

Effect of Fire-Retardant Ratios in Kenaf Fiber for Fire Resistance Properties and Acoustical Performance

Myia Yuzrina Zalkis Ayol¹, Mohd Yuhazri Yaakob^{2*}, Meryl Anyie Tomy², Kamarul Amir Mohamed², Wan Hasrulnizzam Wan Mahmood², Azrin Hani Abdul Rashid³, Zulfikar Achmad Jusuf⁴

¹ Department of Mechanical Engineering,

Politeknik Merlimau, Kementerian Pendidikan Tinggi, Merlimau, Melaka, 77300, MALAYSIA

² Fakulti Teknologi Dan Kejuruteraan Industri Dan Pembuatan,

Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Durian Tunggal, Melaka, 76100, MALAYSIA

³ Department of Mechanical Engineering, Faculty of Engineering Technology,

Universiti Tun Hussein Onn Malaysia, 84600 Kampus Pagoh, 84600 Pagoh, Johor, MALAYSIA

⁴ Fakultas Teknik, Universitas Medan Area, Jl. Kolam No. 1 Medan Estate, Medan, 20223, INDONESIA

*Corresponding Author: yuhazri@utem.edu.my

DOI: <https://doi.org/10.30880/ijie.2024.16.06.019>

Article Info

Received: 26 August 2024

Accepted: 14 October 2024

Available online: 4 November 2024

Keywords

Fire-retardant, ratio, kenaf fiber, fire resistance properties, acoustical performance

Abstract

Nowadays, awareness towards environmental issues increases significantly where people have learned the important of protecting environment for a better future. Thus, this study investigated the embedded kenaf fiber as a natural material with different of fire-retardant loading content towards the fire resistance properties and acoustical performance for insulator application in future building component. Based on the study conducted toward the prepared size 200 mm x 2000 mm x 40 mm of fixed kenaf composition with various fire retardant by 5 wt. % and increasing gradually to 25 wt. %, this study found that the highest value of thermal conductivity which is 0.4472 W/mK and temperature different of 240 °C for S1. Also, this study found the higher percentage of non-burn fiber which is 98.103 % for S6 and the highest peak of 0.9104 coefficient at 1259 Hz and at 1600 Hz with coefficient of 0.9091 for S3. This study showed that kenaf fiber embedded with different of fire-retardant loading content have a potential to replace the current insulator used in industry.

1. Introduction

The use of natural materials has become increasingly important since the growing need to conserve energy, particularly green building materials made from renewable resources. The natural fibre is one the natural materials that Fiore *et al.* [1] classified into three types, which are vegetable, mineral and protein fibre. For vegetable type, it can be obtained from plants which are the seed, stem, leaves and fruit. While for protein type, it can be obtained from animal which are the hair, fur and secretions. Therefore, the use and developments of natural material such as from natural fiber are an important for sustainable green buildings since the materials itself from renewable sources. Florea and Manea [2] mentioned that natural fibers are qualified because it has a low impact on the environment thus achieving the lowest impact and if possible positive on human life.

An acceptable mechanical property, Takagi [3] stated natural fiber-reinforced polymers composites have many unique functional properties, such as thermal insulation, biodegradability, and vibration damping capacity. Here, it concerns also to the functionalities of natural plant fibres are derived from both chemical and microstructural characteristics where for used as reinforcement must be carefully chosen in order to achieve

acceptable functional results. The natural fiber has been proved to be the best material for thermal insulation as it bearing advantages includes low density, high strength and resistance to breakage during processing [4]. The study also highlights that natural fiber has a low energy content and recyclability and has been used in transportation, building and construction industries. However, natural fiber can withstand the heat at a temperature of less than 750 °C [5]. To thermal conductivity and thermal resistance of natural fibre composites, Muthukumar et al. [6] have investigated the analysis to fibers of banana, pineapple, and jute. In their study was found that by combining natural fibres has a significant impact on thermal properties such as thermal resistance and thermal conductivity in this study. Also, Zach et al. [7] added that the natural fibre has a lot of attention as an insulation material, especially in the construction and reconstruction of existing buildings to implement effective energy-saving measures. Here, Bozsaky [8] underlined that because heating our building consumes 30 % of total energy consumption, reducing energy consumption therefore become a priority for engineers. He asserted that the thermal conductivity of some thermal insulation based natural fiber such as bamboo fiber has the highest thermal conductivity which is 0.080 to 0.340 W/mK followed by coconut fiber 0.040 to 0.050 W/mK, palm fiber of 0.041 W/mK. The facts, there are some negative characteristics of material based on natural fiber where it has high wettability [9], high water absorption [10] and poor response to fire [11].

Kenaf or *Hibiscus Cannabinus L.*, is an economically viable and environmentally friendly alternative fibre crop. Recently, Chu et al. [12] state it also a fast-growing dicotyledonous fibre plant from the Malvaceae family native to India and Africa. According to Giwa Ibrahim [13], kenaf is a composed of multiple useful components such as stalks, leaves and seed. Kenaf fiber is a fibrous plant which include in the group of natural fiber. Mahjoub et al. [14] state that kenaf fibre is produced from the bast of kenaf plant. They also found that kenaf fibre is consists of cellulose 56 to 64 wt. %, hemicellulose 21 to 35 wt. %, lignin 8 to 14 wt % and small amounts of extractives and ash. In 2018, Hanan et al. state mentioned in Malaysia, kenaf fibre is considered as an industrial crop. This is due to the fact that kenaf fibre has aided in the growth of environmentally sustainable manufacturing alternatives for the automobile, food packaging, pulp and paper, furniture and sporting goods industries. A study by Elfaleh et al. [15] highlight that because of its lightweight, biodegradability, low cost and good mechanical properties, as well as good thermal stability and solid fiber-matrix adhesion, kenaf fibre was used as a reinforcement for composites. The above finding is consistent with the study by Dinesh et al. [16]. They also stated that kenaf fibre has a lot of potential for use as an automotive and construction material because of its long fibres derived from the bast, which is the outer fibrous bark and makes it qualified to replace synthetic fibre specially glass fibres in reinforcement of composite.

