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Flame retardant sound absorbing panel made from bamboo charcoal and natural kaolin clay

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ABSTRACT

As noise pollution affects mental and physical health, sound absorbing panels are used to reduce noise pollution problems, especially the use of natural materials instead of synthetic materials in the fabrication of sound absorbing panels. Bamboo charcoal and natural kaolin clay were applied for eco-friendly flame retardant sound absorbing panels. The appropriate ratio of natural materials for forming sound absorbing panels to obtain the maximum sound absorption ability was investigated. In addition, the effects of the mixture ratios and thicknesses of sound absorbing panels on sound absorption, mechanical properties, and flame resistance were studied. The noise reduction coefficient (NRC) was determined according to ISO 354:2006 and ASTM C 423. At a thickness of 7 mm, the mixture materials obtained the highest sound absorption coefficient of 0.4 with a weight ratio of bamboo charcoal: natural kaolin: water: latex compound of 97: 3: 200: 50, respectively. It also has properties with a density of 327.62 kg/m^3, a water absorption value of 9.14%, and a maximum tensile strength of 453.66 N, according to TIS 535-2527. The microstructural characteristics of the fabricated sound absorbing panel were investigated using scanning electron microscopy, which revealed good adhesion and high porosity. The flammability tests were performed according to ASTM D3801 and ASTM D635 for the vertical and horizontal positions, respectively. The appropriate mixture ratios presented for vertical burning obtained a V-0 classification, and horizontal burning obtained an HB classification. The flame retardant sound absorbing panel made from natural materials, including bamboo charcoal as a sound absorber and natural kaolin clay as a sound absorbing support, can be achieved because when it is ignited, it turns into ashes that can assist in extinguishing the fire by itself and not spread the flame. Bamboo charcoal powder and natural kaolin clay showed good performance for both sound absorption and flame retardancy. These are the natural alternative materials that can be used to develop commercial flame retardant sound absorbing panels.

Keywords: *Bamboo charcoal, Kaolin clay, Natural material, Noise reduction coefficient, Sound absorbing, Flame resistance*

1. INTRODUCTION

Noise pollution is one of the pollutants that affect humans in terms of mental and physical health and is caused by various sources, such as the sound coming from vehicles, industries, and the construction of buildings and roads. Noise reduction by using sound absorbing materials is an important way to reduce the hazards of noise pollution [1]. In general, sound absorbing materials are made from non-renewable sources such as mineral wool, polyurethane and melamine foams, rubber, fiberglass or glass wool, ceramics, and fabric [2-6]. They regularly provide high sound absorption coefficients, but the synthesis of sound absorbing materials is harmful to human health as well as to the environment [6-7]. In addition to the high cost of production, their production can release more carbon dioxide into the atmosphere compared to sound absorbing panels made from natural materials [6, 8].

Nowadays, sound absorption made from natural materials has received increasing attention because of their low density, high porosity, environmental friendliness, recyclable nature, minimal health impacts, and low cost [9-11]. The natural materials have hollow structures to act as sound absorbers [7]. Several studies have investigated the utilization of both porous materials [12] and natural fibers [13-14] as raw materials. There are many natural sound absorbing materials such as hemp [15-16], sunflower [17], pineapple leaf fiber [18], corn husks [19], sugarcane [20-21], jute [22-23], kenaf [13, 24], sisal [25], coconut husks [25], coconut coir [26-29], kapok [30], bamboo [7, 31] and date palm [32-33].

As there are enormous bamboo stems from processing in Prachinburi Province, Thailand, and bamboo fibers were found to have a sound absorption coefficient similar to that of commercial glass fiber [7] together with the perspective on the use of agricultural waste for maximum benefit, this research focused on the use of bamboo as one of the raw materials to produce the sound absorbing panels. Although natural fibers are receiving increasing attention to replace synthetic materials, they have a serious disadvantage in terms of low flame resistance. Bamboo charcoal is considered to have significant potential as a natural, nontoxic flame retardant [34]. The use of bamboo charcoal as a flame retardant instead of bamboo fiber is applied in this research. Carbon-based materials, such as carbon black and carbon nanotubes, have spawned significant interest in the fabrication of polymer composites/nanocomposites with greatly improved flame retardant performance [35-36]. Moreover, kaolin clay is used to improve flame retardant properties [37-38]. The mixing of kaolin and other retardant materials received attention to improve the flame resistance of polymer insulation, such as nano-kaolin and nano-HAO (nano-sized hydroxyl aluminum oxalate) [39]. However, there are limited studies on the use of bamboo charcoal in the production of sound absorbing materials, especially on the combination of bamboo charcoal and natural kaolin clay as a natural material for sound absorbing materials. Sakthivel et al. [40] proposed eco-friendly sound absorbing composite materials developed from sugarcane bagasse and bamboo charcoal for automotive industry applications.

