AIP Conference Proceedings

RESEARCH ARTICLE | MARCH 18 2024

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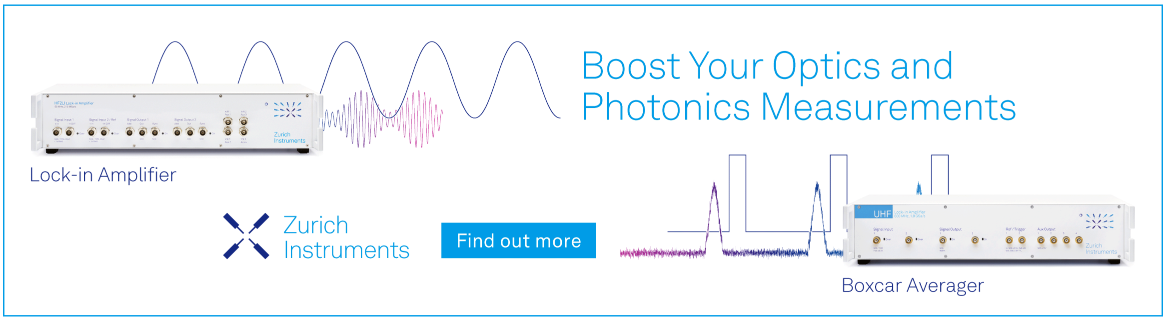
AIP Conf. Proc. 3026, 080001 (2024)
https://doi.org/10.1063/5.0199674



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Development of Insulation Material using Bamboo Fibers for Thermal and Sound Properties

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Abstract. Currently, fiberglass is used as an insulation material, and this synthetic fiber is categorised as non-biodegradable and causes air pollution. This study compared the thermal and acoustical properties of Betong bamboo (*Dendrocalamus Asper*) and fiberglass. Conductivity (K-Value) and sound absorption coefficient (SAC) were measured for both materials. The SAC was calculated using an impedance tube at low and high frequencies in accordance with EN ISO 10534-2:2001, while thermal conductivity was measured using Solteq HE110 thermal conductivity apparatus. From data analysis, the k-values of bamboo and fibreglass were 0.05 and 0.04, respectively. The analysis also showed that the difference in k-value between natural and synthetic fibers was 0.01 at 25 mm thickness, while fiberglass was 4.986. For sound acoustic, bamboo fibre showed 0.54 and 0.86 SAC between 2000 Hz and 2500 Hz, while 0.47 and 0.71 SAC were recorded for fibreglass. It can be concluded that bamboo fibre could be used as thermal and sound insulation, with performance equal to or better than fibreglass. Further research can be extended to make bamboo fibers as natural insulation for ducting, or in building. This study recommends refining bamboo fibres using different binders to increase durability and be used as insulation in the future.

1 INTRODUCTION

Insulation material retards the transmission of energy, such as electricity, heat, moisture, shock, or sound, between the surfaces of adjacent bodies separated by insulation [1]. The primary function of insulation material is to

The 7th International Conference on Science and Technology (ICST22)
AIP Conf. Proc. 3026, 080001-1–080001-10; https://doi.org/10.1063/5.0199674
Published by AIP Publishing. 978-0-7354-4894-0/$30.00

retard the rate of heat flow to prevent or reduce temperature changes [2]. Insulation has a variety of applications, for example, building insulation for comfort and energy savings in buildings; electrical insulation to resist electricity and magnetism; insulated glass for saving energy; acoustic insulation to lower the level of sound; and thermal insulation to limit heat transfer. According to numerous studies, substantial energy is consumed by industry and buildings [3], and the largest proportions of fossil fuels used for building energy are heating and cooling energy. This research focuses primarily on testing fibreglass and organic insulation material, such as bamboo fibres, as a new material for thermal and acoustic insulation to improve the soundproofing and energy efficiency of buildings. The environmental impact of bamboo fibre is less than synthetic fibres. Additionally, bamboo fibres exhibit exceptional sound absorption and sound insulation properties [4]. Some natural insulations may have similar or better thermal and sound properties than synthetic fibres [5].

