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Investigating sustainable insulation materials: Analysis of biofoams and petroleum-derived foams

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SUMMARY
We evaluated the thermal insulation properties of expanded polypropylene (EPP), expanded polystyrene (EPS), corn-based biofoam (CBF), and eggshell-derived polyurethane (PDE) to identify sustainable alternatives to conventional insulators. We hypothesized that bio-derived materials, such as CBF and PDE, could provide comparable or even superior insulating performance while offering significant environmental benefits. Using a heat flow meter, we measured thermal conductivities, revealing that PDE exhibited the lowest conductivity (0.029 W/(m·K), suggesting superior insulative properties compared to EPP and CBF, which demonstrated higher conductivity (0.038 W/(m·K) and 0.045 W/(m·K) respectively). Thermal stability tests under cyclic thermal stress indicated that PDE maintained structural integrity better than other materials, particularly EPS and CBF, which showed considerable degradation. These results support the potential of eggshell-derived polyurethane as an effective, eco-friendly insulation material, warranting further research into its production scalability and environmental impacts.

INTRODUCTION
Pollution has its roots in a vast network of human activities ranging from daily consumer habits to industrial operations, each of which plays a unique role in the decline of the planet's health and the stability of its ecosystems (1). Some of these human activities include deforestation, industrial discharges, vehicle emissions, electronic device waste, synthetic agricultural applications, plastic pollution (2). As a result of the detrimental effects of pollution, the trend of adopting eco-friendly practices is surging nationwide. This reflects a remarkable shift in showing a careful consideration towards environmental consciousness (3).

The next step toward more sustainable practices involves eliminating petroleum-based particle foams due to their detrimental environmental impact (4). These materials are valuable engineering substances used in numerous fields, exhibiting versatile properties depending on the types and compositions of their constituent components. Particle foam is particularly effective in exterior wall sheathing, interior sheathing for basement walls, and insulating roofs down to the foundations of buildings (5). Particle foam refers to a category of porous materials made by expanding plastic particles into a larger, lightweight foam structure, characterized by its excellent cushioning and insulation properties.

Despite the presence of many types of particle foams in the industry, this research will specifically focus on expanded polystyrene (EPS) and expanded polypropylene (EPP). EPS and EPP are materials that significantly harm the environment (6). Styrene and propylene, the major components of EPS and EPP, respectively, are not sustainable or renewable due to their long decomposition time. Additionally, since styrene and propylene are derived from petroleum, these materials can be irritants and possible carcinogens. Their light weight associated with contamination by food or oil makes them difficult to recycle and often impossible. Improper disposal of particle foams pose harm to wildlife since animals can ingest the particle foam and easily choke or starve when the ingested materials cannot be processed by their body systems (7). Additionally, petroleum-based particle foam production is energy-intensive and generates significant greenhouse gases. The hydrofluorocarbons used in its production are released into the air, harming the ozone layer (8). These materials contribute to a lot of environmental problems, mentioning that they tend to persist in the environment because of their resistance to degradation. This, therefore, causes the accumulation of non-biodegradable wastes in landfills and natural habitats that may create long-term environmental risks (9). Moreover, when not disposed of properly, these foams can break down into smaller fragments, adding to the growing problem of microplastic pollution, which threatens aquatic ecosystems and terrestrial wildlife. Finally, harmful substances emitted during the production of petroleum-based foams can off-gas volatile organic compounds (VOCs), which, in turn, can also damage air quality and directly affect human health. (10). Similarly, the production of petroleum-based foams relies greatly on fossil fuels, increasing carbon emissions and therefore depleting non-renewable sources of energy. Together, these problems bring to light the need for new, sustainable alternatives that can minimize their ecological footprint while retaining the practical benefits offered by traditional particle foams.