As mentioned above, this study has an idea to use bamboo charcoal powder made from Tongsriprachin bamboo, a local plant in Prachinburi Province, Thailand, and natural kaolin as a natural material mixed with latex compound to produce the flame retardant sound absorbing panels. The mixing ratios and the panel thicknesses were varied for making sound absorption wall panels to test their properties according to TIS 535-2527 [41], such as density, water absorption, maximum tensile strength, and noise reduction coefficient, in accordance with ISO 354:2006 [42] and ASTM C 423 [43]. After that, the flammability tests were performed according to ASTM D3801 [44] and ASTM D635 [45] for the vertical and horizontal positions, respectively.

2. MATERIALS AND METHODS

2.1. Preparation of Sound Absorbing Panels

The preparation of natural kaolin used as kaolin from Khok Mai Lai Subdistrict, Mueang District, Prachinburi Province, features a large lump mixed with powder to be coarsely crushed and crushed with a stone mortar sifted through a fine sieve of 20-25 microns. Furthermore, the preparation of bamboo charcoal powder used the Tongsriprachin bamboo with old stems from Saphan Hin Subdistrict, Na Di District, Prachinburi Province. It was cut into small pieces and then dried at 60 °C, and then it was baked in a hot air oven at 200 °C for 12 hours; after that ground, until it turned into fine charcoal with a mortar and sifted through a fine sieve of 20-25 microns. As illustrated in Table 1, twelve mixing ratios were used to prepare the samples at 3 mm, 5 mm, and 7 mm thicknesses. Then, samples were placed in a hot air incubator at 100 °C for 2 hours. Scanning electron microscopy (SEM) was used to determine the microstructure and sheet adhesion of the sample materials.

2.2. Sound Absorbing Property Test

2.2.1. Noise Reduction Coefficient

The properties of sound absorption wall panels were tested according to the Thai Industrial Standard (TIS 535-2527) [41], including density, water absorption, and tensile strength. Moreover, the noise reduction coefficient (NRC) test according to ISO 354:2006 [42] was determined. As shown in Figure 1, the device used consists of 2 test boxes measuring 40 x 40 x 40 cm^3, connected to each other, including the sound source box, inside of which is installed a 100-watt speaker that controls the sound system with a generator function, the signal was tuned to the maximum level, and the volume is fixed at 40 watts. The other box is for attaching a test sheet of 9.5 x 9.5 cm^2. Both boxes are attached to the sound level meter. Each set of this test will use the frequencies 250 Hz, 500 Hz, 1 kHz, and 2 kHz as adjusted by the amplifier as the standard frequencies used in the test. The amplifiers, loudness meter, loudspeakers, and sound level meters were set up as pre-powered in a room with a controlled 0 dB sound pressure level and then tested for sound absorption coefficient (SAC) at various standard frequencies. Finally, the sound absorption of the wall in the test box on the side corresponds to the location of the sound source, and the sound source is turned on for 15 seconds.

The difference between outside and inside loudness measurements for the sound absorption value of the wall without the test sheet installed is $I1$, according to Equation 1. The inner ($A1$) and the outer ($A2$) sound level meters were observed, and the results were recorded. Then, the sample sheet was placed inside the test box. At the same position, the timer was set for 15 seconds. The difference between outside and inside loudness measurements for the sound absorption value of the wall with the test plate attached to the box wall is $I2$, according to Equation 2. The inner ($B1$) and the outer ($B2$) sound level meters were observed, and the results were recorded. Then, it was calculated to find the SAC of the sample sheet as in Equation 3.

$$I1 = A1 - A2 \quad (1)$$

$$I2 = B1 - B2 \quad (2)$$

$$\text{SAC} = (I2 - I1)/I1 \quad (3)$$

To determine the noise reduction coefficient (NRC), when the SAC values of 250 Hz, 500 Hz, 1 kHz, and 2 kHz are obtained, the SAC values at 250 Hz, 500 Hz, 1 kHz, and 2 kHz are averaged to obtain the NRC values as shown in Equation 4.

$$\text{NRC} = (\text{SAC}_{250\text{Hz}}+\text{SAC}_{500\text{Hz}}+\text{SAC}_{1000\text{Hz}}+\text{SAC}_{2000\text{Hz}})/4 \quad (4)$$

It is noted that the NRC value must be greater than 0.40 to be considered a sound absorbing material.

