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Optimization of Clay, Alumina, and Starch Composition for Enhanced Thermal Insulation Properties

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Abstract

Efficient thermal insulation materials are crucial in improving performance, minimizing energy consumption, and maintaining safety in various industrial applications. This study investigates the influence of varying clay, alumina, and starch compositions on the physical properties of thermal insulation cylinders. Five composite samples were formulated by adjusting the proportions of clay and alumina while maintaining a constant starch content. The samples were evaluated for water content, density, and porosity. Results indicate that increasing alumina content decreases water content and density while increasing porosity. The sample labeled C6-A2 exhibited the highest water content (9.19%) and density (1,087.04 kg/m³), whereas the C2-A6 sample had the lowest water content (8.69%) and density (1,069.93 kg/m³). Porosity ranged from 25.67% to 26.60%, demonstrating that higher alumina content leads to a more porous microstructure due to its larger particle size and reduced cohesion. These results provide insights into optimizing clay, alumina, and starch compositions to develop customized thermal insulation materials with balanced water resistance, structural integrity, and thermal efficiency.

Keywords:
Composite, heat insulation, water content, alumina powder

1 Introduction

Heat insulation is crucial in several industrial applications, from conserving energy in buildings to safeguarding against high temperatures in manufacturing processes [1]. Advanced thermal insulating materials are essential for improving efficiency, minimizing energy usage, and guaranteeing safety in diverse settings [2, 3]. Historically, insulation objectives have heavily relied on materials such as asbestos [4], fiberglass [5], and ceramic fibers [6]. Nevertheless, health and environmental concerns have motivated the pursuit of safer and more sustainable alternatives. Clay, alumina, and starch have attracted considerable interest in this area because of their advantageous characteristics and possibilities for customization.

Insulation is crucial in keeping systems at a constant temperature, avoiding heat loss or gain, and shielding people from dangerously high or low temperatures. Insulation is vital in the construction industry because it makes buildings more energy efficient, lowers heating and cooling expenses, and lessens environmental impact [7]. Insulation aids in the production process by preventing machinery from thermal stress and damage, increasing process efficiency, and guaranteeing that equipment functions properly. Fibers made of asbestos, fiberglass, or ceramic have long served as the go-to materials for insulation. Once highly valued for its heat resistance and durability, asbestos is now mostly avoided because of the serious health hazards it poses, such as lung ailments and cancer [8]. The inexpensive cost and good insulating capabilities of fiberglass keep it in widespread usage, even though it can irritate the skin and create health problems when inhaled [9]. Ceramic fibers provide great thermal insulation and high-temperature stability, but they can be costly and even harmful if exposed to them for too long [10].

New developments in materials science have prompted investigations into inorganic and natural alternatives that may provide longer-term, less harmful solutions. The naturally occurring substance clay is highly regarded for its cheap cost, vast availability, and outstanding thermal stability [11]. Several industries have used it, including ceramics, building, and insulation. Insulating materials can benefit from clay's natural qualities, which include poor thermal conductivity and strong heat resistance. Clay composites have recently been investigated for their potential to improve thermal insulation. An excellent summary of recent studies on clay composites used in TES applications can be found by Voronin et al. [12]. While identifying areas needing additional research and development, it emphasizes clay's promise as an eco-friendly and cost-effective material. Successful deployment of clay composites in TES systems can be achieved by interdisciplinary collaboration, innovation, and practical trials that address the highlighted limitations and dangers.

Made of alumina, also known as aluminum oxide, ceramics have several desirable properties, including excellent thermal conductivity, mechanical strength, and thermal and chemical deterioration resistance [13]. For uses necessitating excellent mechanical durability and heat resistance, alumina-based composites are the subject of substantial research. Insulating materials can have their structural integrity improved and their thermal conductivity kept low by adding alumina [14]. Alumina improves the mechanical properties of insulating composites, making them more robust and durable under harsh conditions. Incorporating graphene and nano-alumina into epoxy-based composites is suggested as a potential method to improve their qualities [15]. The study finds considerable gains in thermal, electrical, and mechanical qualities, but it also points out areas that need more investigation, like environmental effects, scalability, and long-term stability.