In this study, the kenaf plant was chosen because of its rapid growth and relatively easy to find in Malaysia [17], although kenaf plantations in Malaysia are practically face a number of challenges, including a scarcity of skilled workers and a low profit margin as a function of land area. The researcher stated that woven kenaf has been used in automotive structural components because of its high impact resistance. Yusuff and Sarifuddin [18] added that kenaf fibre is one of the most widely used agricultural fibres as a reinforcement in polymer composites, resulting in kenaf reinforced polymer matrix composites. However, due to their excellent properties such as durability and high mechanical strength, they stated that synthesis fibres such as carbon and glass have become widely used in a variety of applications around the world. This have contributed to the escalating global solid waste issues, with plastic materials accounting for a significant portion of the increase, beside open- burning, unregulated dumping, and landfilling as the most common methods of disposing of these wastes, particularly in developing economies [19].

Ashori [20] investigated chemical (organic and inorganic) and morphological characteristics of kenaf fractions (bast, core, and whole stem) due their weakness in terms of moisture resistance, which leads to high water absorption, alkaline treatment has been used with sodium hydroxide (NaOH) solutions to mercerize the fiber's hydrophilic effect [21]. Saba [22] however stated that not many published Malaysian kenaf research and its international accessibility. Naik et al. [23] in their study highlighted the hydrolysis, oxidation, dehydration, depolymerization, decarboxylation, and recrystallization of kenaf fibre causing the cellulose in the fibre to degrade and lose its mechanical properties. Though studies conducted on the general properties of the kenaf fibre have been carried out, but few look at how to improve the fiber's durability and mechanical strength.

This study is therefore conducted to observe and identify the problem occurred in the development of kenaf fiber as the base material for application, especially for thermal insulation application used in industry. Therefore, to maintain the quality of kenaf fibre and increasingly demand for it as a green material, effective solutions must be found. Particularly, the utility of natural fibre in insulation applications since there no study available related to the potential of kenaf fibre embedded with a fire retardant for use as a heat and fire insulator.

2. Methodology

In this research, Kenaf fibers were purchased from *Lembaga Kenaf dan Tembakau Negara (LKTN)*, Malaysia. The kenaf fiber as shown in Fig. 1(a). In the study, the properties of kenaf fiber were observed, where at the density of 1.4 g/m³, kenaf fiber has the strength of 284 to 800 N/m², modulus elasticity of 21 to 60 GPa and elongation

at break of 1.6 %. The kenaf fiber are soaked into the fire-retardant liquid. This process will take around 24 hours for the kenaf fiber to absorb the fire retardant. Fig. 1 (b) and (c) shows the type of fire retardant that used which is antimony fire retardant and Saytex 8010 flame retardant. Saytex 8010 flame retardant is a non-diphenyl oxide-based product containing a high level of aromatic bromine. This type of flame retardant can be used in a wide range of high-performance application and has very good thermal stability. However, although antimony trioxide is not a flame retardant by itself but when it is combined with halogens such as bromine in polymers, the resulting mixture suppresses, reduces, and delays the spread of flames.

This study uses a constant amount of kenaf fiber but different composition (loading) of fire retardant where the performance of each design sample will be compared. In order to produce the highest quality prototype, the fire-retardant composition plays an important role in improving the performance of sample as insulator. Table 1 shows different design of sample due to the different composition ratio of fire retardant.

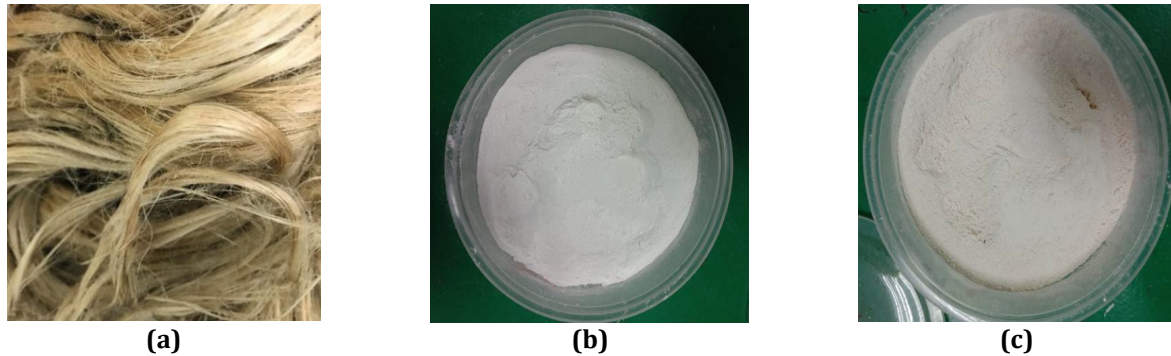


Fig. 1 Main raw materials (a) Kenaf fiber; (b) Antimony fire retardant; (c) Saytex 8010 flame retardant

