IJAME

Int. J. of Applied Mechanics and Engineering, 2025, vol.30, No.3, pp.87-96
DOI: 10.59441/ijame/207768

EXPERIMENTAL INVESTIGATION OF THE THERMAL BEHAVIOR OF SEMI-SOLID MATERIALS

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In recent years, the problem of solid waste has increased due to the growing population and its needs and solid waste disposal is a severe and widespread problem in both urban and rural areas in many developed and developing countries. Waste recycling is one of the effective solutions to clean the environment. The aim of this study is to obtain useful materials such as thermal insulation from recycled waste such as sawdust, paper waste and PVC plastic waste. Fumed silica is a well-known material used in thermal insulation industries. This research will use fumed silica as a reference of thermal conductivity of other materials. In addition, the results of the study showed a clear effect of temperature on the thermal conductivity of the various materials studied. Also, all samples in this work do not have a specific geometric shape and can be inserted between two walls to reduce heat loss in various applications such as buildings and solar thermal collectors. Also, the density of the waste materials included in this study it is low, so it is possible to make light thermal insulators using. The results, also showed that sawdust has thermal conductivity near to that of fumed silica, which may lead to the ability to mix it and reduce the cost of fumed silica.

Key words: thermal conductivity, sawdust, waste paper, waste of PVC plastic, fumed silica, thermal energy.

1. Introduction

Heat storage systems are acknowledged as one of the efficient solutions to improve energy efficiency in recent years, and have garnered increased attention. Phase change materials (PCMs) using in architectural purposes can increase interior thermal comfort as well as energy efficiency. Due to their poor energy charging/discharging rates, PCMs' thermal conductivity must be improved. To achieve high energy transferring rates, heat conductor additives or inserts are sought to enhance conduction or build the composite PCM. One of the physical properties of different materials that deals with thermal behavior is thermal conductivity. One of the most famous methods used for thermal conductivity measurement is the Lee disk method, which can be described by the method depending on Fourier's law in thermal conductivity measurement. The instrument provided in the present study also uses the same principles as those used in the Lee disk method [1-6]. The high expense of some kind insulators forces researchers to develop new, less expensive insulators [7-8]. To analyze the conductivity of several biomass materials, researchers used Lees' Conductivity device to form sawdust as a thin disc and measuring its conductivity of heat at different temperatures. Because of its high insulating capacity, sawdust can be utilized as a substitute to conventional industrial insulators [9]. The conductivities of certain wood products from Nigeria's forest were examined at three categories of particle sizes, $300\ m$, $600\ m$, and $850\ m$ studied by Oluyamo *et al*. [10]. It has been discovered that each form of disc shape wood wastes with a particle size around of $600\ m$ has a poor heat conductivity ranging from 0.045 to $0.067\ W / m \cdot K$. As a result, they considered these types. To tackle issues in the latent thermal energy storage system, Han *et al*. [11] suggested a phase field model. The effective thermal conduction range is calculated. Sankar *et al*. [12] provided a theoretical technique depended on molecular dynamics (MD) to estimate the improvement of metallic nanofluid thermal conductivity. Four significant interactions between nanofluids are considered. After that, molecular dynamics simulations are run. The

