

# Sustainable Building Envelopes: Exploring Alternative Materials for Passive Thermal Regulation Through Hotbox Testing

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## Abstract

Climate change has intensified the need for sustainable building materials that reduce carbon emissions and energy consumption. Traditional construction materials contribute significantly to climate change due to their high embodied energy and limited recyclability. This study is part of a longer project to explore the performance of alternative, sustainable building materials that might be friendlier to the environment. The study is performed using a controlled hotbox experiment. The hotbox, adapted from McCormick's design (2023), provides an accessible, low-cost method for physical testing of thermal performance.

The experimental setup consisted of a double-chambered hotbox, with an interior metering chamber and an exterior unconditioned chamber. Cork, mycelium, and sheep wool materials were developed for initial testing in the hotbox. Temperature sensors recorded heat transfer through the test materials to assess their effectiveness. The results indicated that all three materials performed comparably in limiting heat transfer, with cork maintaining the lowest interior chamber temperature, followed closely by mycelium. Wool exhibited the most stable temperature readings, suggesting strong insulation properties but also potential heat retention. These findings highlight the promise of natural, biodegradable materials as viable alternatives to conventional insulation.

While the study confirms the potential of sustainable insulation materials, further research is needed to refine testing conditions and further develop the hotbox, extend experiments to real-world applications, and evaluate long-term performance under varying environmental conditions. This research contributes to the broader movement towards eco-friendly construction, emphasizing the importance of innovative, accessible testing methodologies in developing climate-resilient building materials.

## Introduction

Climate change has resulted in unprecedented and unanticipated global temperature and carbon emission increases that are projected to intensify in the future. These challenges necessitate a shift towards more environmentally friendly construction practices. Buildings are responsible for 39% of global energy-related carbon emissions: 28% from operational emissions, from the energy needed to heat, cool, and power them, and the remaining 11% from materials and construction (World Green Building Council, 2019). Traditional insulation materials have energy-intensive production methods and are often sourced from petrochemicals, a nonrenewable source. These materials are also rarely recyclable, contributing to the growing issue of construction waste.

Innovative sustainable construction materials offer promising solutions to the challenges caused by traditional construction materials. These alternative materials are naturally sourced, renewable,

biodegradable, and often recyclable. Some are animal-sourced, such as sheep wool, others can be recycled from discarded products in other industries, such as cork, and others are grown and are fungi or plant-based, like mycelium. With new innovations and advancements in technologies, these alternative materials may be able to perform as efficiently as traditional materials, offering additional benefits from their unique properties.

This paper reports on the first phase of a larger project investigating sustainable insulation materials using a simulated environment box. The experimental method involved constructing a controlled hotbox environment, following the hotbox design presented by McCormick (2023). This device allows for affordable, accessible physical testing of materials. The hotbox simulates one thermally controlled chamber (exterior) and one reacting chamber (interior) to test insulation materials. This initial phase focuses on constructing, testing, and calibrating the hotbox to ensure accurate and reliable thermal performance measurements. In this phase of the research, the first materials were developed and used to test the box. The primary objective in this phase was to refine the testing apparatus and methodology. In the next phase, the research will proceed to more comprehensive material assessments. By conducting this foundational work, we aim to contribute to broader discussions on sustainable architecture and inform future construction practices.

## Background

The hotbox design proposed by McCormick was created to address the need for accessible, low-cost physical testing. While digital simulations and technologies have made great advancements, physical testing is still valuable for assessing the thermal properties of new materials. Hotbox testing can be very expensive, costing thousands of dollars, and may require much technical knowledge. These factors prevent hotbox testing from

being accessible to designers and engineers without access or resources.

The hotbox design uses two insulated chambers, an interior metering chamber and an exterior unconditioned chamber, with a material specimen sandwiched between them. This design simplifies traditional hotbox methods by focusing on practical steady-state conditions rather than the stricter requirements of industry-standard apparatuses. The metering chamber is heated using an infrared bulb, while the unconditioned chamber allows ambient environmental changes to be observed. Sensors within the chambers measure dry bulb temperature.