Table 1 Sample's name and code

| Designation | Fire retardant (wt. %) |
|-------------|---------------------------|
| S1 | 0 |
| S2 | 5 |
| S3 | 10 |
| S4 | 15 |
| S5 | 20 |
| S6 | 25 |
| S7 | Synthetic/ market product |

There are three testing methods are used, which are thermal test, fire test and acoustic test according to ASTM C177, ASTM E84 and ASTM E1050-09 respectively. A guarded hot plate method will be used for the thermal test while fire test will use fire torch and acoustic test will use the impedance tube testing method. The thermal test according to ASTM C177 is used to obtain the thermal conductivity of the sample which is the ability of the sample to conduct heat and heat flow of the sample at a maximum temperature of 250 °C. The sample was test about 1 hour with the temperature of 250 °C. The target is to make sure the outer part of the sample is saved to be touched. The working principle of guarded hot plate is first, the sample is placed between two plates. One plate is heated and the other is cooled. The temperature of the plates is monitored using thermocouple until they are constant. An illustration of guarded hot plate is shown in Fig. 2 (a). In addition, the testing was conducted accordance to ASTM C177 Standard test method for steady-state heat flux measurement and thermal transmission properties through the guarded hot plate apparatus. The sample is placed in the middle of the plate then followed by a layer of fiber glass with thickness of 1 mm on the bottom part of the sample. The thermocouple was used to measure temperature on each side of the plate. Currently, glass wool is one of the popular materials used as the thermal insulator used to insulate high temperature application. Glass wool was used as a benchmark in order to make a comparison. All physical aspect was considered and take note especially the dimension, thickness, mass and temperature used to determine the thermal conductivity and heat flow of the layout.

Fire testing used fire torch as the fire supply to be shoot on the surface of the sample. The purpose of this testing is to investigate the reaction of the sample direct toward fire spearing, smoke producing or any related fire effected to fiber. This testing was conducted according to the standard ASTM E84 where this is the standard test method for assessing the surface burning characteristics of building products. Then, the purpose of this test is to investigate how a flame spreads across a sample in order to determine the material's relative burning behaviour. The duration for this testing is 30 minutes. Then, the distance between sample and the fire torch is 10 cm. Therefore, the evaluation will be the sample reacts to the fire. Fig. 2 (b) shows testing setup for the fire test.

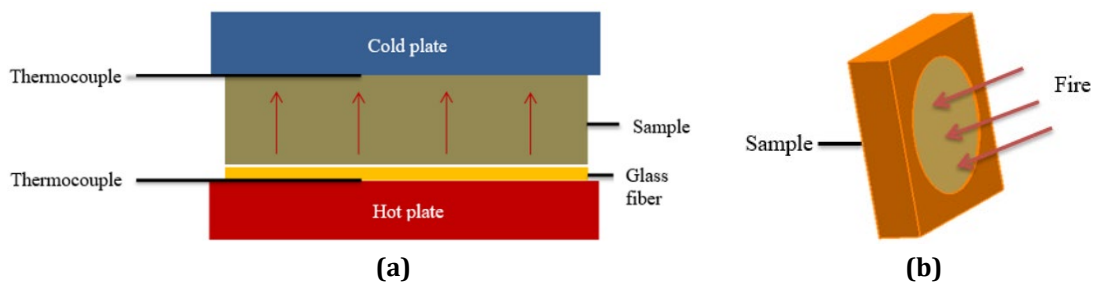


Fig. 2 Schematic testing; (a) Guarded hot plate; (b) Fire test

Sound absorption coefficient was determined using an impedance tube method, and the results show that as fibre content increases, so does the sound absorption coefficient, especially at higher concentrations. In this study, the impedance tube method is used to obtain a sound absorption coefficient (α) based on standard ASTM E1050-09. The sample thickness in the impedance tube is 34.5 mm. Moreover, the frequency range used for impedance tube testing is from 1 Hz to 5000 Hz. Fig.3 shows the apparatus of for the testing. First of all, the first step is to calibrate the impedance tube testing. This step is important to ensure that the device works properly and prevents errors during the testing. The sample with diameter of 34.5 mm and thickness of 40 mm is illustrated in Fig.3 (c) and Fig.3 (b) shows the schematic of impedance tube testing.

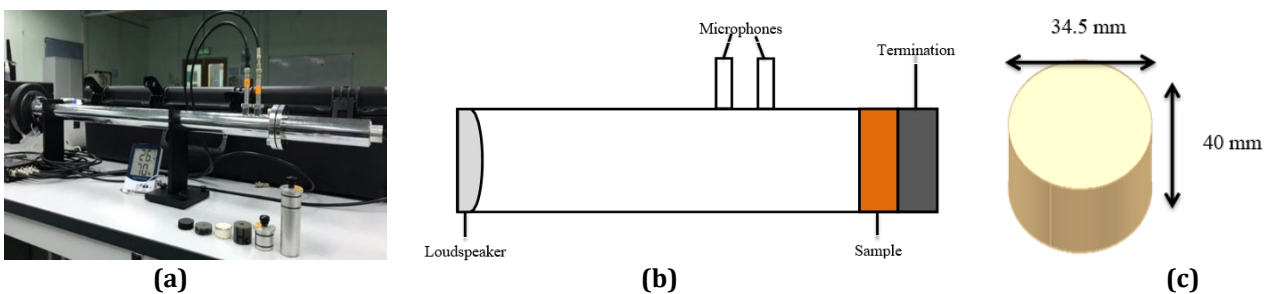


Fig. 3 Impedance tube testing; (a) Actual testing equipment; (b) Schematic; (c) Sample dimension