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simulation result agrees well with Maxwell's model, confirming that the MD approach is a viable method for calculating thermal conductivity in many cases. Nomura *et al*. [13] investigated two methods of producing PCM/carbon fiber composites and used the laser flash method to determine the effective thermal conductivity of the phase change composite. The revolutionary hot-press approach is proven to be a better preparing method than the traditional melt-dispersion method. The thermal conduction is effective of the composite (approximately *25%* carbon fiber) is around $30\ W/m\cdot K$, while PCM (erythritol) has a thermal conductivity of $0.733\ W/m\cdot K$. It is clear that a well-prepared carbon fiber composite can significantly improve thermal conductivity. The study was conducted by Yassien *et al*. [14] discusses the thermal conductivity of sawdust with different particle sizes. The results showed the overall behavior of sawdust's thermal conductivity with different particle sizes exposed to different temperatures. The particle size in the present study was selected to be equal to *2 mm* or less than that. It has been found that particle size affected the thermal conductivity when the temperature was relatively low, but at high temperature, the differences were minimized. Li *et al*. [15] developed nanocellulose aerogels from paper waste achieving thermal conductivity values of $0.028\text{-}0.032\ W/m\cdot K$, slightly outperforming our sawdust composites. However, their production process requires freeze-drying equipment that significantly increases manufacturing costs. For recycled plastic composites: Sharma and Patel [16] created thermal insulators from recycled PET with conductivity values of $0.035\text{-}0.040\ W/m\cdot K$. Their materials showed excellent water resistance but lower temperature stability (maximum *200°C*) compared to our waste-derived materials. Chen *et al*. [17] combined recycled polystyrene with agricultural waste achieving remarkable thermal performance ($0.025\ W/m\cdot K$) but encountered challenges with flame retardancy that our materials did not exhibit. After the brief summary presented above, the aim of this study is to measure the thermal conductivity of different materials obtained from waste, to be able to choose appropriate, cost-effective materials that can be used as thermal insulation in various applications. Sawdust, waste paper, and PVC plastic waste are the materials included in this study to compare their thermal conductivities with that of fumed silica. Fumed silica is one of the relatively expensive materials used in super thermal insulation. The other waste materials, in order to make a comparison between them and find the best choice that has advantages from two sides, are included in this study. The first advantage is minimizing the thermal insulation cost, while the second is environment cleaning from the long-lasting wastes.

2. Experimental setup

2.1. Experimental design

The simplest idea that is measuring the thermal conduction is by exposing the test piece to heat flux from one side and dissipating heat to the heat sink from the opposite side. This method depends on the instrument made up in the Technical Engineering College of Mosul (TECM). It is necessary to say that the instrument holds the Iraqi patent numbered (5278). All measuring devices are calibrated and certificated. Figure 1 shows the instrument used in this study and the schematic diagram of it. This diagram illustrates the structure and operation of the thermal conductivity measurement setup. It highlights the circulation of hot water through two differently sized pipes, creating a thermal gradient across the test piece. The heat flux is directed upward due to the thermosiphon effect, enabling the precise measurement of thermal conductivity.

2.2. Technical specifications

The system consists of two main parts, the upper part is for testing, while the lower part is for heat supply. The heat supply system consists of a water tank containing an electrical heater. The increase in water temperature decreases its density, causing the heat to be carried to the upper portion by thermal siphon effect through the connecting pipes. There are two connection pipes with different diameters. The aim of the difference in diameter of each pipe is to create a difference in water temperature inside the pipes. One of the pipes has a larger surface area than the other, so it loses heat to the ambient environment more than the second one. However, the water filling the wider tube will be cooler than in the other. The temperature differences cause the water movement upward in the hotter tube and downward in the opposite tube due to the fluid buoyancy phenomenon. The heat transfer from the lower portion to the upper portion occurs physically by the mechanism shown. The connection pipes are connected between the lower or heat source tank and the upper portion, which is divided into two parts. The first part, of the upper portion, exposes the test piece to heat, while the second part works to dissipate heat from the test piece. The test piece is inserted between the parts of the upper portion of the instrument, and each of them is made from aluminum with a diameter of *99 mm*. The lower part is hotter than the upper part. All of them are insulated from the environment by thermal insulation to minimize heat loss from the system. A Teflon shell covers the instrument parts to protect the inner components. Figure 2 shows the actual shape of the apparatus. This figure provides a real-world view of the patented thermal conductivity apparatus developed at the Technical Engineering College of Mosul. The device includes a heat source tank at the bottom, a test section at the top, and insulated components to minimize heat loss, ensuring accurate readings.