Starch is a plant-based organic polymer with promising new applications as an insulating material because of its cheap cost, biodegradability, and renewability [16]. Composites with starch have improved mechanical qualities and lower heat conductivity thanks to the binder's binding capabilities [17]. Scientific research has demonstrated that composites made of starch can significantly improve thermal insulation performance without negatively impacting the environment. A new biocomposite enhancement method is described in [17]. The study shows that hot-water-treated hemp shivs can be used for sustainable building because of improved water resistance and thermal insulation. However, more research and development will be needed to address shortcomings and risks such as long-term performance, scalability, and economic viability to successfully utilize these biocomposite boards in the industry. A sustainable, high-performance thermal insulation material development strategy is presented by Zhao Yan-Wen et al. [18]. CNFs improve thermal and mechanical qualities, showing the composite aerogel's versatility.

Considerable advancements have been achieved in clay, alumina, and starch-based insulating materials. However, further investigation is required to determine the ideal composition of these materials to optimize their insulating capabilities fully. Much is still to be discovered regarding the interaction between these materials and how they collectively impact thermal conductivity, mechanical strength, and microstructure. This study seeks to address the existing knowledge gap by thoroughly investigating how different combinations of clay, alumina, and starch impact the properties of thermal insulation cylinders.

2 Research Methods

This study utilized three materials: clay, alumina, and starch. Each of these materials was carefully chosen for their distinct properties and potential impact on the overall performance of the thermal insulation cylinders. Different compositions were prepared by mixing varying proportions of these materials and then homogenized to ensure a consistent distribution. The mixtures were carefully molded into cylindrical shapes and underwent a series of precise processing steps, such as drying and sintering, to attain the desired physical and mechanical properties. The primary ingredient of thermal insulation cylinders, seen in Fig. 1a, is clay. Clay, as shown, is essential to achieve homogeneity in the composite material due to its consistent consistency and small particle size. Its inherent malleability makes it simple to form into any desired cylindrical shape. It also serves as a strong foundation upon which other materials can be added to increase mechanical and thermal properties.

(a) (b) (c)

Fig. 1. Raw materials (a) clay, (b) alumina powder and (c) starch powder

The alumina powder, shown in Fig. 1b, is a strengthening agent integrated into the composite. Powdered alumina has the appearance of a fine, white crystal and is very strong and thermally conductive. The insulating cylinders' general resistance to heat and durability will be improved by its addition. The composite material's ability to endure high temperatures and mechanical stresses is enhanced by the tiny particle size of the alumina, which is distributed uniformly inside the clay matrix. The composite's organic binder, starch, is shown in Fig. 1c. The starch, visible as a fine, off-white powder, is essential because it provides binding characteristics and lowers the composite's thermal conductivity. Starch, when hydrated and dried, generates a gel-like network that helps distribute clay and alumina particles evenly and strengthens the composite. Consistent with eco-friendly engineering principles, using starch from renewable plants adds to the sustainability of the insulating material.

The three types of materials will be combined in various compositions, as illustrated in Table 1. There are five different variations of test samples, each with different percentages of clay and alumina. However, the percentage of starch remains constant across all samples. Maintaining a consistent percentage of starch is to separate the impacts of clay and alumina on the thermal and mechanical properties of the thermal insulation cylinders. This ensures that any differences observed can be attributed solely to the variations in clay and alumina content. The purpose of sample code C6-A2 is to use clay's excellent thermal stability and plasticity while keeping the alumina content modest enough to increase mechanical strength without sacrificing thermal insulation. Sample code C5-A3 increases the alumina content to improve the mechanical qualities further. However, a significant quantity of clay is retained to ensure strong thermal insulation.

Table 1. Composition of mixed materials

Sample	Mixed composition Clay (%)	Alumina (%)	Starch (%)
C6-A2	60	20	20
C5-A3	50	30	
C4-A4	40	40	
C3-A5	30	50	
C2-A6	20	60	

This balanced composition, sample code C4-A4, represents an equal blend of alumina and clay, offering a middle ground for studying the combined effects of both components on the composite's overall qualities. This sample, C3-A5, has a greater alumina concentration and is ideal for usage that calls for long-lasting insulating materials due to its emphasis on mechanical strength and heat resistance. Code C2-A6 is a composition that aims for maximum mechanical strength and thermal resistance with a heavy alumina dominance; nevertheless, the reduced clay percentage may compromise some thermal insulating performance. The decision to maintain a consistent starch percentage of 20% for all samples is rooted in its function as a binder and its ability to decrease thermal conductivity. By ensuring a consistent starch content, the study can conduct a more precise evaluation of how different clay and alumina ratios affect the properties of the composite. Starch is crucial in creating a uniform matrix that effectively binds the other components, resulting in consistent structural integrity throughout all samples.

