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Thermal Performance Analysis and Longevity Testing of Innovative Eco-Friendly Building Insulation Materials in Different Climates

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Abstract: The building sector is one of the largest contributors to global energy consumption and greenhouse gas emissions, largely due to heating and cooling demands. Thermal insulation materials play a critical role in improving building energy efficiency; however, conventional insulation materials are often associated with high embodied energy, poor recyclability, and environmental concerns. This study presents a comprehensive thermal performance and longevity evaluation of innovative eco-friendly insulation materials designed for sustainable building applications across different climatic conditions. Natural fiber-based insulation, aerogel-enhanced composites, and recycled material-based insulators were experimentally assessed for thermal conductivity, heat flux resistance, moisture behavior, and long-term durability. Accelerated aging tests simulating hot-humid, cold-dry, and temperate climates were conducted to analyze performance degradation over time. Results indicate that eco-friendly insulation materials can achieve comparable or superior thermal resistance relative to conventional insulators while maintaining structural integrity and environmental compatibility. The findings support the integration of sustainable insulation solutions in climate-responsive building design and energy-efficient construction practices.

Keywords: Eco-Friendly Insulation, Thermal Performance, Building Energy Efficiency, Climate Adaptation, Sustainable Construction

1. Introduction

Rapid urbanization and population growth have intensified energy demands in the building sector, particularly for space heating and cooling. Buildings account for a substantial proportion of global energy consumption, making thermal efficiency a key focus of sustainable development strategies [1]. Thermal insulation materials directly influence indoor comfort, energy consumption, and carbon emissions. Traditional insulation materials such as mineral wool, expanded polystyrene, and polyurethane foams offer effective thermal resistance but pose environmental challenges related to non-renewability, disposal, and embodied carbon. Consequently, research interest has shifted toward eco-friendly insulation materials derived from renewable resources, recycled waste, and low-energy manufacturing processes. However, their long-term thermal performance under diverse climatic conditions remains insufficiently explored. This study aims to evaluate both the immediate thermal efficiency and long-term durability of innovative eco-friendly insulation materials across multiple climatic scenarios.

2. Overview of Eco-Friendly Insulation Materials

Eco-friendly insulation materials encompass natural fibers, bio-based composites, and recycled materials. Natural fibers such as hemp, jute, and cellulose provide low thermal conductivity due to their porous structure and air entrapment capability. Aerogel-based insulation, though relatively new, offers exceptional thermal resistance at minimal thickness [2]. Recycled materials, including recycled glass and textile waste insulation, contribute to circular economy objectives by diverting waste from landfills. Each category exhibits distinct

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thermal behavior, moisture sensitivity, and aging characteristics, necessitating comprehensive comparative analysis.

3. Experimental Methodology

Material Selection and Sample Preparation

Three insulation materials were selected: compressed hemp fiber boards, aerogel-enhanced bio-composites, and recycled cellulose insulation. Samples were prepared in standardized dimensions for thermal conductivity and aging tests.

Thermal Performance Testing

Thermal conductivity was measured using a guarded hot plate apparatus following standardized testing protocols. Heat flux measurements were conducted under steady-state conditions to determine thermal resistance values.

4. Climatic Simulation and Aging Tests

Accelerated aging tests were designed to simulate climatic conditions representative of hot-humid, cold-dry, and temperate regions. Temperature cycling, humidity exposure, and freeze-thaw cycles were applied over extended periods to replicate long-term environmental stress [3]. Changes in thermal conductivity, mass, and structural integrity were recorded at regular intervals to assess material degradation.

5. Results and Discussion

Initial results indicated that aerogel-enhanced composites exhibited the lowest thermal conductivity, followed closely by hemp fiber insulation. Recycled cellulose insulation showed moderate thermal performance but excellent moisture regulation properties. After climatic aging, natural fiber insulation demonstrated slight increases in thermal conductivity under high humidity conditions, attributed to moisture absorption. Aerogel composites maintained stable thermal performance across all climates, highlighting their suitability for diverse environmental conditions [4].