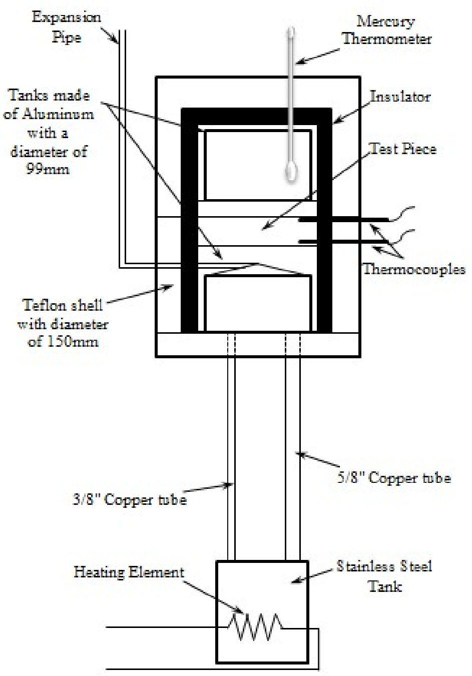

Fig.1. Schematic diagram of the thermal conductivity apparatus.

Fig.2. Thermal conductivity measurement apparatus

To calculate thermal conductivity of a material, it is necessary to know the amount of heat passing through it [18-20]. In this project, the heat dissipation tank contains *0.5* liters of water. The initial temperature of the water inside the heat dissipation tank is measured. Then, the time needed for the water's temperature to increase is computed using a stopwatch. The following formula is used to calculate the heat conducted by the test piece:

$$Q = \frac{m}{\tau} c_p \left(t_2 - t_1\right). \tag{2.1}$$

The amount of heat absorbed by the heat dissipation fluid (water) is represented by Q. m represents the mass of water inside the heat dissipation tank, measured in kilograms. τ represents the time taken for the water's temperature to change from t_1 to t_2 inside the heat dissipation tank, measured in seconds of heat conducted law c_p represents specific heat of the water at constant pressure, which is approximately *4.18* joules per gram per degree Celsius, t_1 represents the initial temperature of the water inside the heat dissipation tank, measured in degrees Celsius. t_2 represents the final temperature of the water inside the heat dissipation tank, measured in degrees Celsius.

A certified electronic thermometer called (AT4208 Handheld Multi-channel Temperature Meter data logger) is used in this work to measure the temperature in different places. This thermometer is used to measure the temperature of the opposite faces of the test piece, as well as the initial and final temperature of the water inside the heat dissipation tank. Figure 3 showing the thermometer is available below. The temperature meter shown here is used for recording temperatures at various key points in the system, including both surfaces of the test piece and the heat dissipation tank. The precision of this device supports the accurate application of Fourier's law in the experiments.

Fig.3. AT4208 Handheld Multi-channel Temperature Meter

The temperature of the heat source is controlled by a thermostat that is fixed in the control box. The control box also includes several controlling devices such as a water level controller to save the electrical heater that is designed to be immersed in water. Auxiliary indicators are contained in this apparatus to ensure its proper functioning.

Fourier's law is a very famous law used to calculate heat conduction by solids. It represents the relation between the conducted heat, thermal conductivity, surface area, temperature difference, and the thickness of the material [21], [22], [23].

$$Q_c = -kA\frac{\Delta t}{\Delta x} \tag{2.2}$$

where Q_c represents the amount of heat conducted by the test piece, measured in watts. k represents the thermal conductivity of the test piece, measured in watts per meter per degree Celsius. A represents the surface area of the test piece, measured in square meters. Δt represents the temperature difference between the opposite faces of the test piece, measured in degrees Celsius. Δx represents the thickness of the test piece, measured in meters.