This study's experimental technique is shown in Fig. 2. The process consists of three steps: getting ready, making the sample, and testing it.

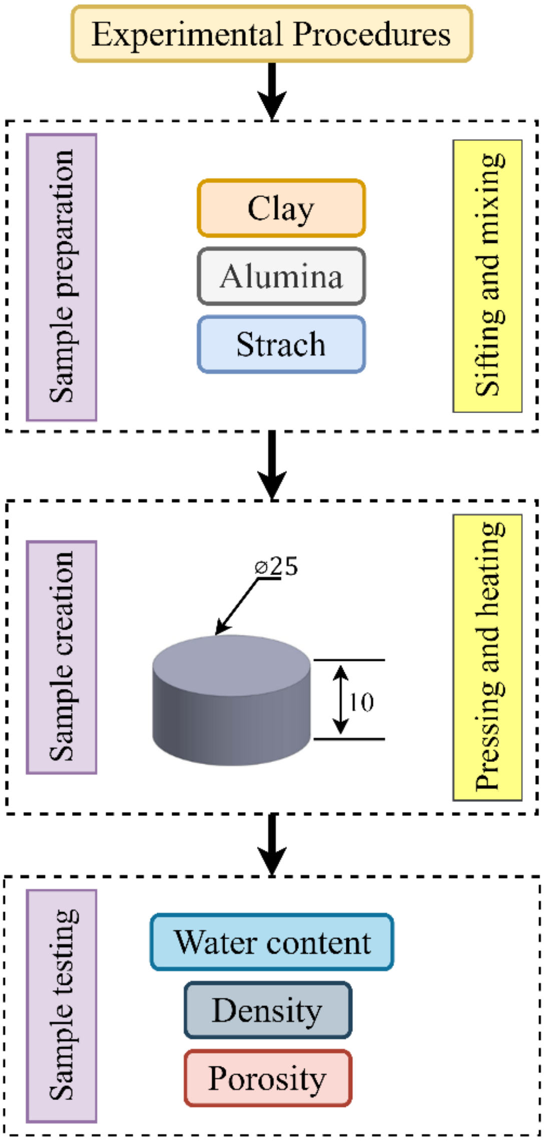

Fig. 2. Experimental procedure for making thermal insulation samples

The first step in getting a sample ready is getting the clay ready. Clay must first be burned to eliminate organic impurities and excess moisture for better thermal and mechanical qualities. Pounding the clay into finer particles is done after burning. The next step is to sift the mixture through a 60-mesh screen to get a constant particle size. This is important because you want your composite to have consistent material qualities. The next step is to create five separate test samples by mixing the ingredients: starch, alumina, and clay—according to the given compositions. To achieve the desired thermal and mechanical qualities in the final product, it is vital to homogenize the mixtures sufficiently so that each component is evenly distributed. Molding the materials into the necessary forms for further testing is the next step after mixing them.

The second step is to make samples, which involves molding and preparing the mixture for testing. The molds used for testing heat conductivity have the same material composition and measure 25 mm in diameter and 10 mm in height. This standard size guarantees that the samples can be evaluated and contrasted consistently. The pressing operation, which requires applying a pressure of 1 ton for 15 minutes, is carried out by placing the mold on a hydraulic press. Precise measurements of heat conductivity are impossible without first compressing the materials to remove air pockets and guarantee a dense, homogeneous structure. Once the pressing is complete, the samples are heated in a furnace. To heat the specimens to a maximum temperature of 800°C and hold them for 1 hour, they are placed in a heating furnace and left there for two hours. The particles are better bonded during the sintering process, which increases the samples' mechanical strength and thermal stability. Regulated heating and holding times are critical to get the necessary microstructural properties, which affect the heat-insulating cylinders' performance.

