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Sound absorption coefficient measurement and analysis of bio-composite micro perforated panel (BC-MPP)

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Abstract The sound absorption performance of bio-composite micro-perforated panel (BC-MPP) made from composite polypropylene (PP) filled rice husk (PP/RH), and coconut coir (PP/CC) is presented. The sound absorption coefficient (SAC) of BC-MPP was obtained via the impedance tube two-microphone method, and the investigation was according to types of fillers, filler compositions, perforation ratio, and the air gap size. It was found that the SAC of BC-MPP PP/RH provides a higher SAC value than BC-MPP PP/CC. Furthermore, the SAC peak was observed to shift to the lower frequency spectrum when there was an increment in filler content, the distance between the perforation, and the air gap size. The SAC value from the simulation also shows a good agreement with the experimental result.

1. Introduction

Sound-absorbing materials are often used to improve sound quality and prevent echoes and unpleasant reverberation inside a space. They consist of resonator-type and porous-type sound-absorbing material [1]. Micro-perforated panel (MPP) is a resonator-type sound-absorbing material with excellent acoustic resistance and a considerable range of absorption bandwidth [2]. MPP is commonly used in harsh and corrosive environments and building areas that require a hygienic environment, such as the food industry, hospitals, and white rooms for manufacturing microelectronic devices [3]. MPP is usually fabricated from metallic materials. However, the fabrication process requires advanced technology to create the hole's submillimeter size, making it difficult and more expensive to produce. In addition, the extraction of metal from its raw materials demands an extensive amount of energy and emits numerous hazardous pollutants into the environment, resulting in various types of pollution [4].

Alternatively, MPP can be fabricated entirely or partially from biobased resources and/or recycled materials known as bio-composite material. Bio-composite materials are polymer matrix composites composed of natural matrix materials such as polylactic acid (PLA), polyhydroxyalkanotes (PHA), poly-caprolactone (PCL), or synthetic matrix materials such as thermoplastic, thermosetting plastic, and one or more reinforcements such as carbon fibers, glass fibers, or natural fibers [5].

Studies have shown that the MPP sound absorber was successfully made from bio-composite materials such as kenaf fiber [4], coconut fiber [6], and oil palm empty fruit bunch fiber (OPEFB) [7] filled polylactic acid (PLA), as an alternative to the metallic materials. The result indicates that the bio-composite MPP made from coconut fiber filled PLA provides higher sound absorption coefficient (SAC) than steel MPP [6]. The MPP made of PLA-OPEFBF composite shows the maximum SAC of 0.99 for the fiber content 5 wt.%, 10 wt.%, and 20 wt%, while 0.98 for the fiber content 15 wt% [7]. Next, the MPP made of PLA-Kenaf shows the highest SAC of 0.987 for 30 wt.% fiber content [4]. The results also indicates that the resonance frequency of bio-composite MPP was also strongly influenced by the MPP parameter such as panel thickness, diameter of perforation, distance between perforation and air gap. These results indicate that MPP made from bio-composite also performs better as a sound absorber than other commercial materials.

Lignocellulosic thermoplastic composite (LTC) is a bio-composite made from agricultural waste and thermoplastic resins that are bio-degradable, recyclable, and have specific stiffness and strength [8]. The impact resistance of LTC is 50 % and 40 % stronger than that of polyethylene (PE) and polypropylene (PP), respectively. In addition, LTC possesses a high modulus, special screw and nail retention, low flame propagation, and excellent thermal characteristics [9]. LTC is produced using similar techniques to plastics or composites processes such as extrusion, injection molding, compression molding, and pultrusion [10]. Although there were many studies on LTC over the last decade, the focus was always to improve the mechanical properties and and processing method but less on the acoustical properties.