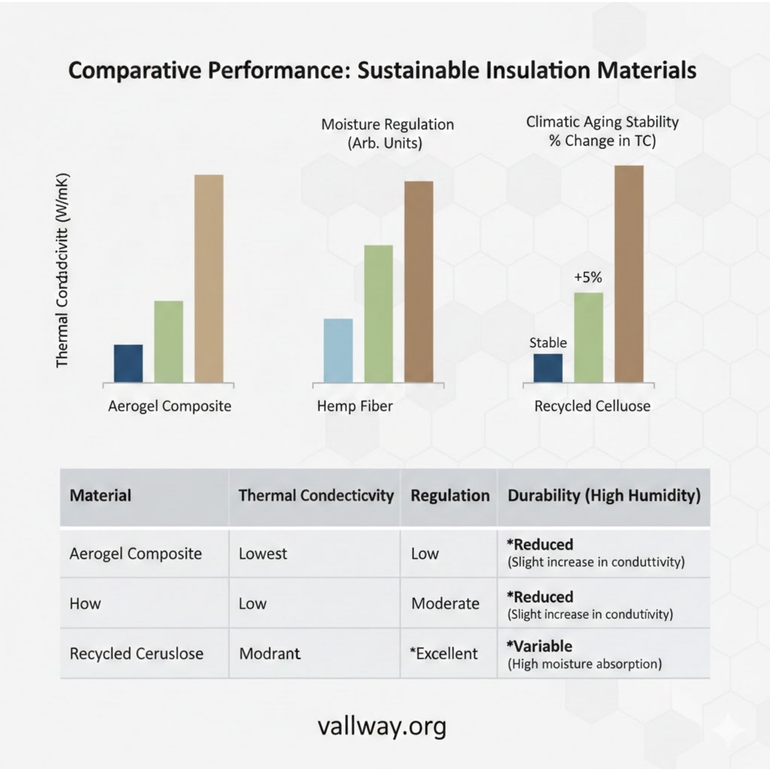

Fig. 1 Comparative Performance

6. Moisture Behavior and Hygrothermal Performance

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Moisture uptake significantly influences insulation efficiency and durability. Hygrothermal analysis revealed that bio-based insulation materials can regulate indoor humidity through moisture buffering, enhancing indoor comfort. However, prolonged exposure to high humidity requires protective design measures to prevent microbial growth.

7. Longevity and Structural Stability Assessment

Mechanical integrity tests conducted after aging cycles showed minimal degradation in compressive strength for aerogel-based materials. Hemp fiber insulation exhibited moderate strength reduction but remained structurally viable for building applications.

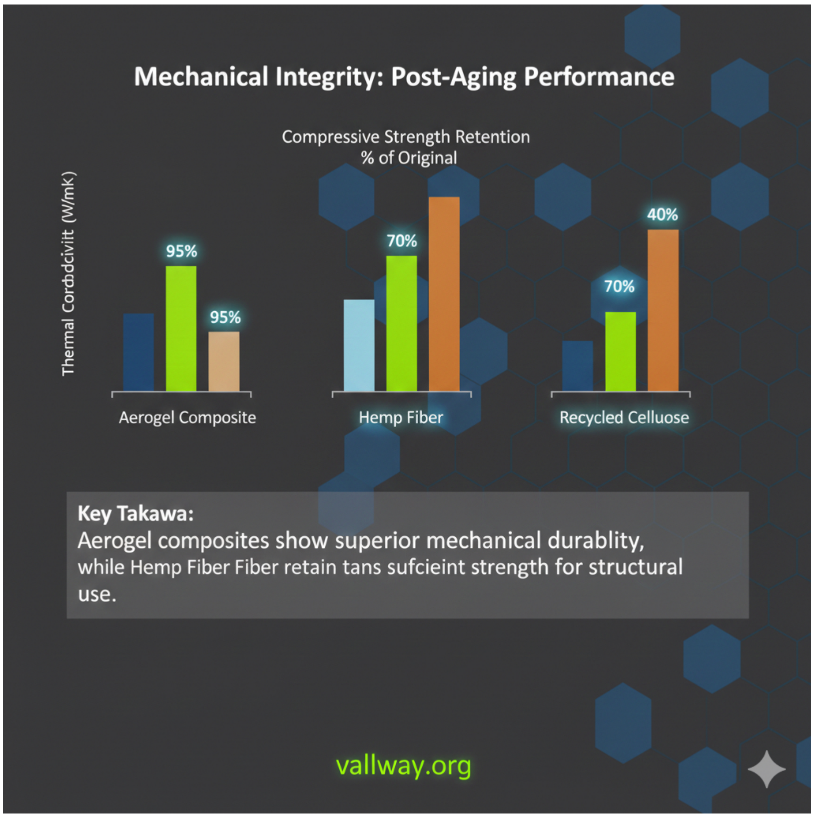

Fig. 2

8. Environmental and Energy Impact Assessment

Life cycle considerations suggest that eco-friendly insulation materials offer significantly lower embodied energy and carbon emissions compared to conventional insulation. When combined with improved thermal performance, these materials contribute substantially to building energy savings over their service life [5].

9. Implications for Climate-Responsive Building Design

The performance variability observed across climatic conditions highlights the importance of climate-specific insulation selection. Designers and policymakers can leverage these findings to optimize insulation strategies for regional climates while meeting sustainability goals.

10. Challenges and Future Research Directions

Challenges include moisture sensitivity, standardization of testing methods, and cost competitiveness. Future research should focus on hybrid insulation systems and surface treatments to enhance durability under extreme climatic conditions.

11. Conclusion

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This study demonstrates that innovative eco-friendly insulation materials can deliver effective thermal performance and long-term durability across diverse climatic conditions. Their integration into sustainable building design supports energy efficiency, environmental protection, and climate resilience.

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