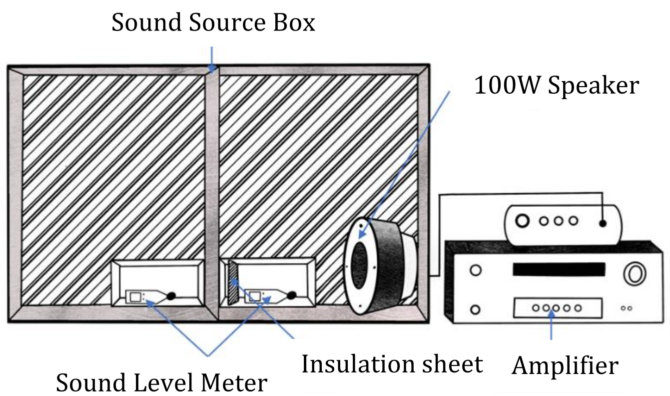


Figure 1 The sound absorption test set of the sample plate

Table 1 Mixing ratio by weight

Type	Bamboo Charcoal: Natural Kaolin: Water: Latex compound (g)
1	0 : 100 : 200 : 50
2	99 : 1 : 200 : 50
3	98 : 2 : 200 : 50
4	97 : 3 : 200 : 50
5	96 : 4 : 200 : 50
6	95 : 5 : 200 : 50
7	94 : 6 : 200 : 50
8	93 : 7 : 200 : 50
9	92 : 8 : 200 : 50
10	91 : 9 : 200 : 50
11	90 : 10 : 200 : 50
12	100 : 0 : 200 : 50

2.2.2. Density

The specimen measuring 5 cm x 5 cm was cut and weighed on two digital scales; length, width, and thickness were measured using a Vernier as a measuring tool, and the average density was found from Equation 5.

$$D = m/V \quad (5)$$

where D is the density of the object (kg/m^3), m is the mass of the object (kg), and V is the total volume of the object (m^3).

2.2.3. Water Absorption

The specimen, measuring 9.5 cm x 9.5 cm, is cut and weighed on two digital balances before immersion *(W1)*. The specimen is then placed in the same plane as the water level, with the upper edge approximately 20 mm below the water surface. The test piece was soaked for 24 hours, and then the specimen was removed from the water. Then, water absorption was weighted (*W2*), and the average percentage was found as given in Equation 6.

$$WA = ((W2 - W1) / W1) \times 100 \quad (6)$$

where WA is the percentage of water absorption, W1 is the weight before soaking (g), and W2 is the weight after immersion (g).

2.2.4. Maximum Tensile Strength

The specimen was cut to a size of 5 cm x 5 cm. The wire was then tied to the specimen and suspended from the floor at a height of 1 m. The bottom of the specimen was then weighed with sandbags by adding a weight of sand until the test strip was torn. The maximum tensile strength was calculated.

2.2.5. Flammability Tests

Flammability testing is a vital part of ensuring the safety and reliability of products as well as meeting quality control and industry and regulatory requirements [46]. The flame retardant properties of the natural material insulation were evaluated using two flammability tests. These tests were carried out according to ASTM D3801 and ASTM D635 for vertical and horizontal flammability procedures, respectively. The test samples were cut out of the insulation sheet with the same dimensions for both vertical and horizontal burning tests. The sample length and width were 125 mm and 13 mm, respectively. For the vertical burning test, the burning time was measured according to the test procedure. For the horizontal burning test, after the flame reaches the 25 mm mark from the end of the specimen, the time (t) in seconds starts to be measured until the flame extinguishes. The burned length (L_b) was measured in millimeters. The linear burning rate (v) in mm/min is calculated using Equation 7 [47].