Thus, in this study, the lignocellulosic thermoplastic composite (LTC) was used to fabricate bio-composite MPP using polypropylene (PP) filled rice husk (RH) and coconut coir (CC) to characterize the acoustic performance of the bio-composite LTC. PP is among polyolefin or saturated polymers that is tough and rigid, which is used in various applications, including packaging, laboratory equipment, automotive components and many more. PP has tensile strength between 26.0 and 41.4 MPa, tensile modulus of 0.95 to 1.78 GPa, and glass transition temperature (T_g) between -23 and -10 °C, depending on its crystallinity [10]. Rice husk is a residue from rice cultivation that generates approximately 136 million tons globally. It contains high silica about 99.5 %, 43.30 % cellulose, 28.6 % hemicellulose, and 22 % lignin [11]. Rice husks are effective as a protective material since they are difficult to burn and less likely to allow moisture to grow mildew or fungi [12]. Coconut fibers are the most waste produced by coconut agriculture. At least 30 million tons of coconuts are produced worldwide every year, widely available on the tropical coast. It contains 30 % fiber and 70 % pith, with high lignin and phenolic content. Coconut fibers are exceptionally elastic, durable, and resistant to rotting due to their high lignin concentration [13].

The utilization of natural fiber as filler in composite acquired acceptance among industries due to its low density, low cost, and unique mechanical properties and enhances composite's mechanical and thermal properties [14]. Reusing agricultural wastes in construction materials not only decreases manufacturing costs but also promotes green construction and offers a feasible solution to environmental challenges [13]. Besides, it significantly contributes to the sustainable management of natural resources, decreasing reliance on nonrenewable resources and reducing the negative environmental impact [15].

This paper presents the sound absorption performance of MPP made from bio-composite polypropylene (PP) filled rice husk (PP/RH) and coconut coir (PP/CC). The effects of natural filler compositions, distance between perforation and air gap size of the bio-composite micro-perforated panel (BC-MPP) on the sound absorption coefficient were investigated.

In addition, this paper also represents the acoustic properties of BC-MPP using Ansys workbench simulation which employed CAD model and Maa model. The purpose is to generate SAC data of BC-MPPs' acoustic properties via simulation. The simulation trend and experimental data of acoustic properties of BC-MPP were compared.

2. Sample preparation

BC-MPP samples were prepared by mixing natural fiber filler in a polypropylene matrix using a heated two-rolled mill at a temperature of 175 °C, and rotor speed of 15 rpm for 10 minutes. Twelve samples were prepared with the various compositions of fiber-matrix as specified in Tables 1 and 2 for bio-composite (BC) polypropylene/ coconut coir (PP/CC) and bio-composite (BC) polypropylene/ rice husk (PP/RH), respectively. Four samples of BC-MPP PP/CC were prepared, which represent of 5 wt.% and 10 wt.% of CC at perforation distance 1.0 cm and 1.5 cm (Figs. 2(a)-(d)). Meanwhile, eight samples of BC-MPP PP/RH were prepared, which represent of 5 wt.%, 10 wt.%, 20 wt.% and 30 wt.% of RH at perforation distance 1.0 cm and 1.5 cm, respectively (Figs. 3(a)-(h)). The composition of fillers was varied to observe and compare the effect of filler loading on the sound absorption performance of both BC-MPP.

Next, the composite was pressed using hot-press to form 1 mm thin sheet and cut into circular shape with diameter of

Table 1. Specification of bio-composite micro-perforated panel (BC-MPP) made from polypropylene filled coconut coir (PP/CC).

Sample	Polypropylene (wt.%)	Coconut coir (wt.%)	Distance between perforation (cm)
A	95	5	1.0
B	95	5	1.5
C	90	10	1.0
D	90	10	1.5

Table 2. Specification of bio-composite micro-perforated panel (BC-MPP) made from polypropylene filled rice husk (PP/RH).

Sample	Polypropylene (wt.%)	Rice husk (wt.%)	Distance between perforation (cm)
a	95	5	1.0
b	95	5	1.5
c	90	10	1.0
d	90	10	1.5
e	80	20	1.0
f	80	20	1.5
g	70	30	1.0
h	70	30	1.5