This study examined the thermal and acoustic insulation performance of fibreglass and bamboo fibres in two different thicknesses (25 mm and 50 mm). The fibre properties were compared to determine material with the best thermal and acoustic properties based on thermal conductivity and sound absorption coefficient.

1.1 Thermal Resistance (R-Value)

Thermal resistance is a unit of measurement that describes the resistance (opposition) to heat flow caused by conduction, convection, and radiation suppression. It is determined by the thermal conductivity, thickness, and density of the material. Thermal resistance, measured in m2-K/W (h-ft2-F/Btu), is denoted by the R-value. The thermal resistance equation is as follows:

$$R' = \text{thermal resistance} = \frac{(X2-X1)}{kA} = \frac{\Delta x}{kA} \qquad \text{(Equation 1)}$$

1.2 Sound Absorption

Sound absorption can be defined as the process by which sound energy is reduced when a sound wave passes through a medium, such as air, or water. In other words, when sound strikes the boundary surfaces of a room, a portion of it is absorbed and transmitted outside the room, while a portion of it is reflected in the room, which is known as sound absorption process. The total amount of sound energy that has been reflected, absorbed, and transmitted is referred to as the sum of energy. Equation 2 presents the calculation of total sound energy, as follows:

$$Ei = Er + Ea + Et \qquad \text{(Equation 2)}$$

1.2.1 Sound Absorption Classification

Acoustic absorbers are rated according to their ability to reduce noise and absorb sound over a wide frequency range. Some are better at a specific frequency, while others are better across a wider frequency range [6]. When it comes to sound absorption, there are specific classes. The sound absorption classes and diagrams are shown in Table 2.3 and Figure 2.2, respectively. The SAC for class A is 0.90, or higher in this case, while the SAC for class B ranges between 0.8 and 0.85. There is a difference between 0.6 and 0.75 SAC for Class C, between 0.3 and 0.55 SAC for Class D, between 0.15 and 0.25 SAC for Class E, and 0.10 SAC or lower for the Unclassified class.

Table 1: Sound absorption classes according to BS EN ISO 11654:1997

No.	Absorption classification	Absorption class explanation	Sound absorption coefficient, αw
1	A	Extremely absorbing	0.90 or higher
2	B		Between 0.8 and 0.85
3	C	Highly absorbing	Between 0.6 and 0.75
4	D	Absorbing	Between 0.3 and 0.55
5	E	Hardly absorbing	Between 0.15 and 0.25
6	Unclassified	Reflecting	0.10 or lower

2 MATERIAL AND METHODS

2.1 Materials Preparation

Materials used in this study were bamboo fibers and fiberglass. The bamboo fibers were obtained from Jerantut, Pahang. Sodium hydroxide (NaOH) was purchased from local seller for use in delignification process. The entire preparation process of the material is explained in the subsequent subtopics.

2.1.1 Selection of Bamboo Fibers

Betong bamboo, or also known as *Dendrocalamus Asper*, was used in this experiment. Raw bamboo from the bamboo grove was supplied by the local community. Table 2 shows the properties of Betong bamboo fibers.

Table 2 Properties of Betong Bamboo Fibers

Fiber	Properties	Value	Source
Betong Bamboo (*Dendrocalamus Asper)*	Holocellulose (%)	74	[7]
	Lignin (%)	28.5	
	Density (Kg/m^3)	559	[8]
	Culm Height (m)	20	
	Internode Length (cm)	37	
	MOR (N/mm^2)	150	
	MOE (N/mm^2)	11,303	

Notes: MOR- modulus of rupture; MOE – modulus of elasticity

2.1.2 Delignification

Natural fibers contain chemical constituents that can be divided into two categories: cellulose and lignin [9]. Lignin is responsible for binding cellulose fibers together. The use of alkali treatment for lignin removal is a common practice in the pulp and paper industry, and it is also used in other industries. Lignin can be dissolved in NaOH solution, and then cellulosic fibers can be easily extracted from the resulting solution [10]. The dissolution of lignin is caused by the breakdown of lignin into smaller segments, where its sodium salt dissolves in the solution.