$$v = 60L_b/t \quad (7)$$

3. RESULTS AND DISCUSSION

3.1. Sound Absorbing Panel Formation

From mixing raw materials according to the specified type, it was found that Type 1, with a weight ratio of bamboo charcoal: natural kaolin: water: latex compound at 0: 100: 200: 50, respectively, could not form sound absorption panels. All three substances will coagulate because the latex has a pH of about 6.8, which is relatively neutral. When adding natural kaolin to water, it has a pH of about 6, which is weakly acid. As a result, when the natural kaolin was mixed with water and latex, it caused those substances to coagulate before pouring into the mold. Moreover, latex contains particles of different sizes suspended in a liquid. These particles are always negatively charged, making them suspended and remaining latex until other factors interfere with the change. This can stabilize the latex and cause it to coagulate. From Type 2 to Type 12, they adhere well to the sheet, are easily bent, and the surface is not separated. A bio-charcoal with an alkaline value (high pH value, thus reducing the pH value of the soil). Mixing natural kaolin with charcoal causes the natural kaolin to have a higher pH value. The latex mixture will not coagulate before it is poured into the mold. This allows it to be molded, and the pH of the charcoal also depends on what is used for incineration. The research results were divided into two main parts: the results from the sound absorbing properties test and the results from the structural analysis and properties of the sample materials.

The sound absorbing panel of Type 4 with a thickness of 7 mm was chosen to investigate the microstructure using SEM, as shown in Figures 2 (A) and (B). The insulation surface from bamboo charcoal mixed with natural kaolin clay obtains good adhesion, and the highly porous surface provides a good space absorption area. The pore sizes are less than 50 µm. Figures 3 (A) and (B) show a surface and material cross-section of commercial acoustic Polyethylene (PE) foam board, respectively. They have low porous, and pore sizes are greater than 500 µm. Clearly, the sound absorption wall panels have more porosity than acoustic PE foam board, affecting the density, water absorption, maximum tensile strength, and sound absorption capability.

3.2. Noise-Reduction Coefficient

Figures 4 (A), (B), and (C) show the SAC values for samples of Type 2 to Type 12 for 3, 5, and 7 mm thicknesses, respectively. It was noted that the sample Type 1 formula could not be formed into a sound absorbing panel. The SAC increases as the thickness of the sound absorbing panels increases. In addition, at the frequency range of 250-500 Hz for all thicknesses, the SAC was similar to a steadily increasing value at a frequency of 1000 Hz or more.

The noise reduction coefficient (NRC) values according to ISO 354:2006 [42], and ASTM C 423 [43] are shown in Figure 5. It was found that the noise reduction coefficient (NRC) of the sound absorbing panels ranged from 0.07 to 0.40. The highest sound absorption ability of 0.40 was found in Type 4 at 7 mm thickness, with the weight ratio of bamboo charcoal: natural kaolin: water: latex compound at a weight ratio of 97: 3: 200: 50, respectively.

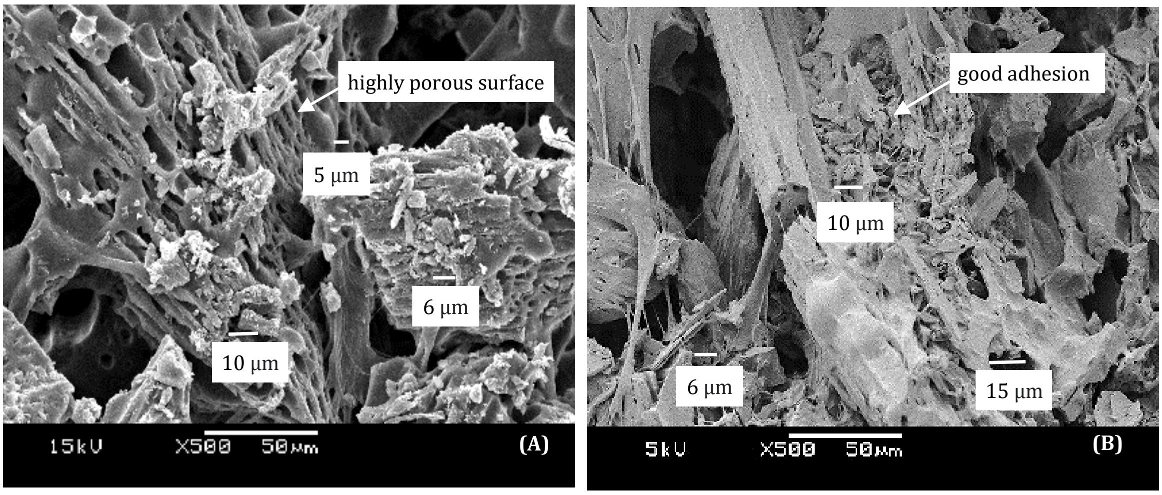


Figure 2 SEM images of the natural sound absorbing material (A) surface and (B) cross-section