3. Results and Discussion

3.1 Characteristic of Kenaf Fiber at Different Ratios of Fire Retardant

Fig.4 (a) shows how kenaf fibre was cut into lengths ranging from 5 to 10 millimeters. The thermal properties of the materials are affected by the length of kenaf fibre used as reinforcement. The ideal length is 5mm, which increases the thermal conductivity of the sample. The thermal conductivity of a fibre decreases as its length increases [24]. Fig.4 depicts the state of the sample before (a) and after (b) the mixing process. The physical properties of kenaf fibre are altered when a fire retardant is added, as shown in the figure.

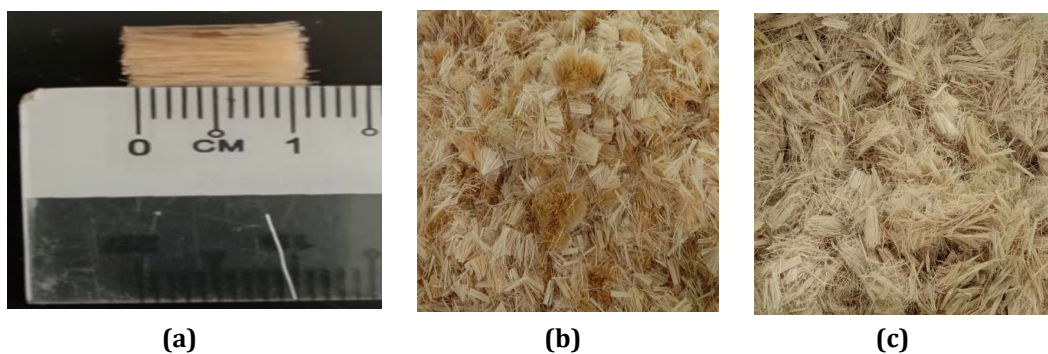


Fig. 4 Kenaf fiber condition; (a) Length range; (b) Before mixing; (c) After mixing

Table 2 show the distribution of density for each sample. This value is directly reflected to loading content of fire-retardant. This content of fire retardant not influenced the mechanical properties, but for sure this will be influenced other properties such as fire resistance, acoustical performance and vibration.

Table 2 Average density value

| Designation | Density (kg/m ³) |
|-------------|------------------------------|
| S1 | 113.958 |
| S2 | 114.667 |
| S3 | 1.222 |
| S4 | 143.167 |
| S5 | 168.333 |
| S6 | 2.834 |

3.2 Performance of Thermal Properties in Kenaf Fiber

Thermal testing was carried out in this study using a steady-state heat flux measurement and a thermal transmission properties test method. The apparatus used was a guarded hot plate, which was tested according to the ASTM C177 standard to determine the sample's thermal conductivity. The thermocouple was another device used. This device's purpose is to measure the temperature on both sides of the plate. After that, the thermal conductivity was determined. At a temperature of 250 °C, the sample will be tested for 1 hour. The goal of this experiment is to see how well the sample can absorb heat. As a result, the testing's impact is examined and discussed in this topic. All of the samples were tested, and the average of the results was compared to the current heat and fire insulators in use in the industry.

The sequence of study to further discuss is thermal conductivity and the heat flow of sample under high temperature heat. Theoretically heat is transferred optimally when go through a solid body while the heat will disperse when there is pore along the pathway of the heat. The average of thermal conductivity and temperature different of all samples is shown in Fig.5. The thermal conductivity of current insulator sample S7 is 0.3934 W/mK with temperature different of 223.333 °C which is the current industry sample. The highest goes to sample S1 with thermal conductivity of 0.4472 W/mK and temperature different 240°C. Sample S1 is made from 100 % pure kenaf fiber and totally natural fiber. Then, the second highest is belong to sample S2 with value thermal conductivity of 0.4360 W/mK with temperature different of 236.667°C. Sample S3, sample S4 was at the fourth and fifth place as the highest thermal conductivity with value of 0.3880 W/mK and 0.3606 W/mK and also temperature different of 221.667 °C and 212.333°C respectively. Next is sample S5 with thermal conductivity of 0.3286 W/mK and temperature different of 200.667 °C. Sample S6 possess the lowest thermal conductivity which is 0.3137W/mK. Therefore, the best composition ratios with the optimum performance of thermal conductivity goes to sample S1 with an optimum average of thermal conductivity and different temperature which is 0.4472 W/mK and 240 °C respectively.