2.1.3 Alkali treatment using NaOH

NaOH was used to extract the bamboo fibers. There are a few guidelines available regarding the alkali treatment of bamboo, and the side effects of harvesting bamboo fibers from the plant. A series of experiments must be conducted to determine the normality of the NaOH solution and the soaking time to maximise the ease of fiber separation [11]. The use of a concentrated NaOH solution with a long soaking time will cause greater lignin dissolution. In this study, alkali treatment was only used as a tool to facilitate the extraction of fiber, and no other effects were observed. The percentage of NaOH used during fiber processing and its parameters can be determined to optimise the separation of bamboo fibers by referring to the properties of processed fiber as shown in Table 3.

Table 3: Effect of NaOH percentage on the properties of processed bamboo fibers [12].

NaOH (%)	Temperature (°C)	Properties of processed bamboo fibers
5	70	Fibers are coarse and hard, but the fibers can be separated and long.
8	70	Fibers are softer than those obtained from previous trial, but some fibers break easily and are brittle.
15	70	Fibers arevery soft, but the fibers are very brittle and break easily when subjected to drying and mechanical processes as separate fibers.

From Table 3, 5% NaOH concentration produces slightly coarse and rough but not easily broken bamboo fibers as desired for this study. NaOH was used at a concentration of 5% to soften the bamboo fibers, which posed no negative impact on the environment due to the small percentage of NaOH used [12,18]. The humidity of the material was taken into consideration when choosing such concentration percentage for this study to meet certain technical requirements of this study. As the fiber material becomes softer or smoother, the amount of moisture in the fiber increases. If the bamboo fiber is not further processed, there is a high likelihood of fungal growth occurring in the fiber. This was the second factor that contributed to the selection of 5% NaOH concentration.

2.2 Bamboo Fiber Extraction Process

The extraction of bamboo fibers in this study began with the collection of Betong bamboo, which was then washed with water to remove dirt and other undesired particles before drying. The bamboo was soaked in water containing NaOH solution, which resulted in the formation of fibrous material. After that, the bamboo lignin was peeled off by hand and rinsed thoroughly with clean water. Clean fibers were dried for 24 hours. The fibers were then extracted using grinder to produce fibers. Subsequently, the fibers were dried for 3 days to remove undesired moister content in the fibers. The final texture of the fibers is displayed in Figure 1.

Figure 1 Final texture of bamboo fibers

2.3 Density

The density of a material is one of the factors that influence thermal conductivity and sound absorption. Table 4 shows the density of the bamboo fiber samples. A lower density indicates that there is less material that can conduct heat, implying that there is more air, or gas to resist heat flow [13]. The higher the fiber content per unit area, the higher the density of the material. Due to the increased surface friction between the sound wave and fiber elements, materials with higher density absorb more sound energy. As a result, the sound absorption coefficient of the material improves [14]. The calculation of density is represented by the following equation.

$$Density = \frac{Mass}{Volume}$$

Table 4: Density of bamboo fiber samples used in this study.

Material of Fiber	*Thickness (mm)*	*Density (kg/m³)*
Betong Bamboo	25	77.60
	50	86.67
Betong Bamboo (Solid)	25	74.22
	50	91.11

2.4 Fiberglass material preparation

Fiberglass was also prepared in the laboratory for comparison purpose with bamboo fibers for thermal conductivity and sound absorption. Fiberglass materials with densities of 28.80 kg/m^3 and 47.55 kg/m^3 for thicknesses of 25 mm and 50 mm, respectively, were tested for thermal and sound insulation properties.

2.5 Thermal conductivity measurement method

Steady State Thermal Transmission Properties (ASTM C518-91,1991), a measurement technique depicted in Figure 4, was utilised to determine thermal conductivity of the materials. The test was conducted at Building Service Technology Laboratory, Department of Civil Engineering Technology (JTKA), Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh Campus.