The general purpose of this work is to confirm the ability of waste materials to be used as insulation to clean the environment. Sawdust, waste paper, and waste PVC plastic are some of the materials tested. The thermal conductivity of these materials will be compared with that of a powder material that is already used as thermal insulation, either in powder form or by mixing with some adhesive materials like cement. Fumed silica powder has been taken as a reference material to compare the other materials' thermal conductivity with its thermal conductivity. The following Fig.4 show pictures the real shape of the samples used in the present study.

a. Fumed silica powder – the reference material for thermal conductivity.
b. Sawdust powder – a common wood waste with potential insulation use.
c. Waste paper – derived from office and printing waste, tested for insulation effectiveness.
d. Waste PVC plastic – collected from industrial production scraps, processed into powder form for testing.

a) b) c) d)

Fig.4. Real shape of samples included in this study:
a) fumed silica powder, b) sawdust powder, c) waste paper, d) wastes of PVC plastic.

3. Results and discussion

Fumed silica is widely used in thermal insulation industries due to its low thermal conductivity. However, the cost of fumed silica is relatively high. Therefore, waste materials may be a good choice to minimize the cost of insulation by partially or completely replacing fumed silica in the thermal insulation industry. This study aims to obtain cheap thermal insulation using recycled materials either by direct usage or by mixing with fumed silica to enhance its advantage by reducing its cost.

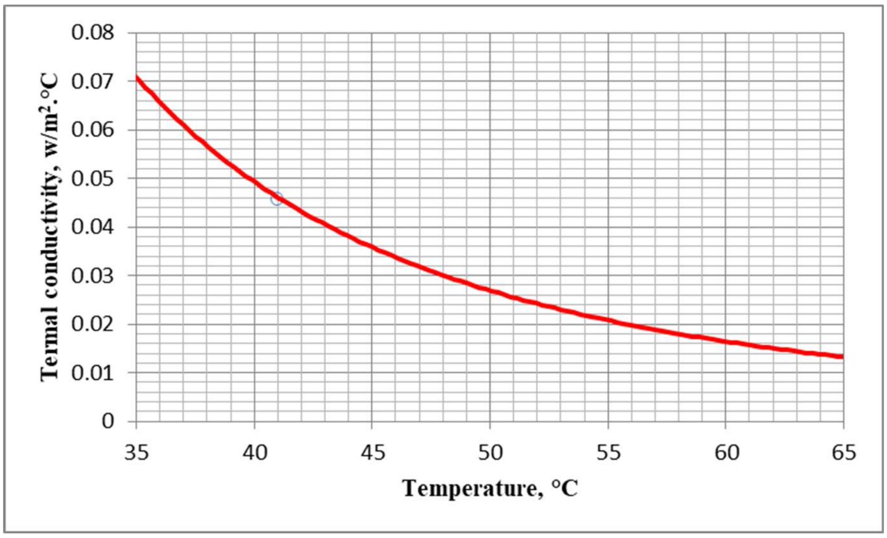

Fig.5. The relation between the temperature and the thermal conductivity of fumed silica.

The fumed silica powder with a density of $48.18\ kg/m^3$ has been tested to study the effect of temperature on its thermal conductivity. The results obtained from the testing are shown in the Fig.5. This graph shows how the thermal conductivity of fumed silica decreases as temperature increases. It confirms its effectiveness as a thermal insulator especially at higher temperatures (above *40°C*).

It is clear that the thermal conductivity of fumed silica is inversely proportional to its temperature. It can be seen that this material is most appropriate as thermal insulation when the temperature exceeds 40°C. The equation governing this relation is given below:

$$k = 1092.4\,t^{-2.712} \tag{2.3}$$

where k represents the thermal conductivity of fumed silica powder, measured in watts per meter per degree Celsius, and t represents the average temperature of the powder, measured in degrees Celsius.