The first and oldest EPS was developed independently and around the same time by Expanded Rubber & Co. in Great Britain and by Dr. Fritz Stastny at BASF (11). Polystyrene, also known as Styrofoam, consists of spherical beads that contain about 98% air. Since 1958, EPS has been used in packaging solutions and more recently for thermal insulation. The chemical structure includes carbon and hydrogen. EPS has two variations: carbon-containing and non-carbon types. The conversion of EPS into the final product involves a three-step process. The first step, known as pre-expansion,

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increases the bead volume approximately 40 times depending on the desired density. After this stage, called maturation, the beads are stored in special silos for 16-48 hours, allowing the ingress of dry air in a process known as maturation. The final stage is molding, where the product is given its final shape. Here, steam energy and pressure are used to bond the beads together and form the shape of the mold (12). EPS offers many benefits. It is unaffected by moisture, impact, and heat. Its soft structure also protects against pressure, scratches, and dirt. Its thermal insulation capability makes it useful as insulation material in various sectors, from food to construction.

EPP foam is a unique raw material that begins with the addition of special additives to polypropylene. The production process continues by transforming EPP into beads with diameters of 1-3 mm. These beads are then injected into a mold, where steam energy and pressure bond them. The resulting molded product is a highly durable and flexible solid material. EPP foam is developed primarily for energy management applications in the automotive industry and as computer packaging material. EPP has extensive use in the automotive industry for energy-absorbing bumpers, side-impact protectors, and other applications. It's also ideal for applications like hobbyist radio-controlled airplanes due to its ability to absorb impacts repeatedly. EPP is a closed-cell foam, meaning its cells are completely enclosed and do not connect to each other. This structure makes it resistant to a wide range of temperatures, chemicals, and is almost unaffected by water, making it suitable for numerous marine applications. EPP is environmentally friendly and easily recyclable and commonly used for packaging and insulation. The primary distinction between EPS and EPP lies in their polymer composition: EPS is constructed from polystyrene, whereas EPP is made from polypropylene. This difference in material composition results in variations in their physical characteristics, such as density, compression strength, and resilience. EPP is typically viewed as more robust and durable than EPS, which is attributed to its greater density and improved resistance to impacts. On the other hand, EPS is lighter, more cost-effective, and offers superior thermal insulation, making it the preferred option for certain uses like packaging (13). The decision to use EPS or EPP will hinge on the particular need of the application while considering factors such as cost and insulation capabilities.

As a result of the fast-growing environmental concern over the waste of particle foam (EPS, EPP), plant-based materials like cornstarch have emerged as promising alternatives. Cornstarch-based materials, like corn-based foam (CBF), can be molded into various forms, thus offering a versatile option for replacing particle foams in food containers and packing peanuts. The production of corn-based foam starts with extracting starch from corn kernels, serving as a renewable raw material. This starch can be polymerized, yielding a material that is very similar to traditional particle foams. The material is expanded into foam beads and can be molded into different shapes. Finally, the product undergoes curing and drying to enhance the stability of the material. CBF is lightweight strength and thermal insulation, while being inherently biodegradable. These developments represent a major step toward replacement of petroleum-based foams with sustainable and environmentally friendly alternatives.

Another new approach is using eggshell powder, an easily available and otherwise neglected waste material, to improve the ecological sustainability of polyurethane foams. A university-published research study produced polyurethane derived from eggshells (PDE) by synthesizing rigid polyurethane foam composites containing various amounts of eggshell powder. The incorporation of eggshells not only reuses waste but also increases the mechanical and insulating properties of the foam, offering a sustainable alternative to conventional petroleum-based foams. Using eggshell powder, this study gives insight on how to improve both the eco-friendliness and the performance of polyurethane foams to address the urgent need for sustainable insulation materials.

In recent years, there has been a global shift towards seeking more organic compounds as alternatives to petroleum derivatives (14). This trend is driven by environmental concerns and the need for sustainable materials (15). Our research focused on comparing the insulation abilities of organic materials like CBF and PDE. The use of eggshells in polyurethane aims to utilize waste products effectively while offering potential environmental benefits. Similarly, corn-based foam presents a biodegradable option that can reduce reliance on traditional, non-renewable foam. These developments exhibit a sustainable and environmentally friendly alternative for manufacturing and construction. We hypothesized that the materials derived from petroleum, which have been widely applied in several industries due to their strength and insulation properties, can be replaced by bio-based materials such as corn-based biofoam and polyurethane foams derived from eggshells because because of their potential to provide equivalent or even better performance, but with significantly lower environmental impacts. Such materials not only help in reducing the environmental footprint but also open new avenues for using renewable resources in everyday products.