The experimental setup in this study consisted of hot plate and cold plate for 300 mm x 300 mm sample size, and thicknesses of 25 mm and 50 mm, respectively. The specimens were inserted into the apparatus and heat flowed through both plates. Data were collected after the temperature for heat density was stabilised.

2.6 Sound absorption coefficient (α) Measurement Method

Figure 5 depicts the impedance tube method used to determine the sound absorption coefficient (α) of the specimens in accordance with EN ISO 10534-2:2001. The measurement was conducted at Building Service Technology Laboratory, JTKA, UTHM Pagoh Campus.

The experimental equipment in this study consisted of circular tubes with diameters of 28 mm and 100 mm, two microphone tubes from 4208 series, Atlas Sound Single Channel Power amplifier of type PA601, and adjustable sample holder according to Bruel & Kjaer 227: 1681. These microphones were place in front of the fibreglass or bamboo fibre specimens to record both the reflected wave signal and sound wave incident. Using AED-1001, the sound waves were converted into digital signals. Acoustic Tube transfer function software was employed in this study. The measurement frequency range was separated into two sections. A tiny tube with a diameter of 28 mm was tested in frequency range of 900 Hz to 6000 Hz, while a large tube with a diameter of 100 mm was tested in frequency range of 60 Hz to 500 Hz. Frequency (Hz) against sound absorption coefficient (α) at both (low and high) frequency regions was plotted to analyse the data.

3 RESULT AND DISCUSSION

There were two main properties analysed, namely thermal conductivity and sound absorption coefficient (α). Both parameters were indicators of the performance of fiberglass and Betong bamboo fibers as thermal and sound insulation materials.

3.1 Thermal conductivity (K-Value)

Three types of materials, such as bamboo fiber, solid bamboo fibers and fiberglass, were subjected to thermal conductivity measurement. Results obtained from measurement are tabulated in Table 5.

TABLE 5: Results of thermal conductivity for three different types of fibers

Material	Thickness (mm)	Density (kg/m^3)	Thermal Conductivity (W/mK)
Bamboo Fibers	25	77.60	0.056
	50	86.67	0.128
Fiberglass	25	28.80	0.04
	50	47.55	0.07
Solid Bamboo Fibers	25	74.22	0.179
	50	91.11	0.293

From Table 2, thermal conductivity values varied according to density of the material. For bamboo fibers, the thermal conductivity value was 0.056 and 1.128 for density of 86.67 kg/m^3 and 77.60 kg/m^3, respectively. Solid bamboo fibers recorded the highest densities of 91.11 kg/m^3 and 74.22 kg/m^3 for both thicknesses, with thermal conductivity values of 0.293 W/mK and 0.179 W/mK, respectively. Finally, fiberglass recorded the lowest density (47.55 kg/m^3 and 28.80 kg/m^3) and thermal conductivity (0.07 W/mK and 0.04 W/mK) for both thicknesses.

From the analysis, it was concluded that the density of fibers is directly proportional to thermal conductivity. The sample with the highest density has the highest thermal conductivity as thermal conductivity could be affected by tiny air spaces inside the fiber. Less convective heat transfer passes through the air in the sample as the space size of the fiber is smaller. This result is supported by Xuan Cao [15]. Meanwhile, the thickness of the fiber also influenced the thermal conductivity, where thickness of sample is directly proportional to the thermal conductivity. Higher thermal conductivity of insulation materials results in lower thermal resistance [16]. Therefore, thickness is a crucial parameter to obtain optimum thermal insulation.

3.2 Sound absorption coefficient (α)

1) Sample with thickness of 25 mm at high frequency

The sound absorption coefficients of sample with 25 mm thickness for three different materials are shown in Figure 2. At 2000 Hz frequency, fiberglass recorded SAC of 0.47, while bamboo fibers recorded SAC of 0.54, and the solid bamboo fibers recorded SAC of 0.12. Meanwhile, the maximum SAC was 0.89 for fiberglass, followed by bamboo fiber (0.87), and solid bamboo fibers (0.275). The results indicated that the bamboo fibers have better sound absorption compared to fiberglass after reaching frequencies between 1500 Hz and 3000 Hz. In other words, this material exhibited good performance at high sound frequency.

