

# Thermal Conductivity Study of Geopolymer Material as a Heat Insulating Material for Thermal Storage

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## Abstract

Thermal insulation is one of the most important components in achieving the ideal thermal storage architecture and becoming the best thermal storage. The primary goals of this work were to investigate the materials employed in geopolymer-based thermal storage structures to determine their elemental composition, measure their density, and analyze their thermal properties, notably their thermal conductivities. This study focused on two parameters: the type of raw samples and the weight of geopolymer material mixes. First, the diameter and thickness of the pellets were assessed after the sample was transformed into a pallet. The SEM-EDX analysis was then utilized to investigate the sample's properties and identify its morphology. The study conducted density measurements to understand their impact on heat conduction in geopolymer materials. Among the mixture samples, the 2g variant showed the lowest density at  $1.752 \text{ g/m}^3$ , while raw limestone had the highest at  $1.826 \text{ g/m}^3$ , followed by coconut peat ash and kaolin. Additionally, the measurement of thermal conductivity was conducted by utilizing a thermocouple to assess temperature, and the application of Fourier's law was employed, revealing that the 6g geopolymer mixture had the lowest thermal conductivity at  $1.3117 \text{ (W/m.K)}$ . In contrast, among raw geopolymer materials, kaolin exhibited the lowest thermal conductivity at  $1.4320 \text{ (W/m.K)}$ . A lower density geopolymer material sample may enhance insulation properties, as lower-density materials typically have lower thermal conductivity. Whereas thermal conductivity is influenced by various material properties such as molecule arrangement, and the presence of certain elements in the sample.

## 1. Introduction

Thermal Energy Storage (TES) systems are essential for efficiently managing energy in applications with temporal mismatches between production and consumption. Ordinary Portland Cement (OPC) based concretes, widely employed in sensible TES, possess a crystalline structure with higher thermal conductivity due to the presence of calcium silicate and aluminate phases. Despite their common use, the elevated thermal conductivity of OPC can be a drawback in certain TES scenarios. In response, geopolymer materials have emerged as alternative solutions, offering lower thermal conductivity than OPC [1]. Geopolymers, formed through the chemical reaction of aluminosilicate materials with alkaline solutions, can be engineered in terms of composition and structure to

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enhance their insulating properties. The amorphous structure of geopolymers contributes to their lower thermal conductivity, making them an attractive choice for TES applications where minimizing heat loss or gain is a priority [2]. This flexibility in material design positions geopolymers as promising candidates for optimizing thermal properties in diverse TES systems.

It is necessary to use thermal insulating materials around thermal energy storage systems to minimize heat losses from the systems [3]. The thermal insulation is provided by embedding insulation materials at least on the roof areas and the vertical walls of the storage systems. Poor thermal insulation of the heat storage systems leads to high heat losses [4]. The study aims to analyze the elemental composition, density, and thermal conductivity of geopolymer materials like coconut peat ash, kaolin, limestone, and barren soil, using SEM-EDX. It also aims to determine the density of these materials by combining kaolin, fly ash, limestone, and barren soil. The density values will be compared with the raw materials densities to understand density variations. The research also focuses on the thermal conductivity of geopolymer insulator materials, providing a comprehensive understanding of the investigated geopolymer materials.

Heat transfer is the transport of heat (energy) caused by variations in temperature and consequent distributions of temperatures and changes [5]. It is a process of the temperature distribution of heat transfer as a function of time; in thermodynamics, the system is in equilibrium. Heat transfer processes are classified into three types: conduction, convection, and radiation. Conduction is a heat transfer process where energy is exchanged between high and low temperature regions in solids or quiescent fluids due to a temperature gradient [6]. Heat transfer has been frequently used in industrial heat exchangers for instance, in a variety of industries, including power generation plants, chemical processing plants, oil and gas, and others [7].

