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Springer

Journal of Mechanical Science and Technology 37 (11) 2023

Original Article
DOI 10.1007/s12206-023-1021-5

Keywords:
· Bio-composite micro perforated panel
· Backed structure
· Impedance tube
· Natural fiber
· Sound absorption coefficient

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Citation:
Wahab, F., Hong, T. W., Azhar, M. H. M., Abdul Rahman, N. H. H. (2023). Acoustic characteristic of bio-composite micro-perforated panel (BC-MPP) backed with natural fiber. Journal of Mechanical Science and Technology 37 (11) (2023) 5823~5829.
http://doi.org/10.1007/s12206-023-1021-5

Received September 23rd, 2022
Revised April 30th, 2023
Accepted July 15th, 2023

† Recommended by Editor Chongdu Cho

Acoustic characteristic of bio-composite micro-perforated panel (BC-MPP) backed with natural fiber

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Abstract We investigated the sound absorption properties of a bio-composite micro-perforated panel (BC-MPP) with a combination of backed-structure and several types of natural fibers such as loofah, kapok, and coconut coir. The sound absorption coefficient (SAC) of different combinations of natural fibers samples was obtained by using a two-microphone impedance tube. In addition, three models, including Delany-Bazley model, Maa theory, and electro-acoustical analogy, were employed to estimate the SAC value of natural fiber, BC-MPP, and BC-MPP with a backed structure, respectively. The experimental results demonstrate that the SAC value was increased to almost 0.99 as compared to BC-MPP alone when natural fiber was introduced at the back of BC-MPP either by insertion in the hole of backed structure or attached directly at the back of BC-MPP. The SAC peak also shifted to a lower frequency bandwidth with the highest peak obtained at 930 Hz, 800 Hz and 640 Hz for MPP with coconut husk, BC-MPP with kapok and BC-MPP with loofah, respectively. The absorption frequency was also observed slightly wider than BC-MPP without natural fiber. In comparison of BC-MPP with loofah and BC-MPP with others natural fibers, the insertion of kapok and coconut coir in the hole of backed structure provides a wider effective sound absorption coefficient. The comparison of experimental result with the theoretical calculation shows that the SAC obtained from experiment provides higher SAC value over the theoretical model for both BC-MPP and BC-MPP backed structure.

1. Introduction

Noise pollution has been recognized as one of the primary pollutants, alongside air pollution, water pollution, and solid waste [1]. Due to increased urbanization and transportation, particularly increased road traffic, it ranks second among environmental pollutants regarding its effects on public health [2]. However, despite the acknowledged adverse effects on both human health and the natural environment, this issue has historically been overlooked.

Implementing sound absorption materials is a practical approach for achieving noise mitigation. These materials are classified into two types: porous and resonator-type sound absorber. This can be implemented at the point of source, along the transmission path, or at the receiver. The prioritization of environmentally friendly and sustainable materials is attributed to the fact that the current sound-absorbing materials are predominantly derived from materials which are not environmentally friendly or recyclable [3]. Moreover, the utilization of synthetic fibers, such as glass fiber, can have a notable effect on human health, particularly during assembly and dismantling [4].

In recent years, there has been an evident surge in the attention devoted to the acoustic characteristics and effectiveness of natural fibers as sound absorbers [5-9]. Natural fibers originating from plants and animals are abundant in the environment and generally inexpensive. However, regardless of the availability of a broad frequency spectrum of sound absorption, the performance of natural fibers requires significant improvement in the lower frequency range, similar to other porous sound-absorbing materials that need a thicker layer of crimped fibers.

A viable alternative to porous sound-absorbing materials is the micro-perforated panel (MPP). MPP is currently acknowledged as an up-and-coming option for next-generation sound-absorbing materials. The concept of an MPP was initially introduced, and its theoretical underpinnings were investigated, by Maa [10-13] as is commonly acknowledged. Typically, MPP comprises a slender panel that measures less than 1 mm in thickness and features submillimeter perforations at a perforation ratio of under 1 %. Implementing MPP typically involves utilizing it as an internal surface with a rigid rear wall and an enclosed air space. This configuration enables the creation of Helmholtz resonators through the presence of perforations and the air cavity. However, due to the resonance effect, the performance is limited in its ability to absorb sound within a narrow frequency range. Alternatively, the absorption frequency range can be expanded by introducing a porous layer in the air cavity which provide supplementary damping if the resistance is appropriately adjusted [14].

This paper reports the findings of a study on the efficacy of natural fiber insertion into the air cavity of MPP as an alternative to overcome the acoustic limitations of both MPP and natural fiber. The MPP was fabricated from rice husk filled polypropylene composite, while the fibers were obtained from the locally available plant including loofah, kapok, and coconut coir to support the environmentally friendly sound-absorbing materials. In addition, the honeycomb-backed structure was attached to the MPP to retain and support the fibers in the air cavity behind MPP.