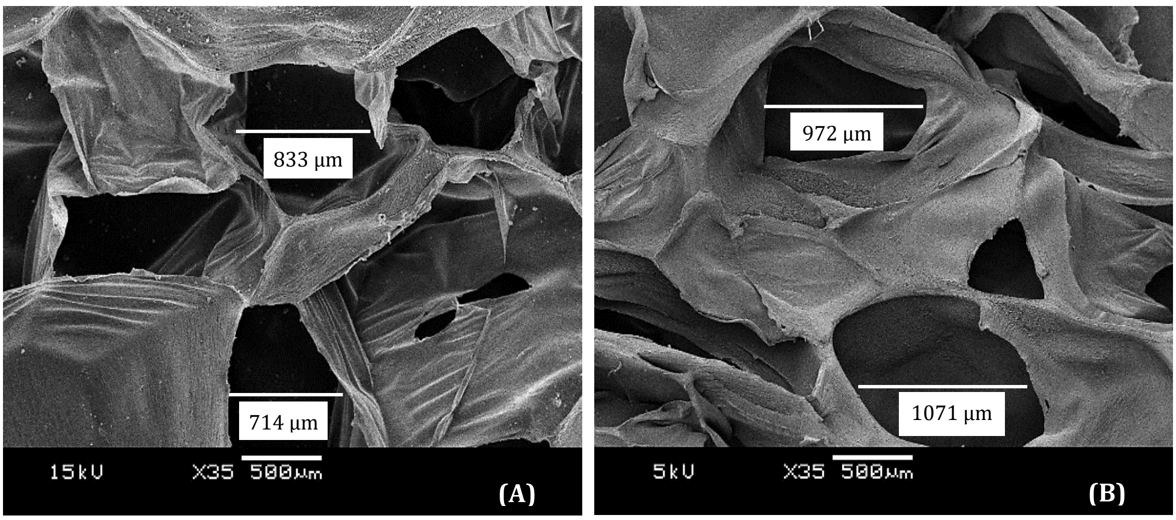


Figure 3 SEM images of acoustic PE foam board (A) surface and (B) cross-section

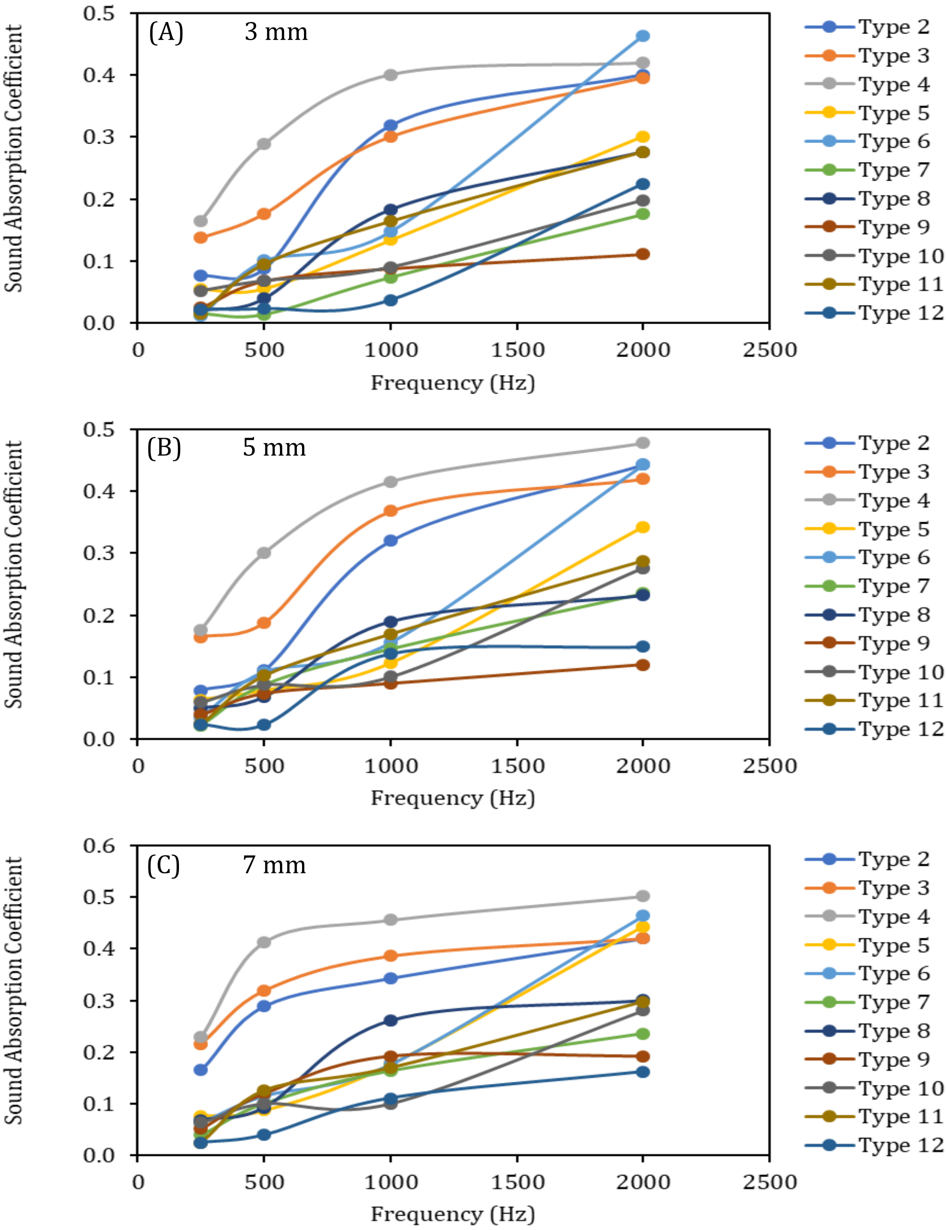


Figure 4 Sound absorption coefficient at a thickness (A) 3 mm, (B) 5 mm, and (C) 7 mm

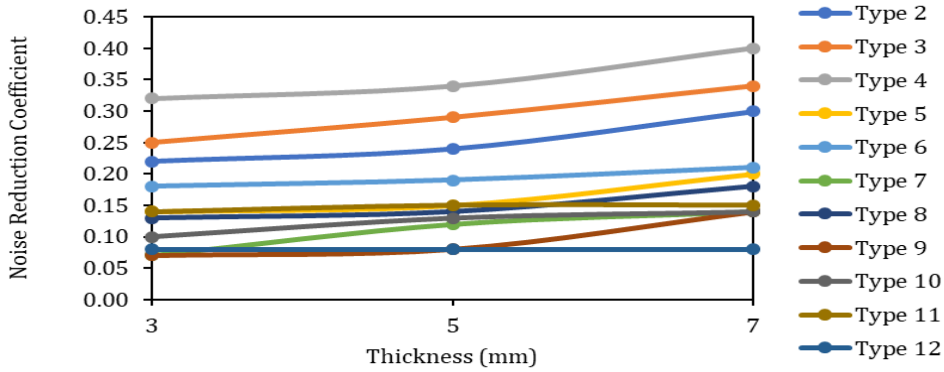


Figure 5 Noise reduction coefficient at thickness 3 mm, 5 mm, and 7 mm

The NRC values obtained from this research were compared to other researches, as illustrated in Table 2. The sound absorption ability of the bamboo charcoal and natural kaolin clay mixture was similar to that of natural materials from coconut coir [13, 26-27], date palm [20], and hemp [13, 15], with a lower value than jute [22], kenaf [13], sisal [25] which, if compared with research that uses bamboo raw materials, is similar to this research. The NRC value obtained from this study was lower than the maximum value of bamboo [31].

The highest sound absorption ability with NRC of 0.4 was found in Type 4 for 7 mm thickness, with a ratio of bamboo charcoal: natural kaolin: water: Latex compound of 97: 3: 200: 50, respectively. The properties of sound absorption panels were tested according to the Thai industrial standard (TIS 535-2527) [41] for mixed materials of Type 4 for a thickness of 7 mm. Table 3 shows that the properties of natural sound absorption panels passed the industrial standard.