Due to the efficiency and simplicity of experimentation, multiple materials were chosen based on their sustainability and tested using the hotbox: sheep wool, cork, and mycelium. These materials were selected for their renewable, biodegradable properties and their potential as eco-friendly alternatives to traditional insulation.

Sheep wool, historically valued for its insulative properties in clothing, is now gaining attention in other industries. Wool is naturally sourced, renewable, and biodegradable. It is also naturally fire-resistant, and has moisture absorbing properties, absorbing up to 35% of its weight in moisture (Denes et al.), which can help regulate indoor humidity levels. Overall, according to Hetimy et al. (2024), wool exhibits excellent thermal and acoustic insulation, durability, and recyclability.

A study of wool as insulation by Denes et al. showed that wool is an efficient insulator, with a considerable advantage in terms of sustainability. Compared to wool, which is produced from a renewable source, polystyrene is produced from crude oil, which is non-renewable. The thermal conductivity of wool, ranging between 0.038 and 0.054 W/mK, is similar to polystyrene, which ranges between 0.031 and 0.043 W/mK.

The main limitation to wool as a material for large scale construction is its high cost. Sheep wool is significantly more expensive than fiberglass insulation. While fiberglass is mass-produced using abundant and relatively cheap materials, wool requires a more labor-intensive production process that involves ongoing care for the sheep. Other considerations that come up are wool's susceptibility to mold under humid conditions. While its moisture absorption abilities allow it to absorb humidity from a space, it can also cause it to grow mold, which may trigger allergic reactions.

Cork is harvested from the bark of cork oak trees, making it a sustainable option since the tree remains intact. About 70% of cork production goes towards wine bottling (Gil, 2014), most of which is usually then disposed of into landfills. To reduce the amount of cork going to landfills, it can be recycled into building materials such as wall or floor finishes and insulation.

Cork is not commonly used as insulation, but its unique properties make it a promising candidate for thermal regulation. A study explored the effects of adding cork on a live wall (Cortes, 2022). It was seen that adding cork caused enhanced evaporative effects, and in a simulated model, cork on the exterior of a building significantly reduced heating and cooling needs by more than 30%. This indicates that cork may be beneficial in various applications in a building for thermal regulation.

Mycelium is the root-like formation of fungi, which grows quickly on agricultural waste, using very little resources. Its cultivation is highly sustainable, requiring very little energy, water, and raw materials. It produces very little waste, and it's completely biodegradable, decomposing naturally without harmful residues at the end of its life. It also acts as a carbon sink during its growth phase, helping offset emissions associated with traditional building materials. Mycelium can be grown in molds to create bricks or sheets that have the potential to be used

in various parts of a building, from load-bearing walls to insulation.

An assessment of mycelium as insulation using EnergyPlus showed that mycelium reduced inner surface temperature fluctuations by 7.39 and 7.85 degrees Celsius on a typical winter day and 6.48 and 7.64 degrees on a typical summer day (Zhang, 2022) in Albuquerque, NM. These findings highlight mycelium's potential for thermal regulation, particularly in regions with extreme temperature variations. Its low thermal conductivity and natural insulating properties make it an effective material for reducing heat transfer and improving energy efficiency in buildings. While further research is needed to assess its long-term durability and resistance to environmental stressors, mycelium offers significant promise as a renewable and sustainable building material, particularly in passive design strategies.

## Methods

The hotbox used in this study was based on the hotbox design by McCormick, which aims to provide a low-cost and accessible method for thermal testing. Using foam and wood as the primary materials, a double-chambered box was constructed to simulate indoor and outdoor conditions.