RESULTS

To evaluate the potential of eco-friendly materials to replace petroleum-derived foams for thermal insulation, we measured the thermal conductivity and resistance of various materials using a heat flow meter, including EPS, EPP, CBF, and PDE (**Figure 1**). The thermal conductivity measurements indicated that the EPS variants had conductivity values ranging from 0.03054 to 0.035844 W/(m·K) for carbon and non-carbon types. EPP exhibited a slightly higher conductivity of 0.037524 W/(m·K). The CBF showed a significantly higher

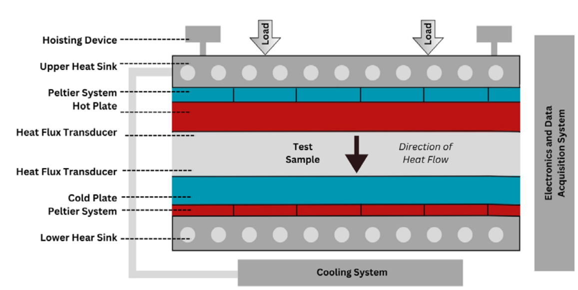

Figure 1. Heat flow meter HFM 436/3. Schematic design of the Heat Flow Meter (HFM 436/3). The device functions on the steady-state heat flow principle, wherein thermal conductivity is calculated by assessing the heat transfer through a sample placed between two temperature-controlled plates. The HFM 436/3's ability to maintain a consistent temperature gradient across the sample, while measuring the resulting heat flux, allows for accurate and reliable thermal conductivity measurements.

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conductivity of 0.045353 W/(m·K), whereas the PDE displayed the lowest value of 0.028817 W/(m·K). The lowered thermal conductivity of PDE reveals its reduced effectiveness in heat transfer, a prime characteristic of a good insulator. This puts PDE into the most promising position for thermal insulation among the compared materials. The low thermal conductivity of PDE indicates its potential to outperform petroleum-based materials in insulation performance, particularly under diverse thermal conditions, as it maintains its low value across varying gradients (**Figure 2**).There was a statistically significant difference in thermal conductivity among the material groups ($F = 19.54$, $p = 0.0075$, ANOVA).

The thermal resistance values, which indicate the material's ability to resist heat flow, were higher for the EPS and EPP materials, with values ranging from 15.6 to 18.3 K/W for the various EPS densities and 16.5 K/W for EPP (**Figure 2**). Notably, the CBF showed a considerably lower thermal resistance of 10.8 K/W, while the PDE aligned closely with the higher resistance materials at 17.8 K/W. This observation highlights PDE's capability to provide insulation performance comparable to EPS, making it a strong candidate for eco-friendly insulation applications (**Figure 2**).

The heat flux, which measures the rate of heat transfer through a material, corresponded inversely to the thermal resistance values. The EPS and EPP variants had lower heat flux values ranging from 1.09 to 1.28 W, while the CBF had the highest heat flux at 1.85 W. PDE maintained a lower heat flux value of 1.12 W, aligning with its higher thermal resistance (**Figure 3**).

DISCUSSION

In this study, we evaluated the thermal insulation properties of EPP, EPS, CBF, and PDE to identify sustainable alternatives to conventional insulators. The results demonstrate that PDE exhibited the lowest thermal conductivity, measured at 0.028817 W/(m·K), indicating superior insulative properties compared to EPP, EPS, and CBF.