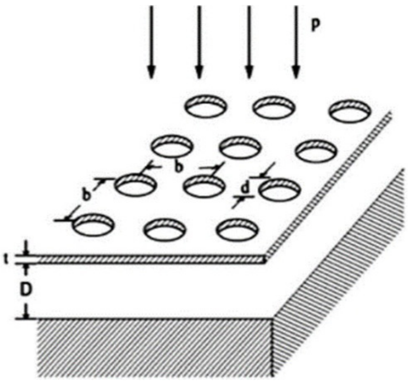
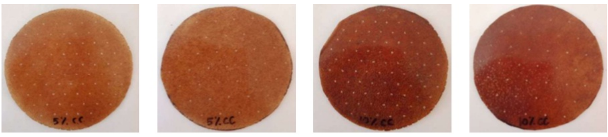
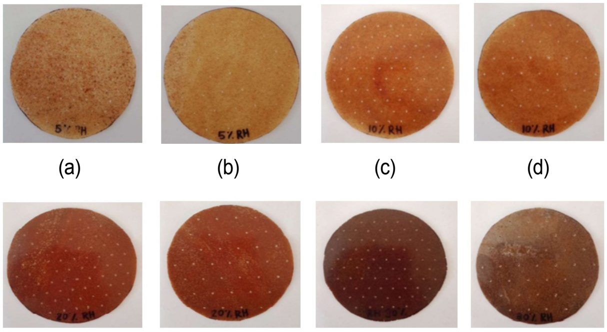


Fig. 1. Isometric view of distance between perforation holes and air gaps [17].



(a) (b) (c) (d)

Fig. 2. Sample of MPP made from bio-composite polypropylene filled coconut coir (BC-MPP PP/CC) consisting of (a) 5 wt% filler with 1.0 cm perforation distance; (b) 5 wt% filler with 1.5 cm perforation distance; (c) 10 wt% filler with 1.0 cm perforation distance; (d) 10 wt% filler with 1.5 cm perforation distance.



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 3. Sample of MPP made from bio-composite polypropylene filled rice husk (BC-MPP PP/RH) consisting of (a) 5 wt.% filler with 1.0 cm perforation distance; (b) 5 wt.% filler with 1.5 cm perforation distance; (c) 10 wt.% filler with 1.0 cm perforation distance; (d) 10 wt.% filler with 1.5 cm perforation distance; (e) 20 wt.% filler with 1.0 cm perforation distance; (f) 20 wt.% filler with 1.5 cm perforation distance; (g) 30 wt.% filler with 1.0 cm perforation distance; (h) 30 wt.% filler with 1.5 cm perforation distance.

100 mm to fit the impedance tube. Then the samples were perforated with 1 mm diameter size using a mini hand drill, with the distance between each perforation varied at 1.0 cm and 1.5 cm. Fig. 1 shows the isometric view of MPP where *t* is the thickness of MPP, *d* is the perforation diameter, *b* is the distance between perforation holes, and *D* is the air gap size of BC-MPP and rigid wall, respectively. *P* refers to the incident sound wave pressure. These parameters provide significant value to the sound absorption performance and determine the resonance frequency of BC-MPP. In this study, the effect of different distance between perforation, *b*, and air gap size, *D*, to the sound absorption coefficient of BC-MPP were investigated.

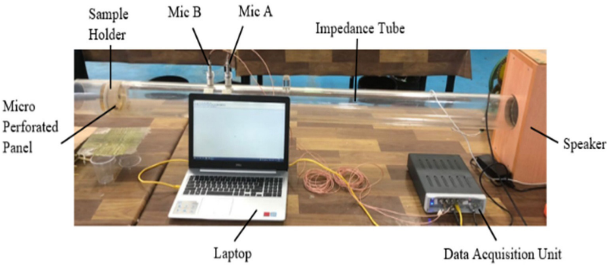


Fig. 4. Experimental setup of impedance tube for sound absorption measurement.

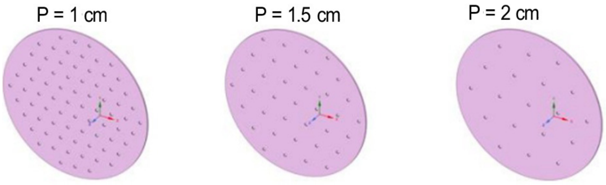


Fig. 5. Modelling of MPP (distance between perforation of 1 cm, 1.5 cm and 2 cm).