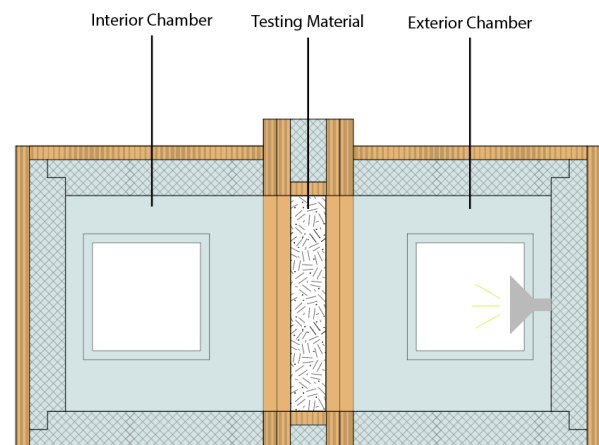


Fig. 1. Hotbox section diagram.

Two key parameters were prioritized in the construction: minimizing thermal bridging with homogeneous, uninterrupted insulation for both chambers and ensuring the box was air-tight. For insulation, 2-inch XPS foam, with an R-value of 10, was used to form the chamber walls. Over this foam, 3/4-inch plywood was used to provide structural durability and improve the box's overall stability. Each chamber included one sealed acrylic window to allow visual access, which was kept small to reduce heat losses. Openings in the box, including those for wires and sensors, were sealed using weatherproofing tape, foam, putty, or 3D-printed components to ensure an air-tight seal. Neoprene sheets were placed between each chamber's plywood components to enhance the seal when the boxes were sandwiching the specimen, and the box was bolted tightly together for added security.



Fig. 2. Interior of hotbox chambers.

The "exterior" chamber of the hotbox was equipped with a heat lamp to simulate outdoor weather conditions. A temperature sensor in the exterior chamber recorded environmental data throughout the experiment. This device was controlled by an Arduino board connected to a relay, which turned on and off based on preset target temperatures. A datalogger in each chamber was recording temperatures during the experiment.

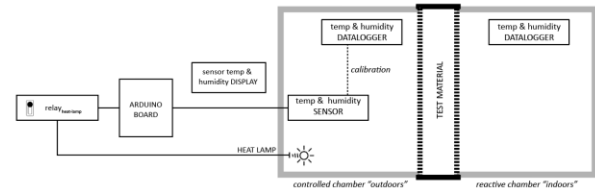


Fig. 3. Controls diagram.

The materials for constructing the hotbox were both inexpensive and readily accessible, with the total cost being about \$500, including the sensors and the controls. This cost efficiency aligns with the goals of the approachable hotbox proposed by McCormick, enabling users to replicate the setup without significant financial investment.

To ensure accurate and reliable temperature measurements, the sensors underwent a thorough calibration process before testing. The calibration involved placing the temperature sensors in a stable thermal environment and comparing their readings to the dataloggers to check for consistency. Any discrepancies were recorded, and necessary adjustments were made through code adjustments. The sensors were checked at multiple points before and during testing to ensure accuracy and to confirm that sensor readings remained stable and consistent. This calibration process was crucial in minimizing measurement errors and ensuring the reliability of the hotbox testing results.

For the material samples, a 12-inch by 12-inch by 2-inch wooden frame was constructed to ensure uniform dimensions across all samples. The cork and wool samples were prepared by cutting them to fit the frame dimensions. The mycelium sample was cultivated using a mixture of agricultural waste, which served as the growth substrate. The substrate was sterilized to eliminate competing organisms, inoculated with mycelium spores, and placed into the wooden frame. Over a period of several days, the mycelium colonized the substrate and was then heat-treated to stop growth and solidify the sample for testing.



Fig. 4. Test materials..

One test was conducted for each of the three materials. Each test lasted one hour, with the exterior chamber preheated to 30 degrees Celsius before starting. Temperature data from both chambers were recorded at regular intervals. The mean, range, and standard deviation of the interior chamber's temperature dataset for each material were calculated to evaluate and compare the thermal insulation performance of the three materials. These metrics provided a quantitative basis for assessing the relative effectiveness of sheep wool, cork, and mycelium as sustainable insulation materials.