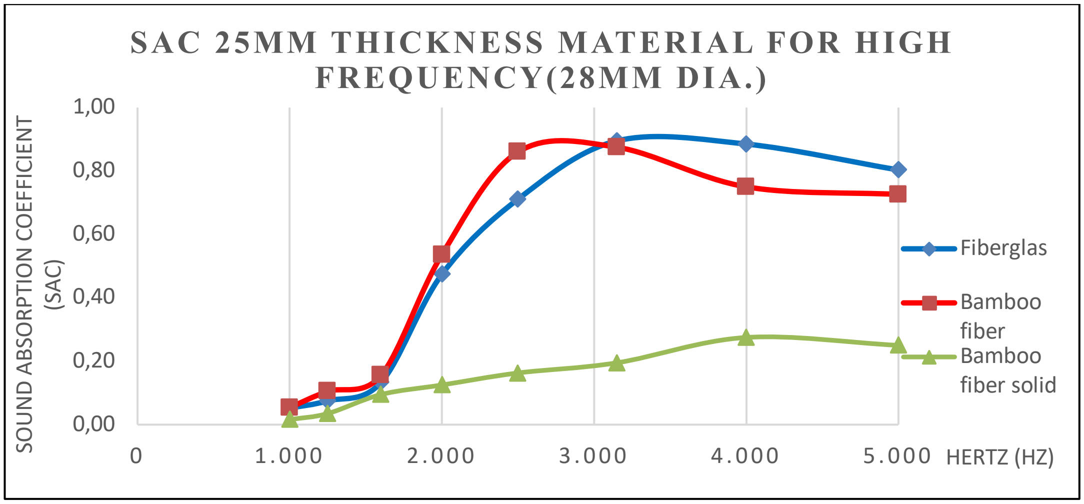

FIGURE 2 Sound absorption coefficient of different materials with 25 mm thickness at high frequency

According to Figure 3, bamboo fibers, solid bamboo fibers and fiberglass with 50 mm thickness were measured at higher frequency. The SAC of bamboo fibers was 0.752 at 2500 Hz, while the SAC of solid bamboo fibers was 0.752. At the same frequency, fiberglass recorded SAC of 0.765. The highest SAC of bamboo fibers was 0.850 at 4000 Hz, while the SAC of solid bamboo fibers was 0.450 at 5000 Hz. Moreover, the SAC of 0.921 was obtained by fiberglass at 3150 Hz. Bamboo fibers had better sound absorption between 1500 Hz and 2500 Hz, but it decreased as the frequency increased. In contrary, fiberglass had better sound absorption between 2500 Hz and 3000 Hz and began to decline with increasing frequency.