The temperature gradient, which refers to the rate of temperature change across a material, plays a critical role in determining heat transfer efficiency. It indicates how heat is distributed throughout the material, and it is very important to understand how effectively the material transfers heat. Normally, the steeper the gradient, the greater the heat transfer rate. The relationship between temperature gradient and thermal conductivity can vary with temperature for many materials. However, in a steady-state heat transfer scenario for a given material, the thermal conductivity is considered constant. According to Fourier's law of heat conduction, the heat transfer rate is proportional to the temperature gradient (17). This implies that at constant thermal conductivity, an increase in the temperature gradient will result in an increased rate of heat transfer. We observed that the thermal conductivity values of the test materials we considered decreased as the thermal gradient increased. A linear relationship indicates a consistent thermal conductivity across the temperature range, suggesting efficient heat transfer that's unaffected by temperature changes. Such analyses are crucial for understanding how different materials behave under varying thermal conditions, which can assist in selecting appropriate materials for thermal management in engineering and scientific applications. Therefore, this research has the potential to contribute to the development of more sustainable materials for insulation applications. One of the major findings in study is the exceptional performance of PDE in terms of thermal insulation. PDE maintained structural integrity better than other materials under cyclic thermal stress, highlighting its potential as a long-lasting insulation material. In contrast, EPS and CBF showed considerable degradation, indicating that these materials may not be as durable in practical applications. According to this comprehensive evaluation and findings, the CBF has demonstrated promising characteristics that suggest it could serve as an alternative to petroleum-derived particle foams like EPP and EPS. This positions CBF and other bio-based foams as valuable subjects for further investigation and

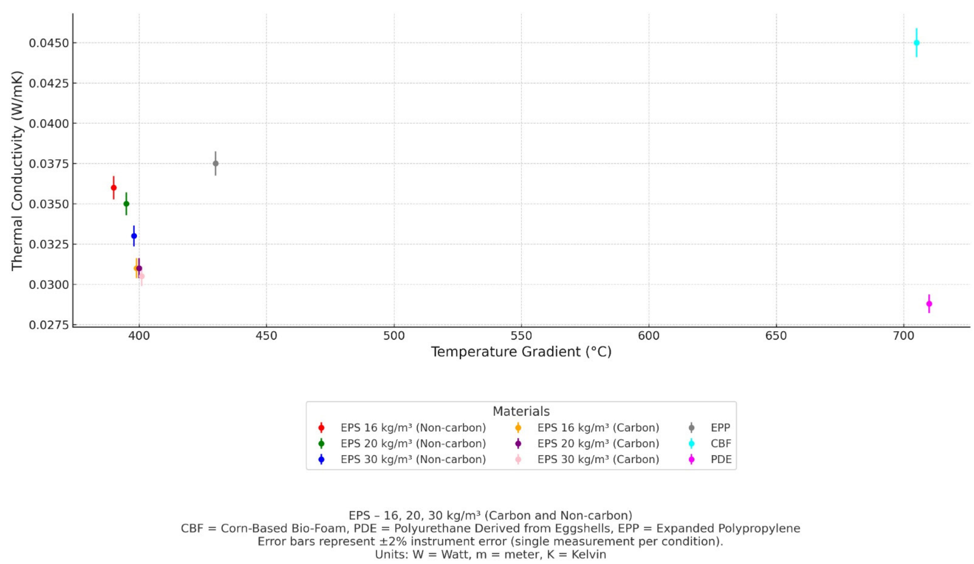

Figure 2. Thermal conductivity and temperature gradient comparison by material type. Relationship between thermal conductivity (measured in W/m·K) and temperature gradients (K/m) for different materials including: expanded polystyrene (EPS), expanded polypropylene (EPP), corn-based biofoam (CBF), and polyurethane derived from eggshells (PDE). Data points represent measurements taken using a heat flow meter and error bars representing a ± 2% instrument error (n=1 per condition).