3.3. Flammability Test

Table 4 illustrates the results of the vertical flammability test, considering the effects of the Type 4 for 7 mm thickness on the burning time. This research considered the material flammability classifications for the vertical burning test method according to ASTM D3801 [44]. For 7 mm thickness, the amount of bamboo charcoal 94 g and the amount of kaolin clay 6 g at the fixed amounts of water and latex compound of 200 g and 50 g, respectively, enhanced fire resistance V-0. In fact, these mixtures presented individual burning times lower than the necessary number to classify the material (10 s). The average results were obtained at 4.88 s.

The result of the horizontal flammability test for sample Type 4 for 7 mm thickness is shown in Table 4. In this horizontal test, the key criterion to classify the materials is the linear burning rate. The results of the horizontal burning test showed that Type 4 for 7 mm thickness was non-burning. It was observed that although it ignited in the beginning, it extinguished itself before reaching the specified distance at the 25 mm mark, and the flame resistance achieved HB rating, as shown in Figure 6. Figure 7 demonstrates the horizontal burning at different thicknesses, and the results showed that an increase of panel thickness decreases the burning.

Table 2 Noise reduction coefficient (NRC) Values

Raw materials	Thickness (mm)	NRC	References
bamboo charcoal /kaolin	7	0.40	this research
hemp	30	0.40	[13]
hemp	40	0.45	[15]
coconut coir	50	0.50	[13]
coconut coir	25 - 45	0.16 - 0.51	[26]
coconut coir	21 - 35	0.26 - 0.40	[27]
date palm	10 - 40	0.18 - 0.45	[32]
date palm	20 - 40	0.24 - 0.42	[33]
jute	25 - 50	0.40 - 0.60	[22]
jute	40	0.65	[23]
kapok	17 - 60	0.31 - 0.67	[30]
kenaf	40 - 60	0.55 - 0.70	[13]
kenaf	10 - 50	0.10 - 0.57	[24]
sisal	44	0.52	[25]
bamboo	20 - 60	0.30 - 0.70	[31]

Table 3 Properties of sound absorption panels from natural materials

Sound absorption properties	Industry Standards	Measured Value	Summary Pass/Fail
Density	Less than 350 kg/m^3	327.62 kg/m^3	Pass
Water absorption	Less than 10%	9.14%	Pass
Maximum tensile strength	Greater than 450 N	453.66 N	Pass

Table 4 Vertical and horizontal flammability tests

Specification	Burning time after removing the ignition source until extinguishing (s)	burning rate (mm/min)
Vertical flammability test	4.88	n/a
Horizontal flammability test	n/a	non-burning

Figure 6 Burning of the sound absorption wall panels made from natural materials

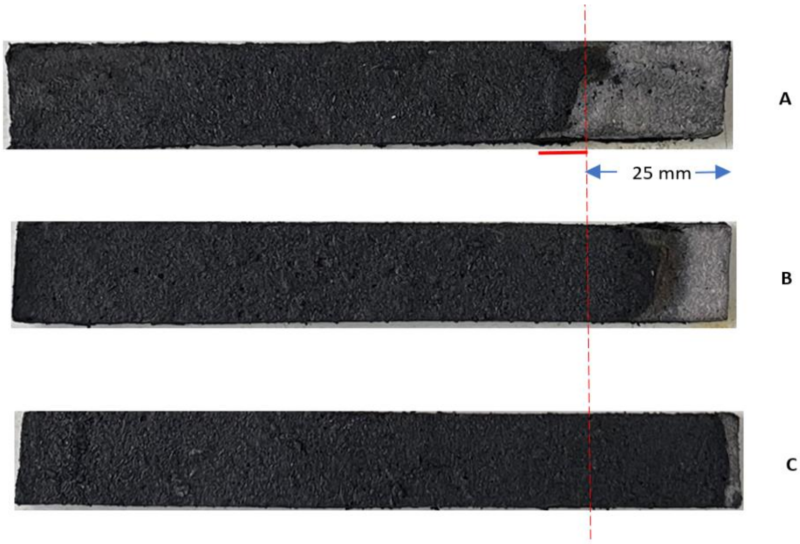
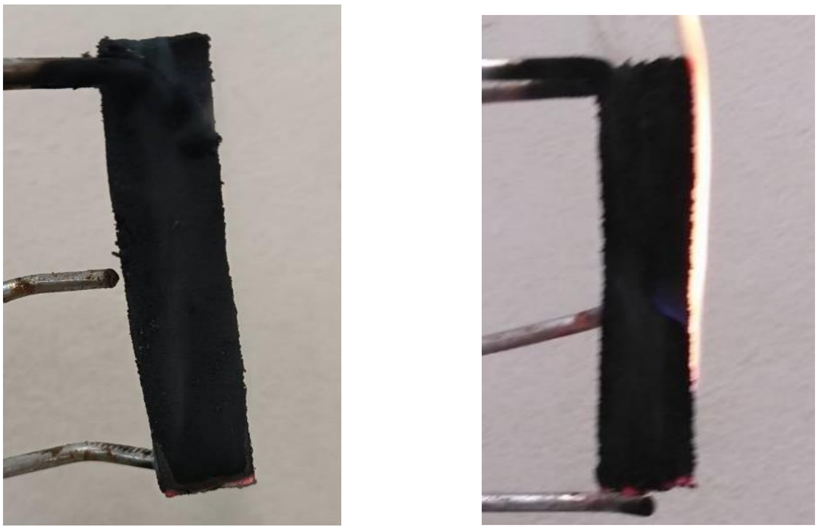