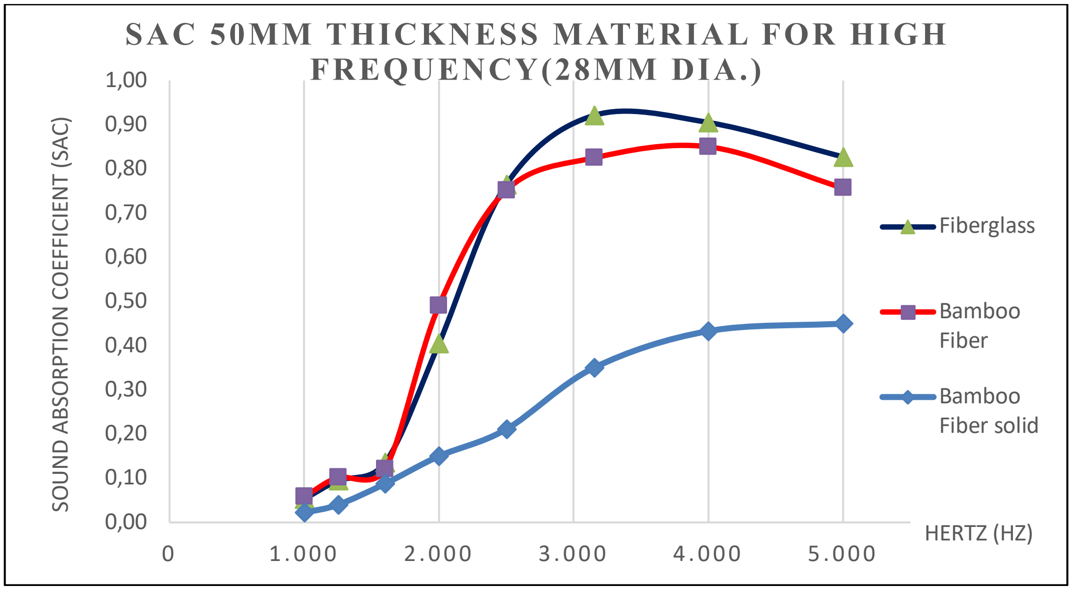

FIGURE 3 Sound absorption coefficient of different materials with 50 mm thickness at high frequency

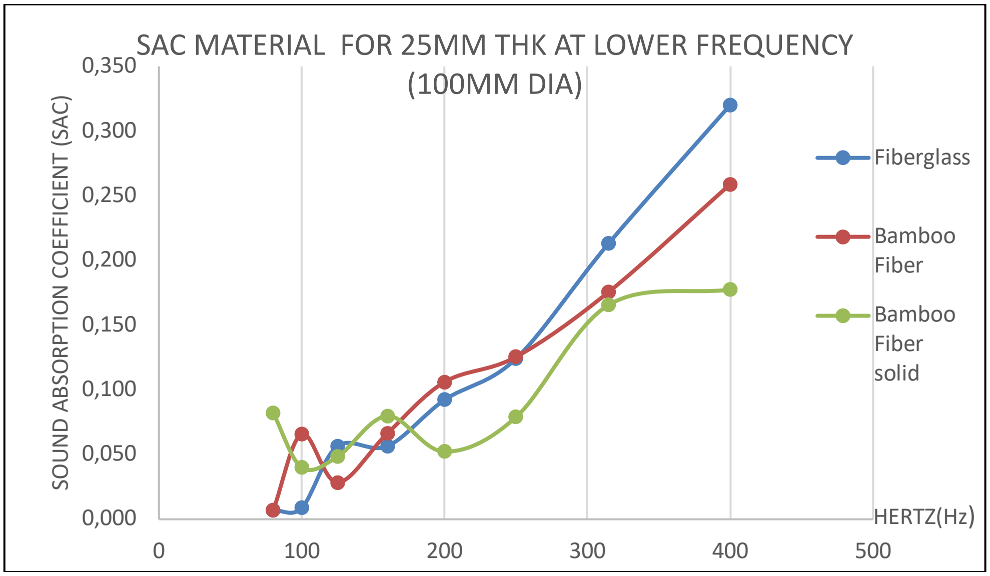

FIGURE 4 SAC against Frequency for three different materials with 25 mm thickness at lower frequency

According to the figure 4, three samples were tested using the impedance tube method. The result shows that the bamboo fiber solid had reached the maximum SAC value of 0.34, while bamboo fiber had maximum SAC of 0.37 and SAC value of 0.46 for fiberglass with the frequency in 500Hz. The frequency of 150Hz, the bamboo had good sound absorption compared to fiberglass and bamboo fiber solid. Overall, the fiberglass had better sound absorption coefficient rather than bamboo fiber and bamboo fiber solid as frequencies of 400 Hz.