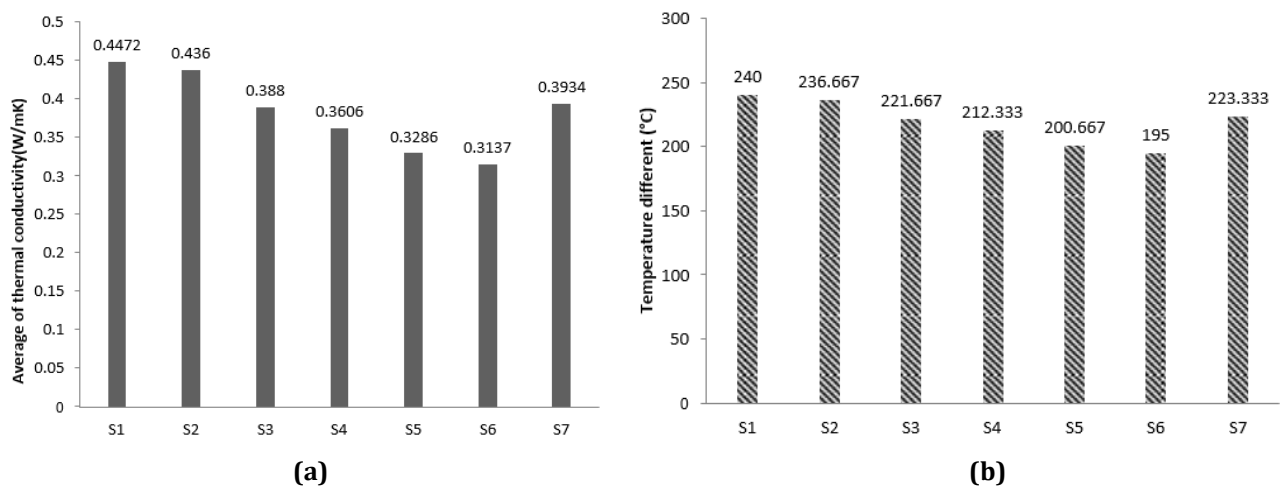


Fig. 5 Average value of (a) Thermal conductivity; (b) Temperature different

3.3 Performance of Fire Reaction Towards the Kenaf Fiber

This testing was carried out in accordance with ASTM E84, which is the industry standard test method for determining the surface burning characteristics of building materials. The reaction of the sample to the fire source will be observed for this testing to see if it burns or just produces smoke and a change in colour, which is black colour. The burn fibre will be separated from the non-burn fibre at the end of the testing. The weight of both burned and non-burned fibre was then calculated. Weighing the sample's burned fibre yielded the percentage of burned fibre in the sample. The different fire-retardant ratios in the kenaf fibre have an impact on the sample's fire reaction. Fig.6 show sample after 30 minutes exposed to direct fire test, from these six images are clearly shown that more fire retardant uses it become more fire resistance.

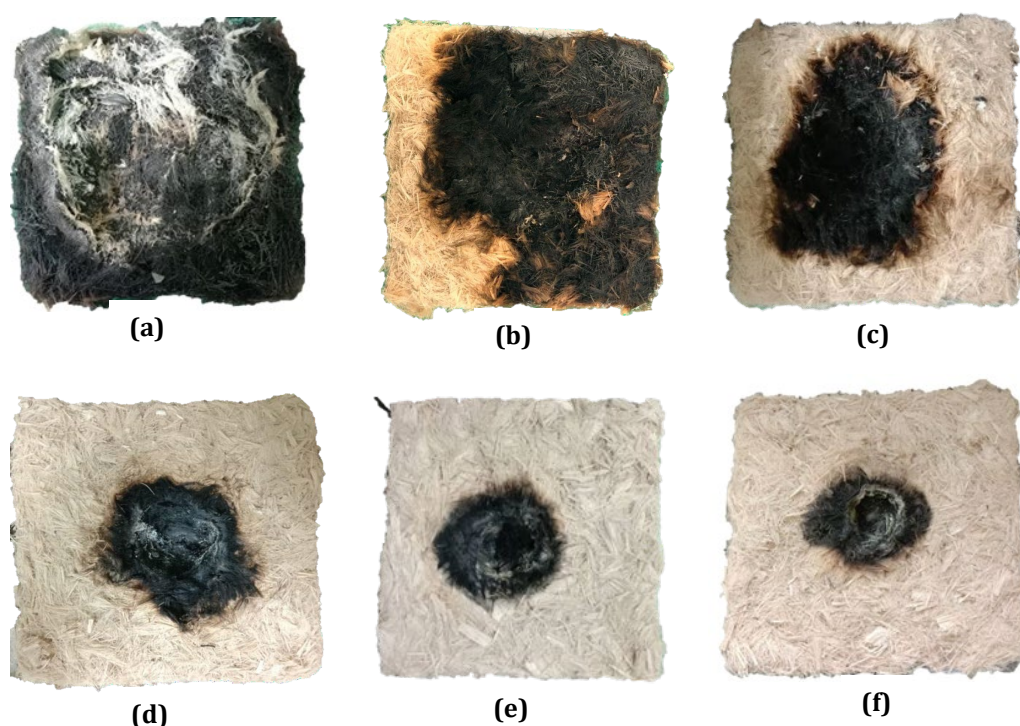


Fig. 6 After 30 minutes burning (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6

In the fire test, where the performance of all sample toward fire was observed based on the result in Table 4.16. The highest non-burn fiber goes to sample S6 with percentage of 98.103% out of the total weight. The second highest non-burn fiber is sample S5 where the percentage of non-burn fiber is 94.277% and followed by sample S4 with percentage of 48.329%. The next sample will be sample S3 and sample S2 where both have the non-burn fiber of 30.767% and 14.22%. The current sample used by industry comes to be the second lowest with percentage of non-burn of 11.389%. The lowest average of non-burn fiber goes to sample S1 which is the pure kenaf fiber with percentage of 8.472%. As a result, the best composition and give the optimum performance is sample S6 which only content 1.897% of average burn fiber.