3. Sound absorption coefficient measurement

Sound absorption coefficient (SAC) was measured via the two-microphone impedance tube method according to ISO 10534-2 standard [7, 16]. The microphones were calibrated before the experiment was conducted to ensure the result's accuracy. The two microphones measure the sound pressure level of the incident sound wave and the reflected sound wave in the impedance tube used to determine the SAC of BC-MPP. The experiment was repeated using all the samples as specified in Tables 1 and 2. The experimental setup is shown in Fig. 4.

4. Acoustical simulation modeling

In addition to experimental measurement, the SAC was also obtained by simulation modeling, which employed AUTOCAD to develop the CAD model for the MPP with three various distances between the perforation holes as shown in Fig. 5. The developed CAD model was then imported into the ANSYS workbench to set up the simulation modeling. In the ANSYS workbench, the MPP was enclosed with the material properties of air. The radiation boundary and the port surface were selected. The sound source was inserted, and the rigid wall was selected at the other end of surface of the model as shown in Fig. 6. Then, the sound absorption coefficients of different geometry of the MPP and air gap were simulated.

The simulation was supported by Maa's theory, which provided the value of sound absorption material via Eq. (1) [17]

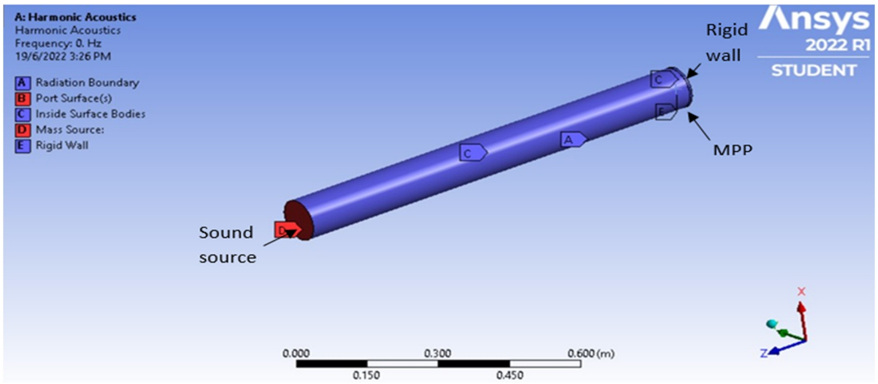


Fig. 6. Simulation modeling.

$$\alpha = \frac{4r}{(1+r)^2 + \left[\omega m\text{-}\cot\left(\frac{\omega D}{c}\right)\right]^2} \tag{1}$$

where ω is angular frequency (equal to 2πf), c is speed of sound in air, D is the air gap size. m and r are the relative acoustic mass, and the relative acoustic resistance given by Eqs. (2) and (3), respectively.

$$m = \frac{t}{\sigma c} \cdot \left[1 + \frac{1}{\sqrt{9 + \frac{k^2}{2}}} + 0.85\frac{d}{t}\right] \tag{2}$$

$$r = \frac{32\mu t}{\sigma c d^2} \cdot \left[\sqrt{1 + \frac{k^2}{32}} + \frac{\sqrt{2}}{8} k \cdot \frac{d}{t}\right]. \tag{3}$$

σ represent perforation rate, d is the perforation diameter, t is the thickness of the sample and k is the perforation constant.

5. Results and discussion

5.1 Effect of types of natural fiber fillers and filler content to the sound absorption performance of BC-MPP

Fig. 7 compares the sound absorption performance of BC-MPP PP/RH and BC-MPP PP/CC with (a) 5 wt.% filler content and (b) 10 wt.% filler content, while the air gap and distance between the perforation remains constant. The graph shows that the SAC of BC-MPP PP/RH is always higher than BC-MPP PP/CC for both 5 wt.% and 10 wt.% of filler content from frequency 1000 Hz to 1750 Hz. However, beyond that frequency, the BC-MPP PP/CC shows greater SAC than BC-MPP PP/RH, as seen in Fig. 7(b). At 5 wt.% filler content (Fig. 7(a)), the highest SAC peak was obtained at 0.75 and 0.68 from the same frequency 1700 Hz for BC-MPP PP/RH and BC-MPP PP/CC respectively. But, for the BC-MPP with 10 wt.% filler content, the highest SAC peak for both BC-MPP was obtained at different frequency, which was 0.78 at frequency 1560 Hz for BC-MPP PP/RH and 0.7 at frequency 1750 Hz for BC-MPP PP/CC. This indicates that BC-MPP PP/RH had better sound absorption at a lower frequency bandwidth than BC-MPP PP/CC. Since the absorption performance of BC-MPP PP/RH is greater than BC-MPP PP/CC, therefore BC-MPP PP/RH was selected for further investigation.