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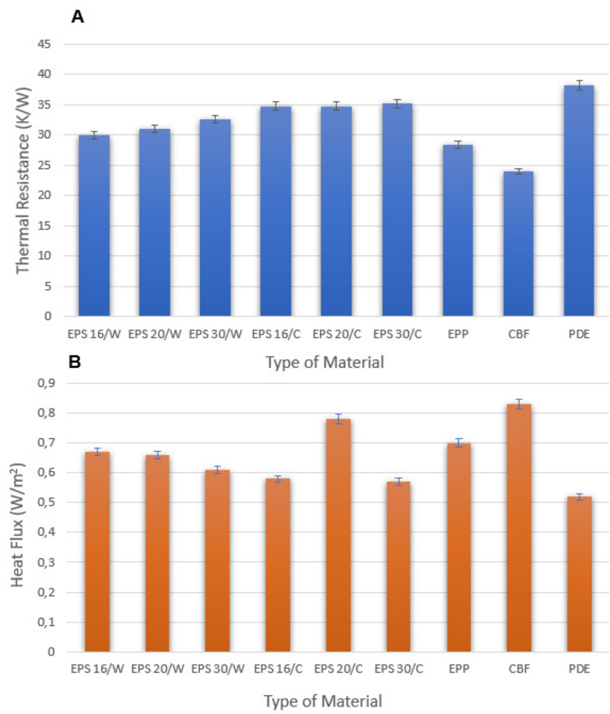

Figure 3. Thermal resistance and heat flux of tested materials. Comparative analysis of **A)** thermal resistance (measured in K/W) and **B)** heat flux (measured in W/m²) for tested materials including: expanded polystyrene (EPS) in both carbon and non-carbon forms at densities of 16, 20, and 30 kg/m³, expanded polypropylene (EPP), corn-based biofoam (CBF), and polyurethane derived from eggshells (PDE). Error bars represent a uniform ± 2% instrument error and are identical in size across all conditions. Units are defined as follows: W stands for watt, m stands for meter, and K stands for kelvin.

exploration of their potential to replace conventional particle foams for various applications.

PDE has been meticulously studied for its thermal conductivity properties, revealing a significant improvement over several conventional materials. The thermal conductivity of this biocomposite is influenced by the incorporating of calcium carbonate ($CaCO_3$) from eggshells, which undergoes a calcination process to form calcium oxide (CaO). The CaO is then reacted with polyols to create a calcium carbonate-polyol mixture, which is used in the polyurethane synthesis. This process results in a material with a lower thermal conductivity than traditional petroleum-based foams and other biocomposites (18).

The unique microstructure of eggshell-derived polyurethane, characterized by the distribution of $CaCO_3$ particles within the polymer matrix, contributes to its enhanced thermal insulation properties. The presence of these particles disrupts the heat flow, leading to reduced thermal conductivity. Measurements have shown that PDE exhibits thermal conductivity values that are superior to those of EPS and some other bio-based foams. This makes it an excellent candidate for applications requiring efficient thermal insulation, such as in the construction, automotive, and packaging industries (19). The improved thermal performance of PDE, combined with its biodegradability and sustainable production process, positions it as a high-performance, eco-friendly alternative. This material not only offers environmental benefits by utilizing waste eggshells but also provides economic advantages with its potential to reduce energy consumption in various applications. The advancement in developing PDE underscores the potential of utilizing waste materials in creating innovative, sustainable solutions in material science.

Our study provides compelling evidence that PDE is a highly effective and sustainable insulation material. This is further supported by statistical analysis, which revealed a significant difference among the tested groups and highlighted PDE's superior insulation performance. However, the statistical robustness of this conclusion is limited by the small sample size for PDE and EPP. Further data collection is essential to validate these findings. Its low thermal conductivity makes it a promising candidate for replacing conventional petroleum-based particle foams (20). As the world increasingly focuses on sustainability and environmental protection, materials like PDE offer a viable path forward. Further research into the production processes and long-term impacts of PDE will be crucial in fully realizing its potential and promoting its adoption in various industrial applications (21).

Additional research is required to make PDE an effective potential alternative to petroleum-based foams. These studies should be performed with an emphasis on lowering cost and scaling up production, coupled with comprehensive durability tests under different conditions — such as humidity, UV exposure, and mechanical stress —to ascertain its long-term performances. A lifecycle analysis, including biodegradability and carbon emissions, will really give insight into the environmental benefits compared to conventional materials.

MATERIALS AND METHODS

We looked at EPP, EPS, CBF, and PDE to explore the effectiveness and viability of these eco-conscious alternatives. The analysis of various EPS samples with different densities helps to better understand how these density variations affect thermal conductivity and insulation performance. This, in turn, provides a more comprehensive standard for evaluating bio-based alternatives.