Thermal conductivity,  $k$ , is defined as the rate at which heat is transported by conduction through a unit cross-section area of a substance when a gradient of temperature exists transverse to the area [8]. If temperature gradients exist, energy may be carried to cooler regions of the specimen, and thermal conduction is the phenomenon by which heat is moved from high to low-temperature regions in a substance. The thermal conductivity of the material is estimated using Fourier's law of heat transmission,  $Q = -kA \, dT/dx$ . The temperature gradient, or the rate of change in temperature per unit length of the path, was comparable to the quantity of heat energy transferred per unit of time [9].

The thermal conductivity of geopolymer materials is a significant aspect in determining their suitability for thermal insulation and energy storage applications. According to research, geopolymer materials can have low thermal conductivity, making them suitable for use as heat-insulating materials and in thermal energy storage systems [8]. A study on geopolymer containing polypropylene fibre, for example, discovered that the thermal conductivity ranged between 0.19-0.82 W/m.°C [10], showing its potential for thermal insulation. Another study found that the thermal conductivity of fly ash geopolymer was greatly lowered by the combined impact of several foaming ingredients, making it acceptable for thermal insulation applications [11]. Previous research on geopolymer concrete's use for thermal energy storage supports its benefits as heat insulators and thermally stored energy materials. Therefore, the research has focused on the results of thermal conductivity for heat insulation utilizing geopolymer material.

## 2. Materials and Methods

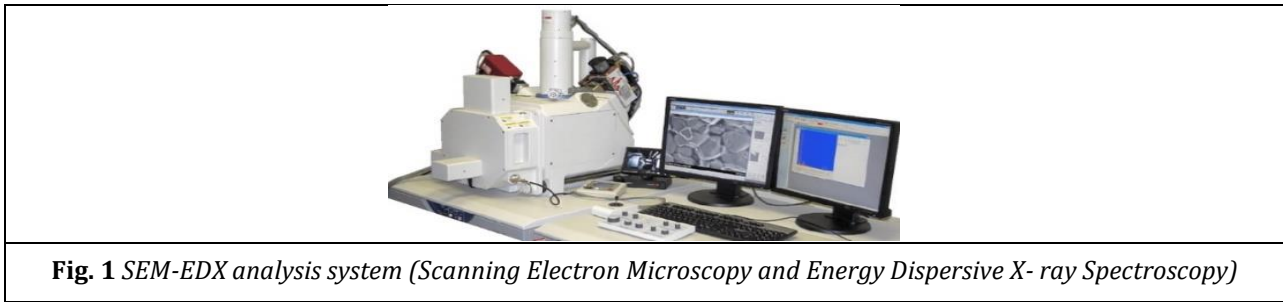
### 2.1 Sample Preparation

In this investigation, the raw materials were ball milled and screened with 250-mesh sieve (75  $\mu$ m). The obtained powders were then weighed at different weights—2g, 3g, 4g, 5g, and 6g for each raw sample. For example, in the case of a 6g sample, the individual masses of raw kaolin, limestone, coconut peat ash, and barren soil were adjusted to 1.5g each. Then, the mixture samples were mixed with the kaolin itself as the binder. The mixtures were pressed by 5-ton pressure using hydraulic compressor machine, moulding it into the shape of a pellet. The formed green bodies were dried in an electrical oven heated at 110 °C for 24 h. The samples were classified into two groups: raw samples and geopolymer material mixtures. The raw samples were formed into a standardized weight of 5g, while the geopolymer material samples were shaped into cylindrical pallets of different weights—Despite sharing a consistent diameter, the thickness of each pallet varied based on its weight, introducing a nuanced aspect to this study.