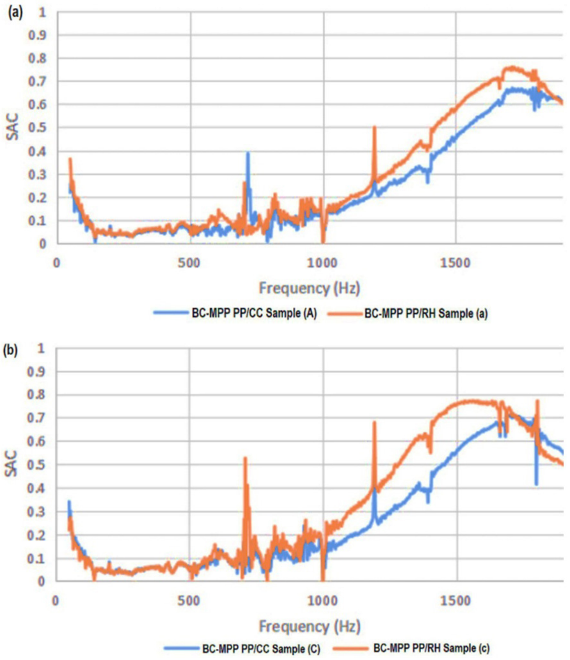
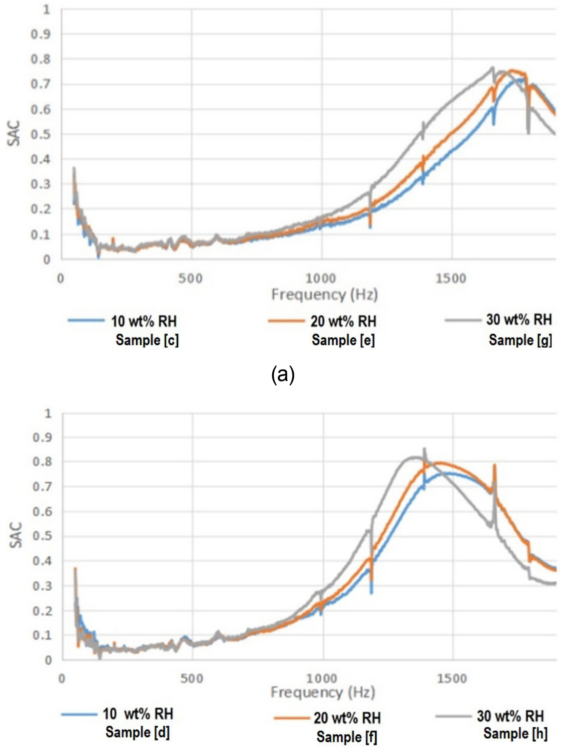


Fig. 7. The comparison of sound absorption coefficient (SAC) of BC-MPP PP/CC and BC-MPP PP/RH at (a) 5 wt.% of natural fiber filler; (b) 10 wt.% of natural fiber filler.