In the third stage, three important tests are carried out to analyze the samples: water content, density, and porosity. These tests are crucial for analyzing the physical properties of the thermal insulation cylinders and gaining insights into the impact of various compositions of clay, alumina, and starch on their performance. The water content test quantifies the moisture content that remains in the test samples following processing. This parameter is of utmost importance as it significantly impacts the thermal and mechanical properties of the insulating material. Having a high water content can result in a decrease in both thermal resistance and mechanical strength. The water content for the test sample is determined using Eq. (1), usually expressed as a percentage of the original mass of the sample before drying.

$$\mathrm{Wc} = \frac{\mathrm{W_0} - \mathrm{W_1}}{\mathrm{W_0}} \text{ x } 100\ \% \tag{1}$$

Where W_0 is the mass of material before heat treatment (grams), W_1 is the dry mass of material (grams), and W_c is the water content (%).

The density of the material plays a crucial role in determining its thermal conductivity and mechanical strength. It can be described as the relationship between the mass of the material and its volume. Eq. (2) is used to calculate the density of the material in this test. High-density materials typically exhibit superior mechanical strength but may also possess elevated thermal conductivity. On the other hand, materials with low density may offer superior thermal insulation but may have lower mechanical strength. Through careful density measurement, this study aims to find the perfect balance of properties for optimal performance in thermal insulation cylinders.

$$\rho = \frac{\mathrm{m}}{\mathrm{V}} \tag{2}$$

Where ρ is the density, m is the mass of the sample, and V is the volume of the sample.

Porosity quantifies the air cavities or voids present in a solid material. The thermal insulation properties are greatly affected by the level of porosity in materials. Materials with higher porosity tend to have lower thermal conductivity because the air pockets hinder heat transfer. The porosity of the material in this test is determined using Eq. (3). The expression of porosity is a percentage, which signifies the amount of air occupying the volume. This parameter is essential for gaining a comprehensive understanding of the material's ability to insulate against heat.

$$\mathrm{P} = \frac{\mathrm{m_b} - \mathrm{m_s}}{\mathrm{m_b}} \text{ x } 100\ \% \tag{3}$$

Where m_b is the mass of the dry sample of the material (grams), m_s is the mass of the sample after being soaked in water (grams), and P is the porosity of the sample (%).

The experimental data-gathering technique is illustrated in Fig. 3. Several procedures are included to guarantee precise sample measurement and analysis of the composite material. Using a vernier caliper to measure the composite material sample is the initial stage in the data-gathering technique. The vernier caliper provides accurate diameter and height measurements of the sample. The volume of the cylindrical samples must be calculated using precise dimensional measurements to determine density and other relevant attributes. A precise balance weighs the sample once the dimensions have been measured. Accuracy is ensured by recording the mass of the sample to the closest milligram. To determine the density of the substance, the mass data will be input with the volume values. Following the collection of measurements, the data is processed digitally.

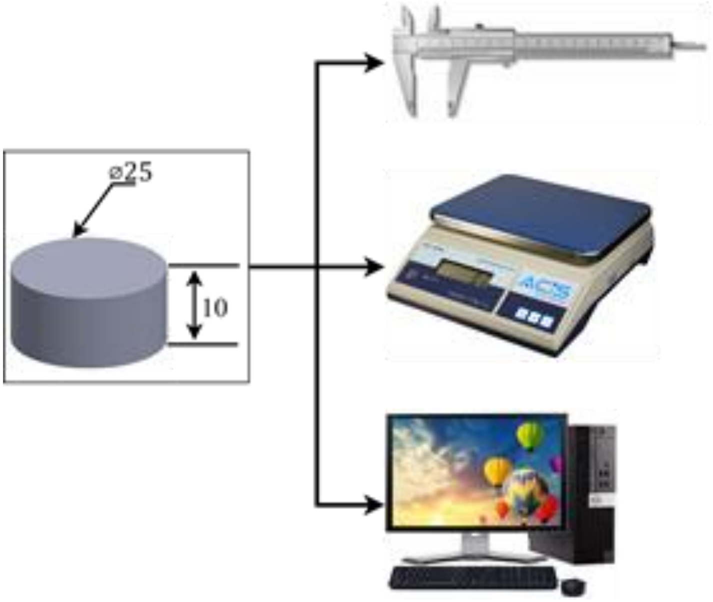

Fig. 3. The experimental data-gathering technique

3 Results and Discussion.

The mass of the sample is displayed in Fig. 4 under various settings and with varying samples. The masses of the samples were 5.30 ± 0.05 grams before they were immersed in water. Following a water immersion, the sample's mass rose to 7.10 ± 0.05 grams, suggesting a water content increase of about 1.80 grams. In addition, 5.80 ± 0.05 grams was the average mass of the sample before heat treatment. The samples' original masses, which average 5.30 grams, are used as a starting point for comparison across various situations. This measurement is essential to comprehending how heat treatment and water absorption impact the composite material.