All samples were prepared to exact dimensions of 305 mm x 305 mm (12 in x 12 in) with a uniform thickness of 100 mm (4 in.), compatible with the NETZSCH Heat Flow Meter HFM 436/3. The above constant dimension was deliberately chosen so that the same test conditions were applied to all materials being tested. This helped ensure that any differences in thermal conductivity or other properties were due to the material composition and not caused by size or geometrical differences. By keeping the dimensions constant, the comparability and reliability of the results across materials tested increased. Measurements were taken from a single sample of each material. Before testing, all samples were properly cleaned to remove surface contaminants for accurate and reliable thermal conductivity measurements. EPP and EPS materials were sourced from a private industrial manufacturer in Turkiye, obtaining products that are commercially available on the market. The CBF sample was made in a custom production process and received from Research&Design department of an industrial production facility in Germany, which specializes in sustainable materials. The eggshell-derived polyurethane foam was produced in a research laboratory in the Department of Chemistry at Eskişehir Anadolu University, from which samples were acquired for this study. Properties and testing of the eggshell-derived polyurethane are extensively discussed

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in previous literature, providing a comprehensive review of its practical effectiveness (22).

Heat flow meters (HFM) are precise, quick, and user-friendly tools designed to measure the thermal conductivity (λ) of low-conductivity materials, such as insulation (**Figure 1**). These meters are calibrated and operate according to ISO 8301 standards (23). A NETZSCH HFM was used to measure thermal conductivity of each material. This method is distinguished by its ability to maintain a steady state, unidirectional heat flux across the specimen by applying a consistent thermal gradient. The heat flow method is suitable to test our hypothesis because it provides measurements of thermal conductivity under very controlled and standardized conditions that are precise and reliable. It is versatile, not only applicable to materials with a thermal conductivity lower than 0.01 W/m·K, but also successfully measures the λ of diverse materials such as wood species and natural plant fibers (24, 25). This approach underscores the method's adaptability and its expanding role in assessing a wide range of materials, from those known for poor heat conduction to more sustainable resources. Moreover, the heat flow method's precision in quantifying thermal conductivity underpins its significance in material science, especially for applications requiring detailed understanding of thermal energy behavior across various materials.

The HFM 436/3 is engineered to assess the thermal conductivity of various materials, from insulating substances like fiberglass and mineral fiber to denser materials such as concrete, wood, and composites. It operates on a steady-state heat flow principle, where thermal conductivity is determined by measuring the heat transfer through a sample positioned between two temperature-controlled plates. This technique is noted for its applicability across a broad spectrum of materials. The device uses thermocouples along with silicone rubber interface sheets to maintain optimal thermal contact and minimize interface resistance, crucial for accurate thermal conductivity measurements. During the assessment, the HFM 436/3 captures temperature and heat flux data to compute the sample's thermal conductivity in a steady state. This involves analyzing the temperature gradient across the sample, ensuring minimal impact from any resistance at the interface between the sample and the plates. For more comprehensive details on the HFM 436/3, including its range of applications and capabilities, NETZSCH Analyzing & Testing and other scientific resources offer extensive insights into the device's use in thermal conductivity experimental studies.

Thermal conductivity measurements were performed on materials with the setup adjusted for temperatures from 0°C to 20°C, targeting the median temperature of 10°C for critical observations. This specific range was selected based on the operational limits of our measuring equipment and the relevance to transformer insulation performance. The experimental setup involved calibrating the lower plate to 0°C, the upper plate to 20°C, and focusing measurements on the resultant 10°C in the middle layer, aligning with the typical operating temperature range for paper insulation in transformers. The values for T_{cold} and T_{hot} were established directly by the Heat Flow Meter equipment, which independently calibrates and controls the underside of the specimen to 0°C and the upper side to 20°C, as part of its standard calibration settings. This calibration ensures equal heating and cooling across the surfaces of the samples. These are fundamental parameters for the machine's operation, which does not require any additional external heating or cooling systems. The measurement time of each sample was determined by the device itself to ensure that thermal equilibrium was reached before measurement. The device applies two temperature-controlled plates, which are in direct contact with the sample in order to heat and cool the surface of the sample. Within these plates, a Peltier mechanism is integrated, which provides accurate control of temperature via a defined thermal gradient. The top plate is heated to the desired temperature, while the bottom plate is set at a far lower temperature. This unidirectionality ensures an effective constant flow of heat through the entire sample, determining thermal conductivity very accurately.