**Results**

The tests showed that the wool, cork, and mycelium performed similarly, remaining near the starting temperature of the interior chamber, with small variations. The exterior chamber temperature was set to 30 degrees. After it reached equilibrium at around 13 minutes after the beginning of the experiment, it fluctuated from approximately 28 to 34 degrees.

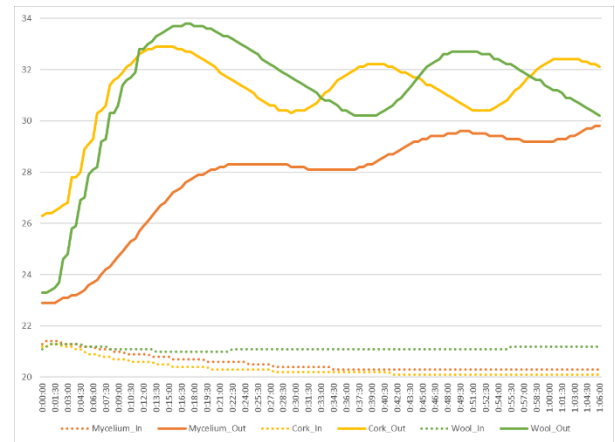


Fig. 5. Time and interior/external temperature graph for mycelium, wool, and cork..

The wool had the most stable interior temperature, even though it had the greatest range of fluctuation in its exterior temperature. The mean “interior” temperature for wool was 21.12 degrees, the range was 0.3, and the standard deviation was 0.07. The range and standard deviation were the lowest of the three data sets, indicating that there was little change in the temperature readings. While the other materials lost more heat through the window than they gained from the exterior chamber, wool seemed to reach a balance of near constant temperature. Based on these preliminary results, wool seems to have the least effective insulation properties.

The cork’s interior chamber temperature dipped the most compared to the other three materials, going from 21.3 to 20.1 degrees. The mean of the interior temperature for cork was 20.34, the range was 1.2, and the standard deviation was 0.33. Cork had the highest range from the materials, suggesting greater variability in thermal performance. Despite this, cork maintained the lowest overall interior temperature, indicating potential to reduce heat transfer. This makes cork particularly promising for applications where maintaining lower interior temperatures is critical, such as in warmer climates or energy-efficient building designs.

The mycelium had the coolest exterior chamber temperature, not exceeding 30 degrees, while the other tests went up to 35 degrees. The mean of the interior temperature for mycelium was 20.56 degrees, range was 1.1, and standard deviation was 0.34. The interior temperature also slightly dipped throughout the test, even as the exterior temperature increased. This indicates that mycelium offers steady thermal performance over time, making it a viable option for thermal insulation in dynamic environments.

In these preliminary tests, all three materials seemed to perform well at insulating the interior chamber from heat transfer. This indicates that they have the potential to offer thermal benefits when used as insulation in larger-scale, real-world applications. The material that maintained the lowest interior chamber temperature was cork, with mycelium performing closely behind and wool maintaining the highest interior temperature. This indicates that cork was the most effective at reducing heat transfer overall.

All three materials had similar results, the interior temperature not changing significantly from the starting temperature. Therefore, while the cork had the lowest temperatures, it can't be conclusively stated that it is the best insulator because the differences between the materials were marginal. In addition, even though the cork had the lowest interior temperatures, it also had the most variation, showing the greatest range. The wool performed the best in terms of stability of interior temperature, with the lowest range and standard deviation.

These findings underscore the potential of all three materials as sustainable insulation options. Their respective strengths highlight the versatility and applicability of these materials in various construction contexts. Further research could explore their performance in long-term, real-world settings to confirm

their practical effectiveness and adaptability to diverse environmental conditions.