After being submerged in water, the samples showed a notable rise in mass, reaching an average of 7.10 grams. The material's porosity and ability to absorb moisture are demonstrated by the 1.80-gram increase, which can be attributed to this process. The small standard deviation (±0.05 grams) shows this rise is constant throughout the samples. The average mass of the samples was 5.80 grams before heat treatment. Compared to both the starting and ending masses, this intermediate mass is rather more significant. This finding implies that the material's porous structure retains some absorbed water, even after the initial drying process [19]. Overall, it demonstrates partial water retention.

Soaking the composite material causes its mass to increase from 5.30 grams to 7.10 grams, demonstrating its strong water absorption ability. The degree to which a material is porous determines this quality. The observed mass increase can partly be explained by the absorbed water filling up the empty spaces inside the composite [20]. The initial drying procedure does not remove the absorbed water, as indicated by the mass measurement before heat treatment (5.80 grams). Because there is still some water in the material, optimizing the drying process to have it completely dehydrated may be necessary. This step is critical to ensure the material's stability throughout use and to prepare it for subsequent processing.

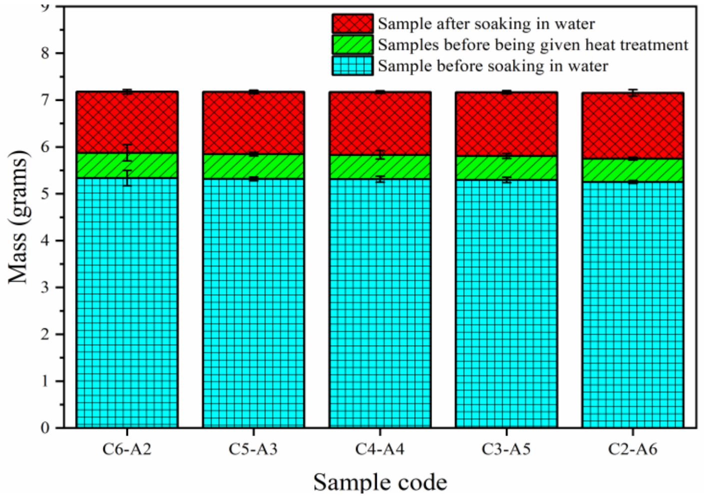

Fig. 4. Sample mass under various conditions

The computed water content, density, and porosity for every sample in the test are displayed in Fig. 5. The water content value for the C6-A2 sample is 9.19%, whereas the value for the C5-A3 sample is 9.06%, which is a little lower. Next, the water content values for the C4-A4 and C3-A5 samples are 8.91% and 8.78%, respectively, while the C2-A6 sample falls at 8.69%. The composition variation of 60% clay, 20% alumina, and 20% starch (C6-A2) has the greatest water content value at 9.19%. In contrast, the C2-A6 sample, 60% clay, 20% alumina, and 20% starch, has the lowest water content value at 8.69%. The water content value of a mixture decreases as the percentage of alumina in the mixture increases. The observed pattern indicates that samples containing higher alumina concentrations have less water content than those containing clay, possibly because alumina has a lesser affinity for retaining moisture [11].