### 2.2 Sample Characterization & Thermal Conductivity Measurement

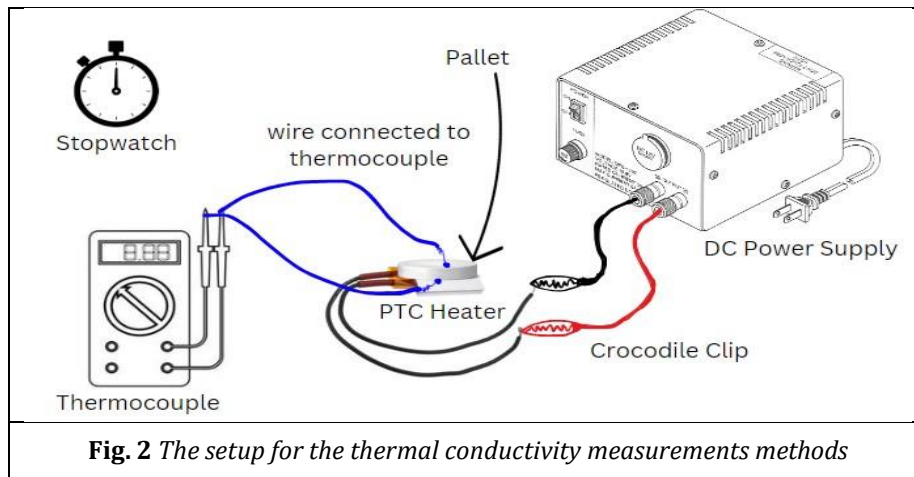
The study utilized SEM and EDX to acquire a morphology structure and elemental composition for a sample. Analytical microscopy using electrons, a technique that combines SEM and EDX, examines nanoparticle structure, size, and composition. The process firstly involves ensuring samples are dry and heat-treated raw material for 24 hours. Then, the samples were coated with Au, a strong electrical conductor, to reduce non-conductive substances and improve SEM picture resolution. This coating reduces charge on the sample surface, resulting in clearer

images at the end of the process. Fig. 1 depicts SEM-EDX analysis system (Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy) used in this study.



**Fig. 1** SEM-EDX analysis system (Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy)

The process of measuring thermal conductivity, as depicted in Fig. 2, involved connecting cables to both the DC Power Supply and the PTC heater. In this experimental setup, the PTC heater functioned as the device to heat the sample. Placing the sample on the PTC heater involved applying a small amount of thermal paste between the heater and the pallet to ensure even heat distribution. After turning on the switch, the DC power supply was set to 5V to generate electricity for the PTC heater and initiate heat conduction to the pallet. Two thermocouples were used on both the hotter and colder sides to measure the temperature, with readings taken every 2 minutes for a duration of 20 minutes. Measurements were spaced every 10 minutes to verify temperature stability. Subsequent to each measurement, the heater was reset to 5V, and the entire process was repeated three times for each sample to obtain mean values.



**Fig. 2** The setup for the thermal conductivity measurements methods

### 2.3 Density and Thermal Conductivity Measurement

Density measurement was done using density formula, calculating mass per unit volume of geopolymer samples. Volume was obtained by multiplying length, width, and height, and mass was weighed individually as shown in Equation 1.

$$\text{Density } (\rho) = \frac{\text{Mass of sample (kg)}}{\text{Volume of the sample (m}^3\text{)}} \quad (1)$$

Where volume of the cylinder is as follows in Equation 2.

$$\text{Volume of cylinder} = \pi r^2 h \quad (2)$$

Meanwhile, for temperature gradient throughout the length of the pallet and the material's coefficient of thermal conductivity were estimated using the Fourier's law of heat transfer equation:

$$\text{Thermal conductivity, } K = \frac{Q(W) \cdot L(m)}{A(m^2) \cdot \Delta T(^{\circ}C)} \quad (3)$$

Where  $K$  denotes the conductivity of heat in  $W/m$ .  $A$  represents the surface area in square meters,  $Q$  represents the heat transfer rate through the substance in Joules/second or Watts, the rate at which heat is transferred through the substance is measured as  $Q$  in Joules/second or Watts,  $L$  represents the measurement of the distance between the two isothermal planes, and  $\Delta T$  represents the Kelvin temperature difference. The radius of the geopolymer materials pellets will be utilized to determine the surface area, thickness, and diameter [10]. The following Equation 4 is the cylinder's surface area formula:

$$A = 2\pi r^2 \tag{4}$$

When there was two different shape of round sample's surface and a square shape of PTC heater, hence the equation of (5):

$$A = \text{area of square} - \text{area of circle} \\ A = (\text{length} \times \text{width}) - (\pi r^2) \tag{5}$$