## Discussion

The initial-level tests show the potential for wool, cork, and mycelium to perform well when used as insulation in buildings. Further testing of each material will be performed in the next phase to further develop the results and clarify their ambiguity. Future tests should prioritize maintaining a stable and consistent exterior chamber temperature to minimize variables that could influence the outcomes. This would ensure more accurate and reliable comparisons between materials. Future tests should also be longer with higher temperatures in the exterior chamber to allow for observations of larger fluctuations and patterns.

The dropping temperatures in interior chamber for all the tests indicates that the interior chamber loses more heat through its envelope than it gains through the testing material. Steps should be taken to eliminate any potential sources of thermal bridging and heat loss within the hotbox. Ensuring airtight seals and improving the design to reduce unintended heat transfer, such as eliminating the window, will confirm that temperature readings reflect the true performance of the tested materials.

Another observation from the findings in this phase is the need to ensure consistency between different testing materials. This need for consistency is indicated by the mycelium, which seems to have a higher heat absorption capacity, delaying the exterior chamber from reaching the set temperature. Therefore, it is essential to minimize variations in the material structure and interaction with the hotbox environment. One approach to achieving this is by sandwiching each insulation material between layers of a uniform material, such as plywood. By using a uniform outer layer, we can ensure that the primary variable being tested is the insulation performance of the

material itself rather than differences in material density or porosity.

While simulating conditions within the hotbox is valuable for assessing materials, a key limitation is that performance in a controlled environment may not translate directly to real-world applications. Large-scale projects encounter diverse weather conditions, airflow patterns, and user interactions that cannot be fully replicated in a laboratory setting. For example, the heat distribution from a single heat lamp in the hotbox differs significantly from the more complex and varied heat distribution experienced in real buildings. Future iterations of testing could explore using more advanced heating systems to better simulate real-world thermal dynamics.

Another important area for improvement is the ability to simulate a wider range of environmental conditions. Currently, the hotbox is limited to testing materials for insulation performance in hot climates. Developing a method to simulate colder climates, such as incorporating a cooling mechanism or refrigeration system in the exterior chamber, would allow for the evaluation of materials' effectiveness in retaining heat. This enhancement would make the hotbox more versatile, enabling it to test materials for applications in a broader range of climates and environments.

In addition, long-term testing could provide valuable insights into the durability and real-world performance of these materials. For instance, evaluating how the materials perform under prolonged exposure to moisture, UV radiation, or fluctuating temperatures could help identify potential limitations or maintenance requirements. Combining these real-world insights with controlled laboratory tests would provide a more comprehensive understanding of each material's potential as a sustainable insulation option.

Finally, incorporating additional sensors to measure heat flux, airflow, and surface temperatures could provide a more complex picture of material performance and open up new possibilities for material innovation. By addressing these limitations and pursuing these enhancements, the hotbox could evolve into an even more valuable tool for sustainable material testing and development.

### **Conclusion**

This project involved constructing a hotbox and evaluating the thermal performance of nontraditional, sustainable materials such as wool, cork, and mycelium. By analyzing the results from these tests, the project demonstrated the potential of these materials to be used as greener alternatives to traditional materials, especially as greater advancements are developed in these materials. These findings are especially relevant in the context of global warming since buildings must be rethought to bring down carbon emissions.

Furthermore, this study emphasizes the importance of developing accessible, low-cost testing methods, such as the hotbox, to evaluate emerging materials. These tools enable rapid experimentation and democratize material innovation, empowering designers and engineers to prioritize sustainability without the need for expensive resources. By exploring the viability of these nontraditional materials, this project contributes to a broader movement toward reducing the environmental impact of the construction industry.

In the face of an evolving climate and increasing global temperatures, it is imperative to adopt innovative and sustainable solutions. By shifting to sustainable, renewable materials, the construction industry can play a pivotal role in achieving energy efficiency and reducing carbon emissions. This study serves as a step forward in rethinking how we build to adapt to and mitigate the impacts of climate change, providing a foundation for

future research and development in sustainable architecture.

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