Figure 7 Burning of the sound absorption wall panels made from natural materials (A) 3 mm, (B) 5 mm, and (C) 7 mm thickness

In addition, as shown in Table 5 and Figure 8, the sound absorption wall panels in this research were compared with the commercial acoustic polyethylene board; the results showed that the burning rate of natural insulation was lower than that of commercial insulation and acoustic board made from polyethylene. This was because commercial insulation sheet and acoustic polyethylene board contain flammable ingredients, but major components of natural insulation are bamboo charcoal as flame resistance.

Table 5 Flame resistant comparison between the sound absorption wall panels and the commercial insulation sheet

Insulation type	Vertical flammability test	Horizontal flammability test: burning rate (mm/min)
Natural materials of Type 4 for 7mm thickness	V-0	non-burning
Acoustic polyethylene board 7 mm	No classification	126.7



(A) (B)

Figure 8 Burning of the sound absorption wall panels (A) and acoustic polyethylene board (B)

The results showed that bamboo charcoal, as a flame retardant, can effectively prevent the flammability of the sound absorbing panel. Carbon nanomaterial additives in the polymers and composites are used to form a char layer so that the flow rate of combustible fuels reaching the gas phase is reduced; this limits the potential number of exothermic reactions and prevents oxygen from reaching the polymers [36]. Moreover, carbon nanofillers as new flame-retardant additives not only improve the flame retardancy of polymers but also reinforce them [48]. Therefore, the use of a large amount of bamboo charcoal, approximately 28 wt% of the mixture of Type 4, showed a maximum tensile strength of 453.66 N, greater than 450 N of the industrial standard. The addition of kaolin to the polymer improves its adhesion to the polymer and disperses it easily. It also improves the flame retardant performance of the polymer [37]. Consequently, the addition of both bamboo charcoal and natural kaolin showed good performance as fire retardants for the sound absorbing panel.

4. CONCLUSION

The popular materials for sound absorption affect the environment and health and also have to be imported from abroad. Therefore, this study focused on using natural materials that are environmentally friendly to reduce the cost of importing them from abroad. Sound absorption wall panels in the building were developed from natural materials containing bamboo charcoal, natural kaolin, water, and latex instead of synthetic materials. The weight ratios of bamboo charcoal, natural kaolin, water, and latex, as well as the thickness of sample sheets, were varied. The noise reduction coefficient (NRC) values for the sound absorption ability according to TIS 535-2527 were investigated to obtain the suitable mixing ratio and thickness. The results showed that the NRC value increases with the thickness of the sound absorption wall panels. The NRC values of the indoor sound absorption wall panels made from natural materials were between 0.07 - 0.40. The highest NRC of 0.4 was obtained with the ratio of bamboo charcoal: natural kaolin: water: latex chemical compound (g) at the ratio of 97: 3: 200: 50 at 7 mm thickness. In addition, the properties of density, water absorption, and maximum tensile strength followed the Thai industrial standard (TIS 535-2527). From the flammability tests, it can be rated a V-0 classification in the vertical flammability test and an HB classification in the horizontal flammability test.

In this approach, the sound absorption wall plates from natural materials can be used as a material in the building to add more features in other areas to be better. It is to create value for materials and can be an environmentally friendly alternative material.

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