Sawdust is produced during industries that use wood as a raw material. The amount of sawdust around the world is so much that it is very cheap and available everywhere. To get rid of sawdust, it may be burned as a biofuel. This study aims to make the cheapest thermal insulation using waste materials, where sawdust is one of them. The sample of sawdust taken in this study has a particle size up to *2 mm*, and its density is $105.562\ kg/m^3$. The sample of sawdust is dried by exposing it to microwaves that heat it, to delete the effect of the moisture content of the wood. The results of sawdust thermal conductivity measurement are shown in Fig.6. Sawdust exhibits a similar thermal behavior to fumed silica, with decreasing thermal conductivity at higher temperatures. This makes it a promising low-cost alternative or additive to traditional insulators.

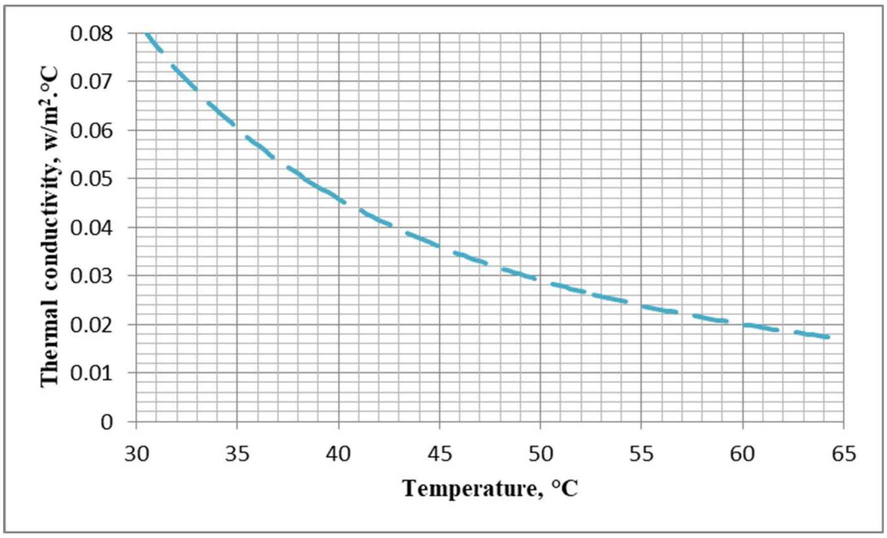

Fig.6. The relation between the temperature and the thermal conductivity of sawdust.

The thermal conductivity curves of fumed silica powder and sawdust are similar in their behavior. The governing formula for this relation is given below:

$$k = 87.936\,t^{-2.049}. \tag{2.4}$$

The next sample is waste paper, which is shown in Fig.4-c. Each office around the world produces a lot of waste paper per year. Recycling paper is a famous process, even in thermal insulation making. The rigid thermal insulation based on waste paper started in Latvia in 2017. Their product is called Eco wool. They found a method to make thermal insulation with fixed dimensions for construction applications. The funds in this field are about *3* million euros. In recent years, this matter has become one of the most seriously discussed topics in environmental cleaning and CO_2 emission reduction studies [24-26].

Above studies have reported on the ability of waste paper to be used as thermal insulation when pressed into uniform shapes with identified dimensions [27-28]. In the present study, waste paper will be used as a filling pack between two walls to reduce heat transfer to and from the conditioned space. The process starts by measuring the thermal conductivity of waste paper with a density of $68\ kg/m^3$, where the dimensions of its particles are $2.5\times 7\,mm$. The sample is inserted into a thermal conductivity measurement instrument where the exposing temperature gradually increases. The results are shown in the curve in Fig.7. Waste paper also demonstrates an inverse relationship between temperature and thermal conductivity. This suggests its viability as a thermal insulation filler, especially when shaped or packed into wall cavities.

