study, conducted the data analysis, and prepared the first draft of the manuscript.
Amir Arshid contributed to the design methodology, interpretation of results, and critical revision of the manuscript.

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