The measurements made during the course of this experiment were done under controlled conditions, in that the temperature in the room where the experiments were conducted was held steady at 25°C. On average, samples were kept in the device for about 1 hour. This whole process was repeated identically for all samples to ensure homogeneity in every respect. The error margin of the measurements was within the equipment's specified range; hence the results are reliable. The standard error, together with the uniformity of the experimental procedure, contributed to minimizing variability in the measurements. Such precision and consistency confirm the validity of the obtained thermal conductivity values. To determine whether thermal conductivity values varied significantly across different material types, a one-way Analysis of Variance (ANOVA) was performed using Python's `*scipy.stats*` library (26). The groups analyzed were EPS White, EPS Carbon, EPP, and PDE, each representing distinct material categories. Due to the preliminary nature of the study, PDE and EPP were represented by a single data point.

Thermal resistance and heat flux calculations

Thermal resistance measures the difficulty of heat conduction between two points. It's defined by the temperature difference across these points divided by the heat flow rate between them. Thus, a higher thermal resistance indicates a greater challenge for heat conduction to occur, and the lower the thermal resistance, the easier it is for heat to pass through. The following equations and image illustrate thermal resistance for thermal conduction.

Heat is conducted from one end of an object to another transitioning from temperature Thot to Tcold across a cross-sectional area *A* and length *L* (**Figure 4**). The thermal resistance *R* of the material can be expressed as:

$$R = d \,/\, (\lambda \times A) \quad \text{(Eqn 1)}$$

where *d* is the thickness of the material, *λ* is the thermal conductivity of the material, and *A* is the cross-sectional area through which heat is conducted. The heat flux *Φ*, representing the rate of heat transfer, is then given by:

$$\Phi = (T_{hot} - T_{cold}) \,/\, R \quad \text{(Eqn 2)}$$

In this relationship, T_{hot} is the temperature at the hotter end, T_{cold} is the temperature at the colder end, and *R* is the thermal resistance. Heat flux refers to the thermal energy transfer rate across a unit area of a surface, such as within a heat exchanger, and is a critical factor in calculating heat transfer. Heat flux can be classified into three main types to differentiate the mechanisms of heat transfer: convection, conduction, and radiation. This classification aids in understanding the specific processes involved.

Initially, we introduce thermal resistance R_{th}, which quantifies the temperature gradient between T_{hot} and T_{cold} as a function of the heat flux. This relationship is established in the first equation. Following this, the second equation delineates *Rth* in terms of the object's physical attributes. Drawing parallels from the visual and mathematical expressions, it's evident that thermal resistance during conduction mirrors the concept of sheet resistance in conductors, where thermal conductivity substitutes for resistivity. Just as resistivity is intrinsic to the conductor's material, thermal conductivity is likewise inherent to the material under thermal analysis.

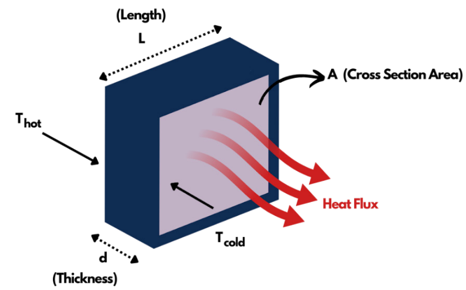

Figure 4. Configuration of material testing. Detailed visualization of the configuration used for testing the thermal properties of various materials. It depicts the process of heat conduction from one end of an object ($T_{hot)}$ to the other end (T_{cold}) across a specific cross-sectional area (A) and length (L). The figure is crucial for understanding the experimental setup, as it illustrates how heat flux (ϕ) and thermal resistance (R) were calculated based on these spatial and thermal parameters.

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