Calculation of the other data were as follows as in Equation 6 and 7:

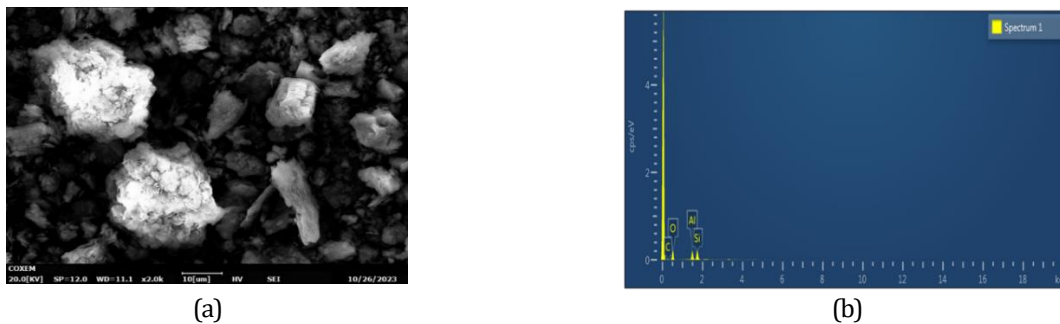
$$\text{Thermal difference, } = T_1 - T_2 \tag{6}$$

$$\text{Heat transfer rate, } q = q \left( \frac{w}{m^2} \right) \times A (m^2) \tag{7}$$

### 3. Results and Discussion

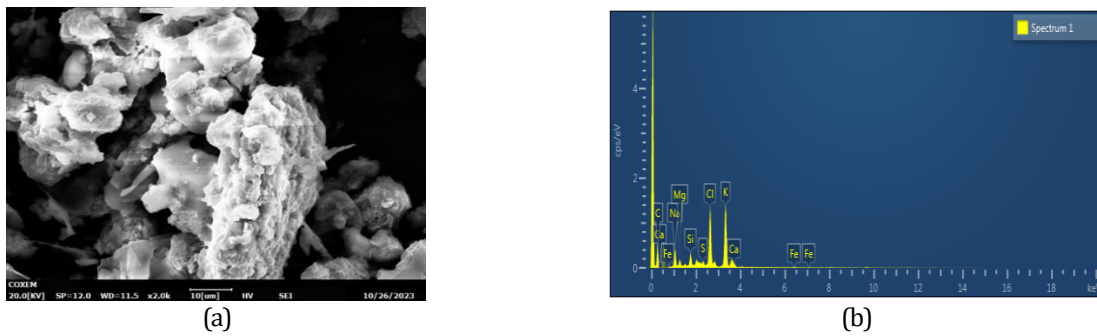
#### 3.1 Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDX) Analysis

The geopolymer composite samples were photographed and analyzed using scanning electron microscopy (SEM) to allow for the visual inspection of the morphology, agglomeration, and interface of insulating geopolymer material. The electron micrograph, EDX-spectrum, and elemental percentage of four different raw samples are provided in Figure 3-6.