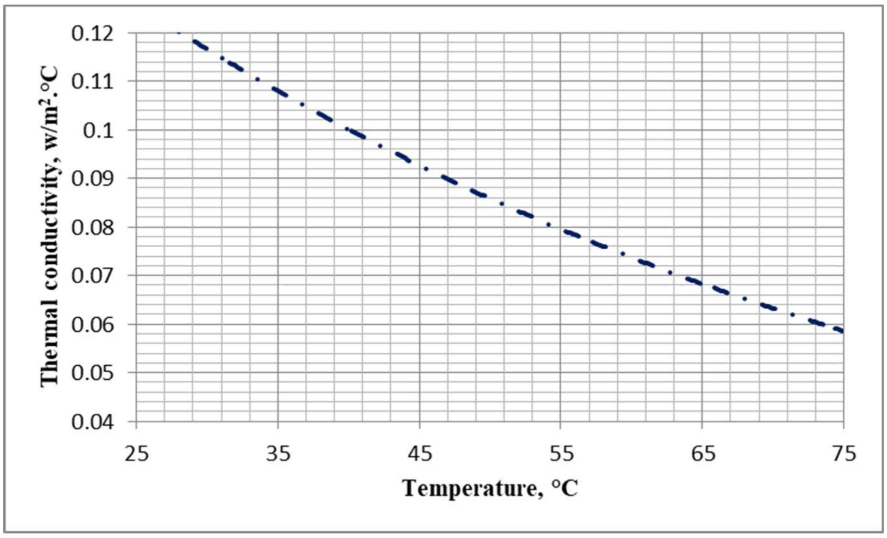

Fig.7. The relation between the temperature and the thermal conductivity of waste paper.

As in the other samples in this study, the thermal conductivity of waste paper is inversely proportional to its temperature. The formula representing the curve in Fig.6 is given by:

$$k = 87.936\,e^{-0.015t}. \tag{2.5}$$

Finally, the waste of PVC plastic is also included in this study. In recent years, the usage of PVC plastic has increased in windows and door frame manufacturing due to its advantages. A large amount of PVC plastic waste is produced due to this industry. This type of waste cannot be consumed by nature because it is not organic and its life cycle is too long. The recycling of PVC plastic is a common process. It is also used as thermal insulation in different applications, such as warm water pipe insulation for solar water heating systems and warm water supplies [29]. Different types of plastic waste are recycled to prevent environmental pollution. In this study, the usage of PVC plastic waste as thermal insulation will be compared with other types of materials shown above for their thermal conductivity. The source of the PVC plastic waste in this study was from factories that manufacture PVC plastic frames for windows and doors. As shown in Fig.4-d, the sample was in powder form to allow for its usage as a filling pack between two walls in buildings or in solar thermal collectors [30].

The density of the PVC plastic sample in this work was $140\ kg/m^3$. The effect of temperature on its thermal conductivity is shown in Fig.8. The thermal conductivity of PVC plastic waste decreases with rising temperature. This supports its reuse as insulation in applications such as piping and structural wall fills, aiding both energy efficiency and waste reduction.

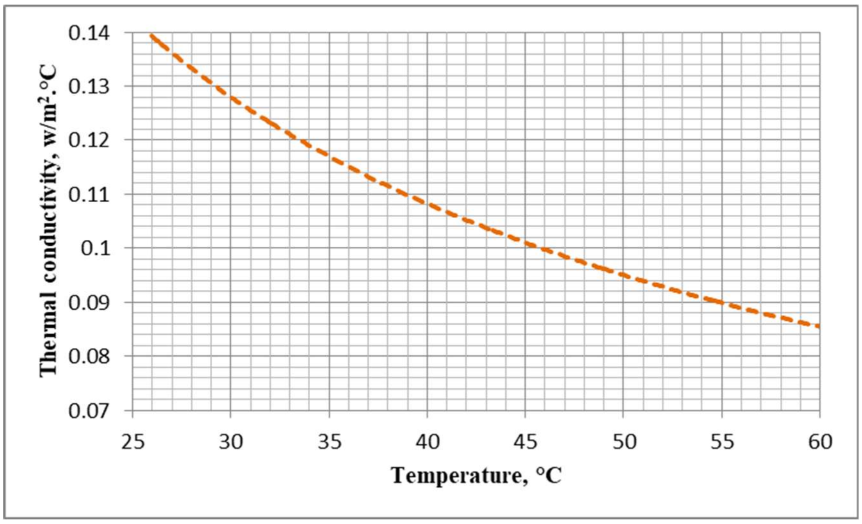

Fig.8. The relation between the temperature and the thermal conductivity of waste PVC plastic.