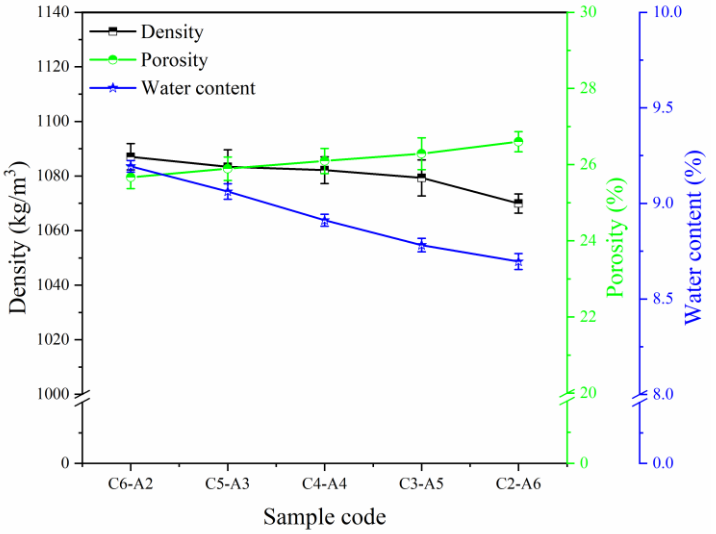

Fig. 5. Thermal insulation characteristics in several composition variations

Fig. 5 illustrates the density value of the C6-A2 sample, measured at 1,087.04 kg/m^3. The density value of the C5-A3 sample is slightly lower at 1,083.37 kg/m^3. The density values for the C4-A4 and C3-A5 samples are 1,082.15 kg/m^3 and 1,079.30 kg/m^3, respectively. The C2-A6 sample has a density value of 1,069.93 kg/m^3. Sample C6-A2 has the highest density value of 1,087.04 kg/m^3, whereas sample C2-A6 has the lowest density of 1,069.93 kg/m^3. Based on the data presented in Fig. 5, it can be observed that there is an inverse relationship between the percentage of alumina powder in the material mixture and the density value of the material. At first glance, this trend may appear counterintuitive, considering the naturally high density of alumina in comparison to clay. Further examination shows that the trend observed may be linked to the development of a more porous microstructure with higher alumina content. This could result from the interaction between alumina particles and the starch binder [21].

The highest density recorded was 1,087.04 kg/m^3, which indicates that a higher amount of clay produces a denser and maybe less porous structure. Due to their smaller size and higher cohesiveness, clay particles may be able to pack more densely, leading to less space and more density. The more noticeable impact of alumina is emphasized by the lower densities of 1,079.30 kg/m^3 and 1,069.93 kg/m^3, respectively. In C2-A6, the density decreases even more as the alumina content reaches 60%. This suggests that the greater alumina may produce a more porous microstructure through its interactions with the starch binder and possibly a larger particle size than clay [22].

Porosity values range from 25.67% for the C6-A2 sample to 26.60% for the C5-A3 sample; 25.89% is a slightly higher porosity value for the C5-A3 sample; 26.08% is the porosity value for the C3-A5 sample; and 25.67% is the porosity value for the C4-A4 sample. Porosity values range from 25.67% in the C6-A2 sample to 26.60% in the composition variation of 20% clay, 60% alumina, and 20% starch. This material's porosity value increased as the alumina % in the combination increased (Fig. 5). It is well-known that alumina, which has bigger particles and less cohesion than clay, increases the creation of voids in composites, and this tendency supports that notion.

The porosity value of 25.67% suggests a compact packing structure with minimal empty spaces. With its high clay content, this composition benefits from the finer particles and increased cohesiveness of clay, leading to decreased porosity. The porosity values of 26.08% and 26.60%, respectively, indicate a notable influence of alumina on the microstructure. When the alumina content reaches 60% in the C2-A6 sample, there is a significant increase in porosity. This indicates that the presence of alumina particles disrupts the compact arrangement of the clay, resulting in more air cavities within the material [23].

4. Conclusions.

The study has provided valuable insight on the effect of clay, alumina, and starch composition on the characteristics of thermal insulation cylinders. The key findings include:

1. Porosity and Water Absorption: Composite samples exhibited an increase in mass from 5.30 ± 0.05 g (dry) to 7.10 ± 0.05 g after submersion, indicating significant porosity and water retention. Residual moisture after drying suggests that these materials can maintain some water content, which may enhance thermal insulation performance by reducing thermal conductivity.
2. Material Composition Influence: Increasing alumina content resulted in decreased water content and density, with the C6-A2 sample exhibiting the highest water content (9.19%) and density (1,087.04 kg/m^3), while the C2-A6 sample had the lowest values (8.69% water content and 1,069.93 kg/m^3 density). These results suggest that alumina contributes to a more porous structure, reducing material compactness and increasing porosity.

These findings highlight the importance of material composition in optimizing thermal insulation properties, providing a foundation for future studies to explore enhanced formulations for industrial applications.

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