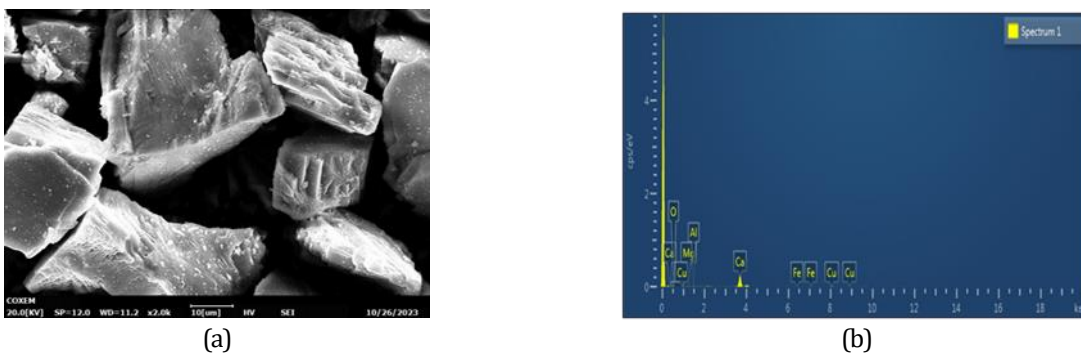
**Fig. 3** The surface morphology and elemental analysis of raw kaolin (a) SEM image (b) EDX spectrum

According to the analysis, the structure of raw kaolin can be characterized by an irregularly shaped porous cellular arrangement of particles. The elemental composition of raw kaolin, primarily consisting of Si, O, Al, and C as shown in Fig. 3, indicates a predominant presence of oxygen at approximately 56.59% of atomic composition, surpassing the other elements. Silicon, aluminum, and carbon follow with atomic percentages of 7.85%, 7.18%, and 28.38%, respectively. The higher percentage of oxygen suggests its prevalence within the porous structure of the sample. Silicon is identified as the second most abundant element within raw kaolin.



**Fig. 5** The surface morphology and elemental analysis of raw barren soil (a) SEM image (b) EDX spectrum

Subsequently, particles of raw barren soil are closely packed, yet there are noticeable void spaces, or porosity, between them, presenting a fairly homogenous and coarse structure. The EDX spectrum analysis, depicted in Fig. 5, reveals the elemental composition of raw barren soil. Oxygen dominates with the highest percentage at 62.34%, followed by silicon at 10.65%, aluminum at 10.06%, and carbon at 4.5%. The data underscores that oxygen is the most prevalent element in raw barren soil, while carbon represents the least abundant. Despite its relatively low proportion, carbon still retains the ability to function as a heat insulator.