Table 3 Percentage of burn and non-burn in sample

| Sample | Average Non burn fiber (%) | Average Burn fiber (%) |
|--------|----------------------------|------------------------|
| S1 | 8.472 | 91.528 |
| S2 | 14.292 | 85.705 |
| S3 | 30.767 | 69.233 |
| S4 | 48.329 | 51.671 |
| S5 | 94.277 | 5.723 |
| S6 | 98.103 | 1.897 |
| S7 | 11.389 | 88.611 |

3.4 Performance of Sound Absorption Coefficient in Kenaf Fiber

The test was carried out in accordance with ASTM E1050-09. In this test, all 18 samples were recorded. After that, the sample of sound absorption coefficients was averaged. The sound absorption coefficient's performance is evaluated using an impedance tube testing lab in accordance with ASTM E1050-09 standard. The samples were taken at every frequency peak in the range of 500Hz to 5000Hz. Every frequency's highest peak was recorded, and the results were compared.

The best composite composition for sound absorption is sample S3 with 10% of fire retardant illustrated in Fig.7. Sample S3 showed the best result, reaching the highest peak at 1259 Hz with a 0.9104 coefficient and 1600 Hz with a 0.9091 coefficient. Referring to the graph, S4 shows the lowest peak among all the samples which is the value of 0.8243 coefficients at 1000 Hz. The average of all samples' total peak coefficients is 0.9111, indicating that kenaf fibre has good sound absorption properties, as demonstrated by the current study, which is in line with Berardi and Dembsey [25]'s study of acoustic characterization of natural fibres for sound absorption applications. Higher fibre content allows sound waves to pass through an even more tortuous path that enables more excellent resistance, leading to higher energy losses. Besides, natural fibres have a porous structure and an inner structure with even a hollow lumen that dissipates sound waves [26]. It can be concluded that by using less fire retardant significantly affects the sound absorption properties.

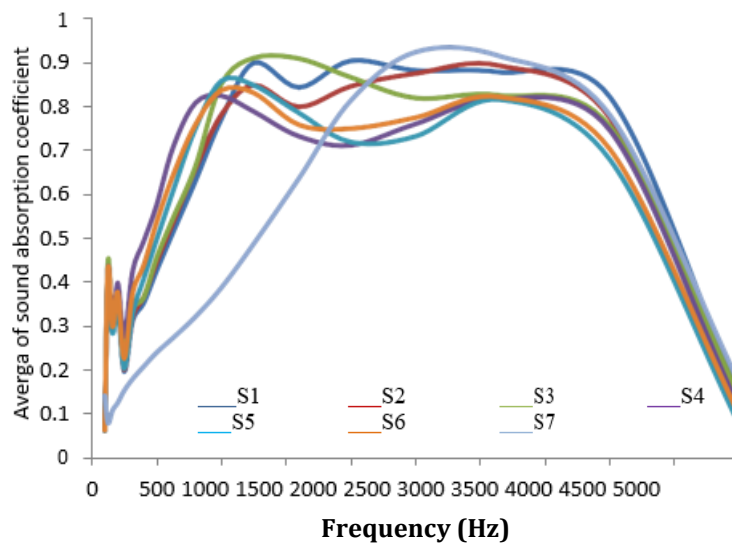


Fig. 7 Average sound absorption coefficient

4. Performance Summary

Based on analysis performed, it can be concluded that the thermal conductivity and density of the material is depends on the material composition. The composition of kenaf fiber and fire retardant is enhanced the specific properties of heat and fire insulator since kenaf fiber contribute to the absorption of heat and disperse heat through pores. The insulation performance of samples which consist of kenaf fiber and fire retardant is tested using guarded hot plate method. From the results obtained the density of kenaf fiber and lumen in fibre influence the heat transferred through the sample thickness, while the addition of fire-retardant help to improve the quality of absorption. Other than that, the sample possesses the lowest thermal conductivity due to the compactness of kenaf fiber which forms an empty cavity and causing the air filled the void and air is the good transportation retardant.

Moreover, the testing for surface burning characteristic of the sample was conducted accordance to ASTM E84 standard. The equipment used for this test was fire torch with gas butane. In the testing, the fire torch with fire on it was pointed directly to the center point of the sample. From this testing, the reaction of kenaf fiber was observed where reaction was depending on the composition ratios fire retardant added in the sample. The higher the composition ratios of fire retardant, the slower the fire will spread on the sample and even able to stop the fire from keep burning after the fire torch was take off.

The next testing is acoustic testing, where the performance of sample as a good sound absorption was test. Then, the best sample has been chosen with optimum result. In this test, the equipment used was impedance tube according to standard ASTM E1050-09. The coefficients of each sample were taken at every frequency peak in the range of 500Hz to 5000Hz. Every frequency's highest peak was recorded, and the results were compared. From these testing can be observed that, the performance of sample as a good sound absorption was depending on the density of the sample. In general, sample with higher density, have a lower the coefficient of sound absorption.

Other than that, the heat transferred through 40 mm sample is observed, the data found that the heat is move through the center of the sample and start to diminish on the middle of the sample as illustrate in Fig.8. It is experimentally proven that the usage of natural fiber as heat and fire insulator is an alternative material to replace synthetic fiber which was a non-biodegradable fiber and help to preserve the healthy environment.