Fig. 8 shows the effect RH filler content in the BC-MPP PP/RH with different distance between perforation at (a) 1.0 cm and (b) 1.5 cm. The air gap size remained constant. The trend from Figs. 8 (a) and (b) observed that when the percentage of rice husk filler was increased from 10 wt.% to 30 wt.%, the peak of SAC also showed a slight improvement and shift toward the lower-frequency spectrum. This is because the increment of filler loading has increased the density of BC-MPP. According to Sekar et al. [7], the increment of density causes



(a)

(b)

Fig. 8. Effect of different filler content to SAC of BC-MPP PP/RH with perforation distance of (a) 1.0 cm; (b) 1.5 cm.

the absorption peak to shift to a lower frequency due to the increment of small pores resulting from the natural fiber filler. The same trend was also observed when the distance between perforation was increased from 1.0 cm to 1.5 cm. The highest SAC for Fig. 8(a) is 0.75 at frequency 1700 Hz, which was obtained from sample [g] and the highest SAC for Fig. 8(b) is 0.82 at frequency 1300 Hz, which was obtained from sample [h]. This finding is due to the behavior of the porous and tortuous structure of natural fiber inside the BC-MPP, which provides a superposition effect from pores and microperforated holes to absorb sound [6]. When the BC-MPP is exposed to a sound wave, the air molecules inside the hole vibrate and rub against the pore wall and surface; thus, the sound energy is dissipated and converted into heat energy. Besides, when the sample receives a sound wave, the sound energy is dispersed when the air is compressed and released regularly. This motion that happens inside the BC-MPP will cause energy dissipation. Therefore, when the percentage of natural fiber content increases, the peaks of sound absorption coefficient will be shifted to a lower frequency.

5.2 Effect of the distance between perforation and air gap size on the sound absorption performance of BC-MPP PP/RH

Figs. 9 (a) and (c) compare the effect of distance between the perforation holes of the BC-MPP PP/RH to SAC with filler content (a) 10 wt.%, (b) 20 wt.% and (c) 30 wt.%. From the graph, it is observed that when the distance between the perforation holes of the BC-MPP was increased from 1.0 cm to 1.5 cm, the peak of sound absorption coefficient was shifted toward the lower-frequency spectrums for all filler content 10 wt.%, 20 wt.%, and 30 wt.%. This trend is explained by Eq. (1), where the resonance frequency of MPP relates to the perforation ratio of MPP, P, which is attributed to the diameter of perforation and distance between perforation. From Eqs. (1) and (2), f_0 is the resonance frequency of MPP, P is the perforation ratio (in %), c is the speed of sound, 344 m/s, t is the thickness of MPP, D is the air gap (in mm), d is the diameter of perforation and b is the distance between perforation.

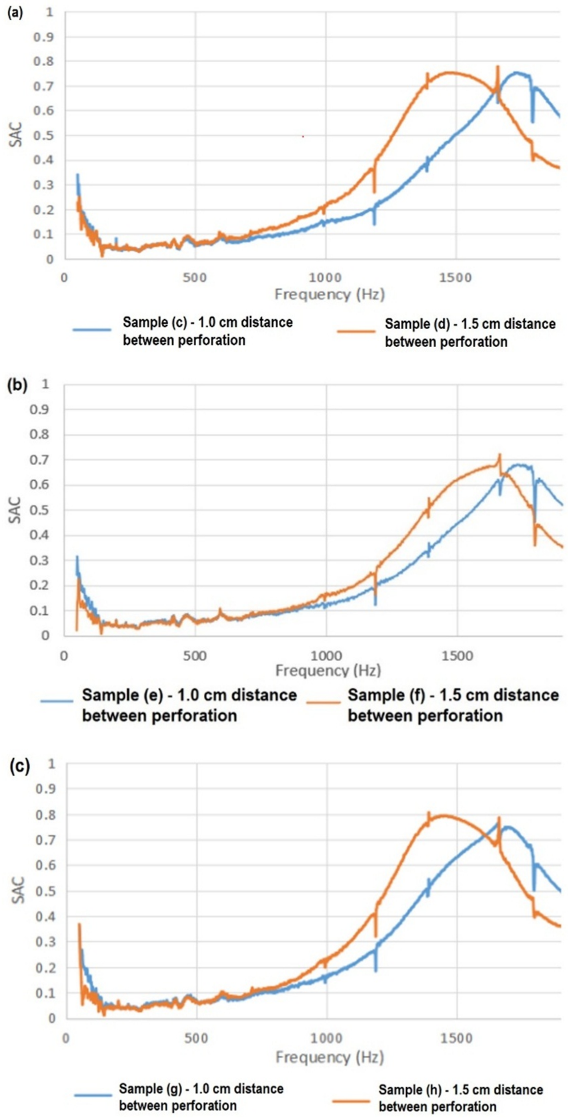


Fig. 9. Effect of distance between perforation holes of BC-MPP PP/RH with (a) 10 wt.%; (b) 20 wt.%; (c) 30 wt.% of filler content.