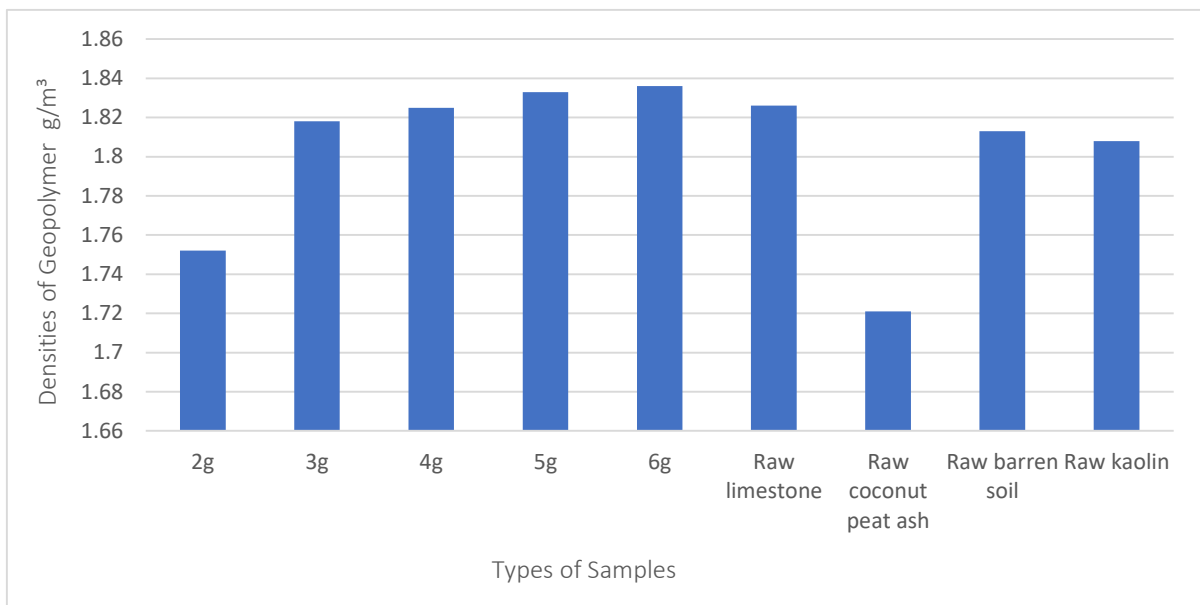


**Fig. 6** The surface morphology and elemental analysis of raw limestone (a) SEM image (b) EDX spectrum

Lastly, the structure of raw limestone can be characterized by a coarse crystalline texture with a granular appearance, as depicted in Fig. 6. The spectral analysis of raw limestone reveals the presence of oxygen, calcium, aluminum, and magnesium. The predominant element in Fig. 6 can be delineated in terms of percentages: 75.79% for oxygen, 4.3% for calcium, 0.65% for aluminum, and 4.5% for magnesium. The analysis indicates a higher carbon content in raw limestone compared to raw kaolin. However, both samples include the crucial carbon element necessary for effective heat insulation in a system due to carbon's covalent bonding. Materials with robust covalent bonds exhibit lower thermal conductivity, making them more efficient insulators. The study posits that materials based on carbon demonstrate exceptionally high intrinsic thermal conductivity due to their strong sp<sup>2</sup> bonding. Additionally, these materials boast various advantages, such as low thermal expansion, mechanical strength, flexibility, and a lightweight nature [12]. Considering the significant carbon content in kaolin and its combination with raw coconut peat ash, which also has a substantial carbon component, the resulting mixture could prove effective for insulation against heat. The collective properties of these constituents, particularly their carbon content, may contribute to an improved capacity for thermal insulation in the composite material.

### 3.2 Density Measurement

For density measurement in this study, a calculation method was employed utilizing the data gathered during the research. This approach involved analyzing the collected data to determine the density of the material under investigation. The calculation method served as a reliable means to derive accurate density values as in Fig. 7, providing the reading of the samples for understanding the physical properties of the studied materials.



**Fig. 7** Calculated density values ( $g/m^3$ ) of geopolymer samples for different type of samples.

In general, lower-density compounds have lower thermal conductivity. From the analysis, the 2g mixture of geopolymer material sample has the lowest density at  $1.752\text{ g/m}^3$ , while the 6g mixture of geopolymer material sample has the highest density at  $1.836\text{ g/m}^3$ . While for the raw material, limestone has the highest density at  $0.001826\text{ Kg/m}^3$ , followed by raw coconut peat ash at  $0.001721\text{ Kg/m}^3$ , and raw kaolin at  $1.808\text{ g/m}^3$ . The density of samples that starting at 4g, 5g, and 6g samples follows an ascending sequence, with the 5g and 6g samples having close densities at  $1.836\text{ g/m}^3$  and  $1.826\text{ g/m}^3$ , respectively. Density could be a factor influencing thermal conductivity. It is known that density and heat conductivity have a direct relationship. A study found that by increasing the density, the solid content of the system will be higher consequently the thermal conductivity of solid parts become more dominant [13]. Specifically, as the density of a material decreases, the solid content within the system is lower, and this tends to result in lower thermal conductivity. Lower thermal conductivity is generally favorable for thermal insulation because it means that the material is less effective at conducting heat, thereby reducing the heat transfer through the material. Therefore, lower-density materials often exhibit better thermal insulation properties.