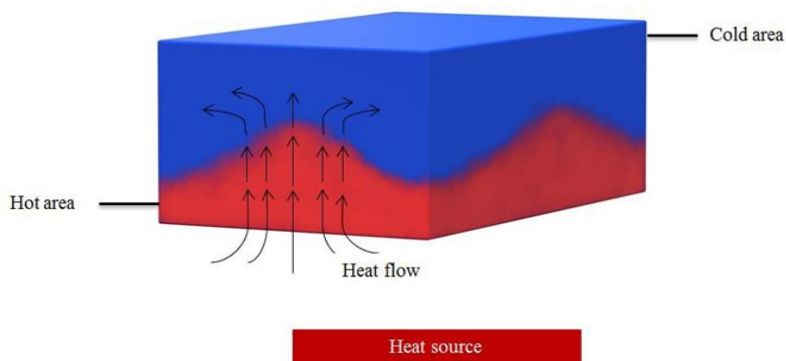


Fig. 8 Illustration of heat moves along the sample

5. Conclusion

The current study aimed to embed kenaf fiber in fire retardant with different composition ratios of fire retardant using a common mixing method. The significant conclusions are as follow:

- (a) Thermal conductivity analysis shows that the effect of fire retardant in kenaf fiber with 25 % of composition is proven has an ability to insulate heat and fire better than current insulator used in industry.
- (b) The result of fire test, it can be concluded that the fire stop spread with high composition which is 25 % of the fire retardant added in the sample. The sample with less amount of fire retardant will burn easily especially with high temperature. Kenaf fiber is seen to having more ability to trapped heat energy compared to current insulator sample.
- (c) From the overall result of acoustic test, the composition of fire retardant in kenaf fiber and the density of sample affects the acoustics properties. In general, the fiber content more fire retardant observed to have lower sound absorption.
- (d) Sample S1 show the best performance for thermal transmission with the highest value of thermal conductivity compare to other sample which is 0.4472 W/mK with temperature different of 240°C.
- (e) Sample S6 with the higher percentage of non-burn fiber has become the best sample with good insulation towards fire where the result is 98.103% of non-burn fiber.
- (f) Sample S3 come out with the optimum result performance as a good sound absorption by reaching the highest peak at 1259 Hz with a 0.9104 coefficient and 1600 Hz with a 0.9091 coefficient.

The evidence from this study suggest that this study sample can replace the current insulator used in industry.

Acknowledgement

This research was not funded by any grant.

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:** Kamarul Amir Mohamed; **data collection:** Meryl Anyie Tomy; **analysis and interpretation of results:** Wan Hasrulnizzam Wan Mahmood, Azrin Hani Abdul Rashid, Zulfikar Achmad Jusuf; **draft manuscript preparation:** Myia Yuzrina Zalkis Ayol, Mohd Yuhazri Yaakob. All authors reviewed the results and approved the final version of the manuscript.*

References

- [1] Fiore, V., Di Bella, G., & Valenza, A. (2019). Effect of sheep wool fibers on thermal insulation and mechanical properties of cement-based composites, *Journal of Natural Fibers*, 17(10), 1532-1543. <https://doi.org/10.1080/15440478.20.1584075>