$$f_0=\sqrt{\frac{P}{t}\left(\frac{c}{8\pi D}\right)} \tag{4}$$

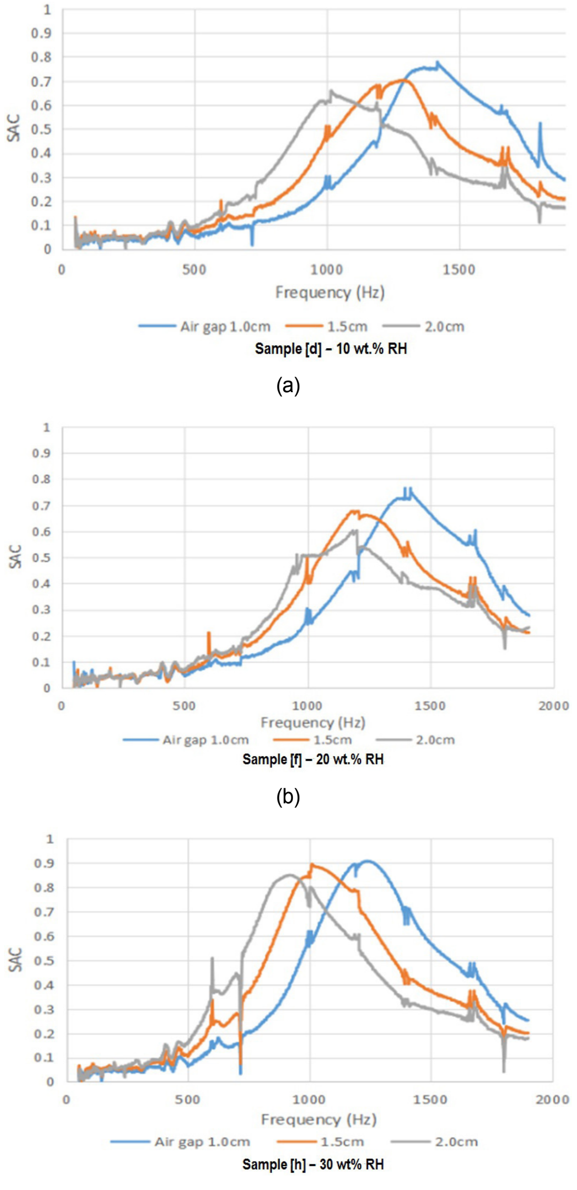


Fig. 10. Effect of the air gap size of BC-MPP PP/RH with (a) 10 wt.%; (b) 20 wt.%; (c) 30 wt.% of filler content.

$$P = \frac{\pi}{4}\left(\frac{d}{b}\right)^2 . \quad (5)$$

According to Eqs. (4) and (5) the distance between perforation is inversely proportional to perforation ratio, P, and resonance frequency of MPP, f_0. Thus, the increase of distance between perforation causing the sound absorption coefficient peak is shifted to the lower-frequency spectrums.

Figs. 10(a)-(c) show the effect of air gap size to the SAC of BC-MPP PP/RH with filler content 10 wt.%, 20 wt.% and 30 wt.%. The distance between the perforation of samples [d], [f], and [h] is 1.5 cm. The result indicates that when the air gap behind the BC-MPP PP/RH was increased, the peak of sound absorption coefficient was slightly decreased and shifted toward the lower-frequency spectrums. Sekar et al. [7] also indicate the same trend when the distance between the perforation holes is increased. This phenomenon happens due the air inside the holes working like an acoustic mass while the air layer behind the BC-MPP functions like a spring. Therefore, when the air gap is increased, it will cause the reduction of stiffness and cause the peaks of the sound absorption coefficient to shift to a lower frequency spectrum [4]. This finding also is equivalent to Eq. (1), where the air gap, D, is inversely proportional to MPP's resonance frequency, which explains the shifting of SAC peak to the lower frequency spectrum when the air gap increases.