### 3.3 Thermal Conductivity Measurement

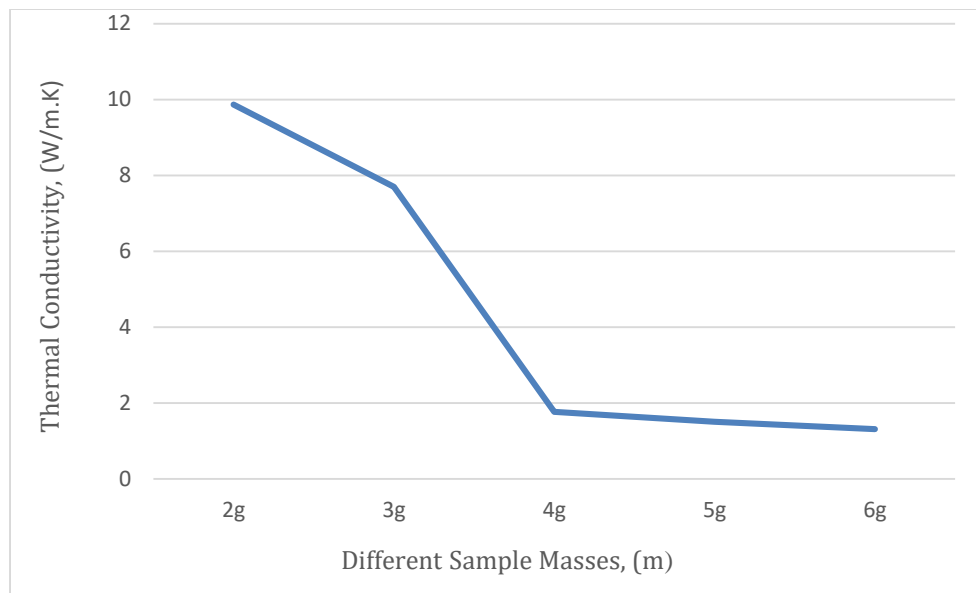
Table 1 presents a comprehensive overview of the thermal conductivity values for each sample, with these values derived through calculations using Equation 1 and subsequently summarized. The investigation specifically targeted the thermal conductivity of geopolymer material mixtures, varying in weights from 2g to 6g. Figure 8 visually encapsulates the thermal conductivity outcomes across all geopolymer mixture samples, encompassing combinations of kaolin, coconut peat ash, barren soil, and limestone.

**Table 1** List of Different Types of Samples and their Thermal Conductivity

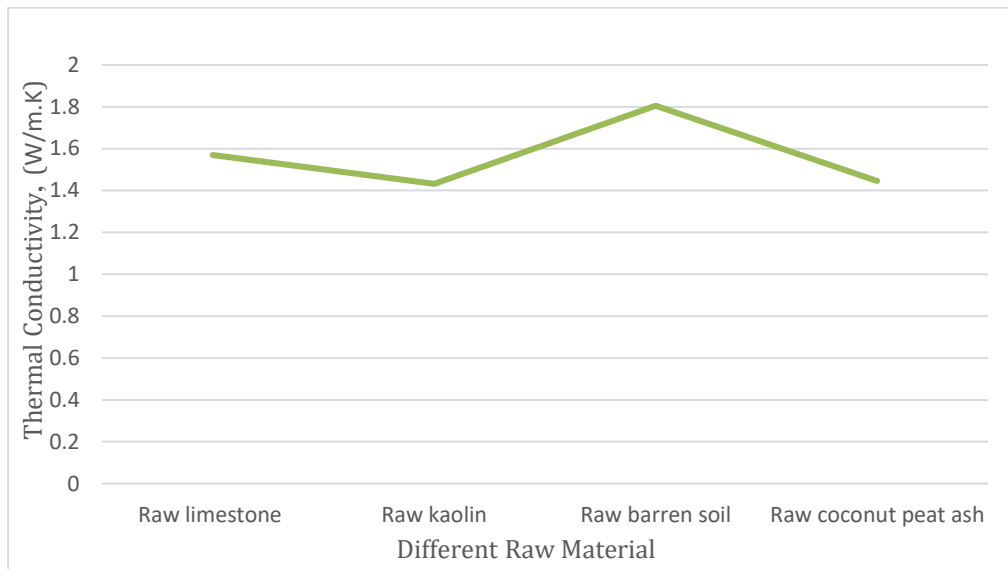
Samples	Density ( $g/m^3$ )	Thermal Conductivity (W/ m.K )
2g of each raw materials sample	1.752	9.8624
3g geopolymer mixture sample	1.818	7.6953
4g geopolymer mixture sample	1.825	1.7654
5g geopolymer mixture sample	1.833	1.5041