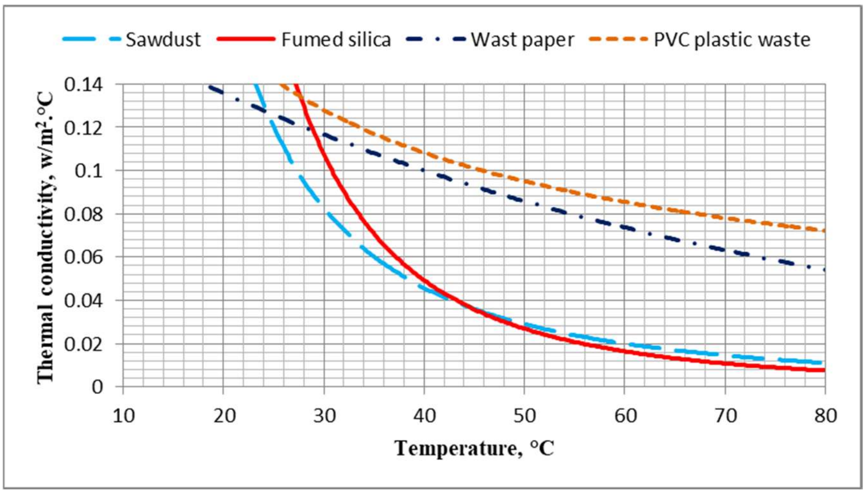

Fig.9. The relation between temperature and thermal conductivity of all samples.

The formula that governing the curve in the Fig.7 is written bellow:

$$k = 0.9313 t^{-0.583}. \tag{2.6}$$

However, the samples in this study are different, but their thermal behavior is the same. The relation between temperature and thermal conductivity is inversely proportional. The general graph that shows the relation between temperature and thermal conductivity of all samples is shown in Fig.9. This combined graph illustrates the thermal performance of all studied materials, highlighting their similar downward trends with increasing temperature. It offers a clear comparative view that supports the feasibility of using waste materials as effective thermal insulators.

4. Conclusions

Thermal behavior of semi-solid materials has been characterized in this study to measure the thermal conductivity of different materials obtained from waste, to be able to choose appropriate, cost-effective materials that can be used as thermal insulation in various applications. Sawdust, waste paper, and PVC plastic waste. From the results, the following conclusions are made:

1. For all samples, the temperature increment negatively affects thermal conductivity.
2. The thermal conductivity of sawdust is similar to that of fumed silica, which can lead to the ability to mix them and decrease the cost of fumed silica.
3. All samples in this study are best suited for relatively high temperatures.
4. The density of the waste materials included in this study is low, therefore, it is possible to make light thermal insulations using them.
5. The unfixed shape of samples in this work gives the advantage of inserting these materials everywhere, because of their unlimited geometry.

Acknowledgment

The authors gratefully thank the staff of the laboratories of Northern Technical University for their support during the realization of the study.

Nomenclature

c_p – specific heat
k – thermal conductivity
m – mass flow rate
Q – heat dissipation
Q_c – heat conducted
t – average temperature of the powder
t_1 – initial temperature of the water inside the heat dissipation tank
t_2 – final temperature of the water inside the heat dissipation tank
Δt – temperature difference between the opposite faces of the test piece
Δx – thickness of the test piece
τ – time

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Received: March 22, 2025
Revised: July 1, 2025