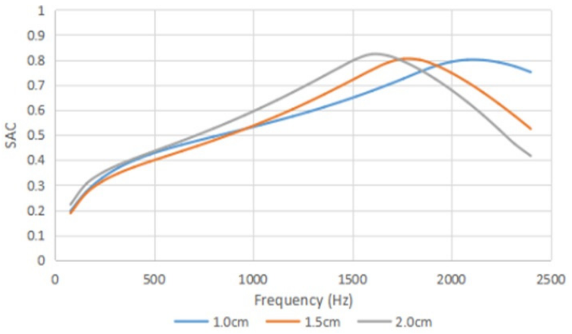


Fig. 11. Effect of distance between perforation holes in simulation modeling.

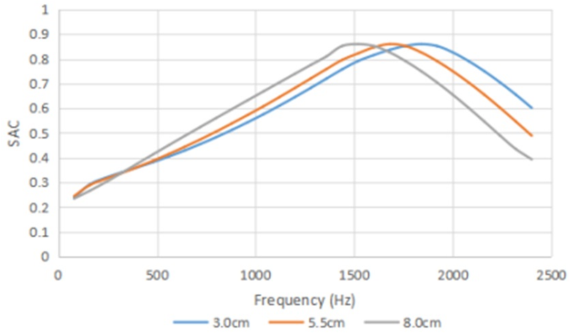


Fig. 12. Effect of air gap in simulation modeling.

5.3 Simulation results on the effect of the distance between perforation holes and air gap size

In addition to the experimental measurement of SAC, the simulation model generated from ANSYS workbench software shows a similar trend to the experimental result. Theoretical formula from Maa seems fit for SAC simulation of BC-MPP sample. Figs. 11 and 12 show that the SAC peak shifted to a lower frequency spectrum as the distance between perforation and the air gap was increased. However, the value of SAC slightly deviates from the experiment results due to the effect of natural fiber filler in BC-MPP, which influences the porosity, and density [7] of the BC-MPP is not considered in the simulation using Maa model.

6. Conclusions

By conducting this study, there is sufficient evidence to prove that the geometry of the distance between the perforation holes and the air gap behind the BC-MPP significantly influences the sound absorption coefficient (SAC) of the BC-MPP. The type of natural fiber and the fiber content percentage also affect the SAC peak and the resonance frequency of both BC-MPP. The experimental measurement shows that the SAC of BC-MPP PP/RH is higher than BC-MPP PP/CC from a frequency range of 1000 Hz to 1750 Hz. When the percentage of natural fiber content was increased, the SAC peak frequency was also shifted to the lower frequency spectrum due to the presence of the small pore by the introduction of natural filler. Furthermore, when the distance between perforation holes and the air gap behind the BC-MPP was increased, the sound absorption coefficient's peak shifted to the lower frequency spectrum. A similar trend was also shown in the simulation modeling of BC-MPP using ANSYS software. This finding demonstrates that the BC-MPP made from polypropylene filled rice husk and coconut coir has a similar performance to existing MPP made from steel, with the additional advantage of utilizing agricultural waste in the recyclable polymeric material. However, further analysis has to be considered to verify the effect of natural fiber filler on the density and porosity of the BC-MPP composite-filled rice husk and coconut core. In addition, for application in habitable spaces, such as buildings and transportation, the safety aspect, such as flammability resistance, has to be further investigated and improved. Furthermore, since the BC-MPP uses natural fiber filler, the moisture resistance properties need to be analyzed and enhanced to ensure the materials' durability and stability during application.

Acknowledgments

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Nomenclature

BC-MPP	: Bio-composite micro-perforated panel
PP/CC	: Polypropylene filled coconut coir
PP/RH	: Polypropylene filled rice husk
MPa	: Mega pascal
GPa	: Giga pascal
PLA	: Polylactic acid
PP	: Polypropylene
RH	: Rice husk
SAC	: Sound absorption coefficient
T_g	: Glass transition temperature
cm	: Centimeter
Hz	: Hertz
wt.%	: Weight percent
%	: Percent

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