6g geopolymers mixture sample	1.836	1.3117
Raw limestone	1.826	1.5693
Raw coconut peat ash	1.721	1.4461
Raw barren soil	1.813	1.8054
Raw kaolin	1.808	1.4320

Analysis of Table 1 reveals that raw kaolin exhibits the least thermal conductivity, while the 6g geopolymers mixture stands out with significantly low thermal conductivity values, measuring at (1.3117 W/m.K). Data in Table 1 further illustrates the thermal conductivity of raw kaolin (1.4320 W/m.K) and raw coconut peat ash (1.4461 W/m.K), both notably lower than others. This indicates their inherent low thermal conductivity, likely influenced by the porosity of these materials, as pores typically contribute to thermal insulation [14]. These observations align with the porosity evident in the morphological structures depicted in Fig. 3 and 4. Thus, this study underscores the complex interplay of material composition, weight, and porosity in shaping the thermal characteristics of the examined geopolymers mixes.



**Fig. 8** The Thermal Conductivity (W/m.K) against Different Sample Masses (m)



**Fig. 9** The Thermal Conductivity (W/m.K) against Different Raw Materials.

Fig. 8 and Fig. 9 outline a noticeable pattern in the thermal conductivity (k-values) of geopolymer materials, illustrating variance in values as the ratio or weight of each sample increases across various pallets. The data highlights the substantial impact of sample weight on thermal conductivity measurements. Specifically, a 2g geopolymer sample, with a thickness of 9.59 mm, exhibits the highest k-value, reaching approximately 9.8624 W/m.K. Conversely, other sample mixtures show diminishing k-values at (7.6953 W/m.K), (1.7654 W/m.K), and (1.504 W/m.K) for 3g, 4g, and 5g geopolymer samples, respectively. Significantly, the study identifies raw kaolin as an excellent material for thermal storage applications, attributed to its low thermal conductivity of 1.4320 W/m.K. This quality positions raw kaolin favorably for geopolymer applications due to its unique attributes and mineralogical composition contributing to advantageous thermal conductivity in various geopolymer applications. Kaolin, recognized as a commonly used natural mineral for producing cordierite ceramics, has been subject to numerous studies focusing on the solid-state sintering of cordierite ceramics utilizing different types of kaolin minerals [15]. Cordierite ceramics, with extensive applications in waste heat recovery, refractories, and other areas, are deemed ideal for thermal storage owing to their high thermal storage capacity, low thermal expansion coefficient, good chemical stability, low manufacturing cost, and excellent thermal shock resistance.

#### 4. Conclusions

In summary, the study concluded with several key points. The examination of sample morphology through SEM-EDX proved insightful, affirming the presence of various phases and providing detailed insights into the geopolymer's structure. Notably, the density analysis revealed that raw coconut peat ash exhibited the lowest density at (1.721 g/m<sup>3</sup>), while among the geopolymer mixture samples, the 2g sample mixture had the lowest density at (1.752 g/m<sup>3</sup>). Furthermore, the analysis of density and thermal conductivity highlighted the significant influence of sample density and weight on thermal conductivity values. Finally, the study identified kaolin as a promising candidate for thermal storage due to its advantageous properties, particularly the presence of carbon that facilitates efficient heat transfer. These findings collectively contribute to a comprehensive understanding of the thermal characteristics and potential applications of the examined geopolymer materials especially in the design of thermal storage system.

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#### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design, data collection, methodology, analysis and interpretation of results:** Nur Athirah Wahida, Zaidi Embong and Ahmad Hassan Sallehudin. All authors reviewed the results and approved the final version of the manuscript.

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