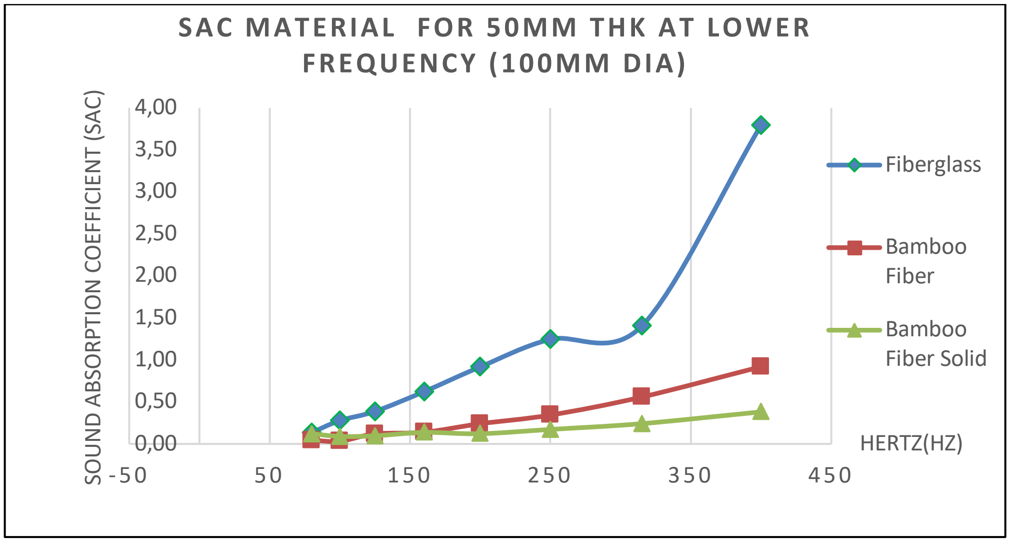

FIGURE 5 SAC against frequency for different materials with 50 mm thickness at lower frequency.

From Figure 5, the minimum sound absorption coefficient of bamboo fibers was 0.03 at 80 Hz frequency. When reaching 400 Hz, bamboo fibers obtained the maximum SAC with 0.92. Finally, fiberglass had achieved the maximum SAC of 3.79 at 400 Hz frequency, which is beyond the maximum value of 1. Edge or diffraction effect may occur when the SAC is greater than 1 as a result of wave diffraction at the edge of the specimen [17]. The effect was most noticeable on most low-frequency results for highly absorptive specimens.

CONCLUSION AND RECOMMENDATIONS

This study developed bamboo fibers as heat and acoustic insulation material. The thermal conductivity and SAC of fibreglass and bamboo fibers were measured to evaluate their performance. Considering that bamboo fibres eco-friendly, it can be used as an alternative insulation material in diffusers, ducts, and roof attics. Therefore, it is advantageous to introduce this fibre as sound absorbing material, with the potential to replace synthetic fibres. Additional research is required to investigate the mechanical properties of bamboo fibers to meet industry requirements for acceptance as natural material thermal and acoustic insulation applications.

As for recommendation for future research, some weaknesses in this study need to be improved. To escalate the application of natural fibers for thermal and sound insulation, the recommendations are as follows:

1. Develop another type of binder to bind bamboo fibers together. The researchers found that the current type of binder, which made of starch, is not satisfactory for binding the fibers together. There is a possibility that the fibers are too brittle to be used as the insulation material.
2. Develop a hybrid insulation material, consisting of bamboo fibers and synthetic fibers at a ratio of 50:50, or other suitable ratios based on previous studies.
3. Evaluate sound transmission loss (STL) by comparing the SAC of both bamboo fibers and fiberglass.
4. Investigate the durability of bamboo fibers by performing relevant tests in real conditions for insulation performance, for example in the buildings (used in roof attic or in Hvac ducting system) and analyse the lifetime services of bamboo fibers over fiberglass.
5. Vary the thickness of each insulating material, apart from 25 mm and 50 mm thicknesses, to find the optimum thermal insulation materials.
6. Evaluate the potential of waste to be used as insulation materials to mitigate environmental pollution.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Fahmi Jamaludin for supplying Betong Bamboo as research materials for this study, and to all researchers who contributed directly to this research. Finally, the authors would like to thank the Faculty of Engineering Technology, UTHM for the support provided.

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