- [2] Florea, I., & Manea, D. L. (2019). Analysis of thermal insulation building materials based on natural fibers. *Procedia Manufacturing*, 32, 230-235. <https://doi.org/10.1016/j.promfg.20.02.207>
- [3] Takagi, H. (2019). Review of functional properties of natural fiber-reinforced polymer composites: thermal insulation, biodegradation and vibration damping properties, *Advanced Composite Materials*, 28(5), 525-543. <https://doi.org/10.1080/09243046.20.1617093>
- [4] Ramasubbu, R., & Madasamy, S. (2022). Fabrication of automobile component using hybrid natural fiber reinforced polymer composite. *Journal of Natural Fibers*, (2), 736-746. <https://doi.org/10.1080/15440478.2020.1761927>
- [5] Spinnler, M., Winter, E. R., & Viskanta, R. (2004). Studies on high-temperature multilayer thermal insulations. *International Journal of Heat and Mass Transfer*, 47(6-7), 1305-1312. <https://doi.org/10.1016/j.ijheatmasstransfer.2003.08.012>
- [6] Muthukumar, K., Sabariraj, R. V., Kumar, S. D., & Sathish, T. (2020). Investigation of thermal conductivity and thermal resistance analysis on different combination of natural fiber composites of banana, pineapple and jute. *Materials Today: Proceedings*, 21(1), 976-980. <https://doi.org/10.1016/j.matpr.20.09.140>
- [7] Zach, J., Hroudová, J., Brožovský, J., Krejza, Z., & Gailius, A. (2013). Development of thermal insulating materials on natural base for thermal insulation systems. *Procedia Engineering*, 57, 1288-1294. <https://doi.org/10.1016/j.proeng.2013.04.162>
- [8] Bozsaky, D. (2019). Nature-based thermal insulation materials from renewable resources—A state-of-the-art review, *Slovak Journal of Civil Engineering*, 27(1), 52-59. <https://doi.org/10.2478/sjce-20-0008>
- [9] Atmakuri, A., Palevicius, A., Siddabathula, M., Vilkauskas, A., & Janusas, G. (2020). Analysis of mechanical and wettability properties of natural fiber-reinforced epoxy hybrid composites. *Polymers*, 12(12), 2827. <https://doi.org/10.3390/polym12122827>
- [10] Väisänen, T., Das, O., & Tomppo, L. (2017). A review on new bio-based constituents for natural fiber-polymer composites. *Journal of Cleaner Production*, 149, 582-596. <https://doi.org/10.1016/j.jclepro.2017.02.132>
- [11] Kim, N. K., Dutta, S., & Bhattacharyya, D. (2018). A review of flammability of natural fibre reinforced polymeric composites. *Composites Science and Technology*, 162, 64-78. <https://doi.org/10.1016/j.compscitech.2018.04.016>
- [12] Chu, C. C., Chew, S. C., & Nyam, K. L. (2021). Recent advances in encapsulation technologies of kenaf (*Hibiscus cannabinus*) leaves and seeds for cosmeceutical application. *Food and Bioprocess Technology*, 127, 99-113. <https://doi.org/10.1016/j.fbp.2021.02.009>
- [13] Giwa Ibrahim, S. A., Karim, R., Saari, N., Wan Abdullah, W. Z., Zawawi, N., Ab Razak, A. F., & Umar, R. U. A. (2019). Kenaf (*Hibiscus cannabinus* L.) seed and its potential food applications: A review. *Journal of Food Science*, 84(8), 2015-2023. <https://doi.org/10.1111/1750-3841.14714>
- [14] Mahjoub, R., Yatim, J. M., Sam, A. R. M., & Raftari, M. (2014). Characteristics of continuous unidirectional kenaf fiber reinforced epoxy composites. *Materials & Design*, 64, 640-649. <https://doi.org/10.1016/j.matdes.2014.08.010>
- [15] Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnier, C. (2023). A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. *Results in Engineering*, 101271. <https://doi.org/10.1177/1477760620953438>
- [16] Dinesh, V., Shivanand, H. K., Vidyasagar, H. N., & Chari, V. S. (2018). Investigation of mechanical properties of kenaf, hemp and E-glass fiber reinforced composites. In *AIP Conference Proceedings* (Vol. 1943, No. 1). AIP Publishing. <https://doi.org/10.1063/1.5029693>
- [17] Lee, C. H., Khalina, A., Nurazzi, N. M., Norli, A., Harussani, M. M., Rafiqah, S. A., ... & Ramli, N. (2021). The challenges and future perspective of woven kenaf reinforcement in thermoset polymer composites in malaysia: A review. *Polymers*, 13(9), 1390. <https://doi.org/10.3390/polym13091390>
- [18] Yusuff, I., Sarifuddin, N., & Ali, A. M. (2021). A review on kenaf fiber hybrid composites: Mechanical properties, potentials, and challenges in engineering applications. *Progress in Rubber, Plastics and Recycling Technology*, 37(1), 66-83. <https://doi.org/10.1177/1477760620953438>
- [19] Vanapalli, K. R., Samal, B., Dubey, B. K., & Bhattacharya, J. (2019). Emissions and environmental burdens associated with plastic solid waste management. In *Plastics to Energy* (pp. 313-342). William Andrew Publishing. <https://doi.org/10.1016/B978-0-12-813140-4.00012-1>
- [20] Ashori, A., Harun, J., Raverty, W. D., & Yusoff, M. N. M. (2006). Chemical and morphological characteristics of Malaysian cultivated kenaf (*Hibiscus cannabinus*) fiber. *Polymer-Plastics Technology and Engineering*, 45(1), 131-134. <https://doi.org/10.1080/03602550500373782>
- [21] Yusuff, I., Sarifuddin, N., & Ali, A. M. (2021). A review on kenaf fiber hybrid composites: Mechanical properties, potentials, and challenges in engineering applications. *Progress in Rubber, Plastics and Recycling Technology*, 37(1), 66-83. <https://doi.org/10.1177/1477760620953438>

- [22] Saba, N., Jawaid, M., Hakeem, K. R., Paridah, M. T., Khalina, A., & Alothman, O. Y. (2015). Potential of bioenergy production from industrial kenaf (*Hibiscus cannabinus* L.) based on Malaysian perspective. *Renewable and Sustainable Energy Reviews*, 42, 446-459. <https://doi.org/10.1016/j.rser.2014.10.029>
- [23] Naik, N., Shivamurthy, B., Thimmappa, B. H. S., Gupta, A., Guo, J. Z., & Seok, I. (2022). A review on processing methods and characterization techniques of green composites. *Engineered Science*, 20(10), 80-99. <http://dx.doi.org/10.309/es8d713>
- [24] Liu, K., Takagi, H., Osugi, R., & Yang, Z. (2012). Effect of lumen size on the effective transverse thermal conductivity of unidirectional natural fiber composites. *Composites Science and Technology*, 72(5), 633-639. <https://doi.org/10.1016/j.compscitech.2012.01.009>
- [25] Berardi, U., & Dembsey, N. (2015). Thermal and fire characteristics of FRP composites for architectural applications. *Polymers*, 7(11), 2276-2289. <https://doi.org/10.3390/polym7111513>
- [26] Lakshmanan, A. (2019). Engineering Acoustic Protein Nanostructures for Non-invasive Molecular Imaging Using Ultrasound. (CaltechTHESIS:06062019-165907194) [Doctoral dissertation, California Institute of Technology]. CaltechTHESIS.