2. Methodology

2.1 Preparation of bio-composite micro-perforated panel (BC-MPP) with backed structure

The BC-MPP used was made from bio-composite polypropylene filled 5 wt.% of rice husks. The MPP samples have 1 mm thickness and 100 mm diameter with perforation dimension as illustrated in Fig. 1. The BC-MPP was then attached with two types of natural fibers--long fiber (kapok and coconut coir) and rigid form fiber (loofah)--at the back of BC-MPP as illustrated in Fig. 2. Kapok and coconut coir were inserted in the hole of honeycomb structure while loofah was attached directly at the back of BC-MPP as shown in Fig. 3. Five samples as specified in Table 1 were prepared to compare the effect of natural fibers attached to the performance of MPP. Three samples were prepared to measure the performance of BC-MPP backed with different types of natural fibers (sample Nos. 3-5) while the other two samples (samples No. 1 and No. 2) were prepared for comparison.

2.2 Sound absorption measurement

The sound absorption coefficient (SAC) of BC-MPP backed with natural fiber was obtained through experiment and theoretical calculation. The SAC was determined via experiment in accordance with ISO 10534-1:1998 [6], at normal incidence using a two-microphone impedance tube. The experimental setup is shown in Fig. 4. The impedance tube's internal diameter, 100 mm, is acceptable for measuring frequencies ranging from 20 Hz to 2000 Hz. Prior to conducting the measurement, the microphones underwent calibration using a sound level calibrator (center 326) as depicted in Fig. 5, to ensure measurement accuracy.

As shown in Fig. 6, the present methodology involves the utilization of a loudspeaker positioned at a specific end of the tube to produce a planar sound wave. This wave is subsequently reflected by the specimen located at the opposite end

Table 1. Different types of sample structure of BC-MPP backed honeycomb structure and natural fibers.

Sample no.	Sample structure
1	BC-MPP
2	BC-MPP + honeycomb structure
3	BC-MPP + honeycomb structure + kapok
4	BC-MPP + honeycomb structure + coconut coir
5	BC-MPP + loofah

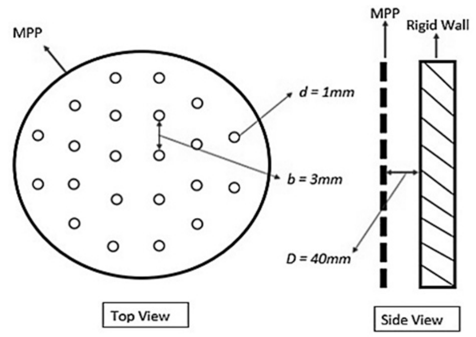

Fig. 1. Schematic diagram of BC-MPP absorber.

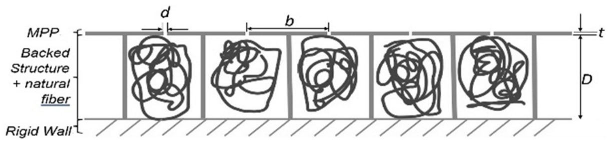

Fig. 2. Schematic diagram of BC-MPP with honeycomb-backed structure.

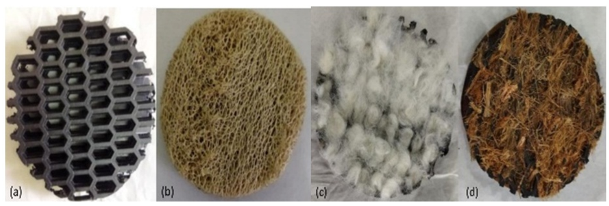

Fig. 3. The combination of BC-MPP backed with (a) honeycomb structure; (b) loofah; (c) honeycomb structure filled kapok; (d) honeycomb structure filled coconut coir.

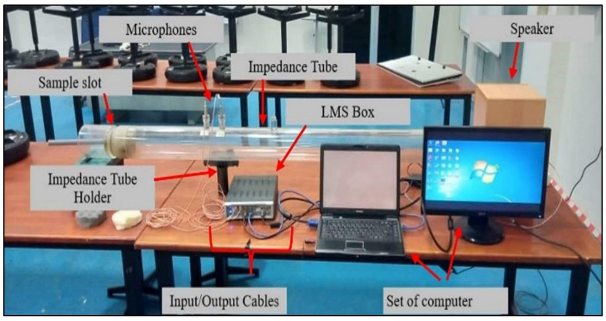

Fig. 4. Experimental setup of impedance tube for sound absorption measurement.

Fig. 5. Sound level calibrator for microphone calibration.

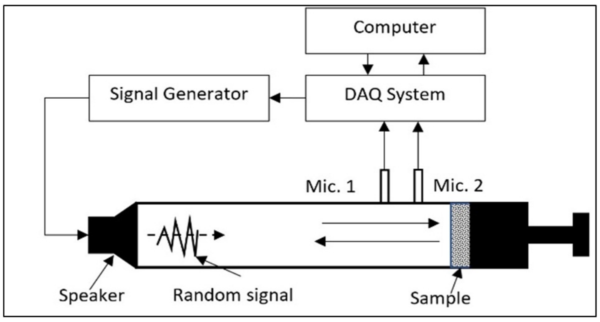

Fig. 6. Schematic diagram of impedance tube for sound absorption measurement.

of the tube. The attenuation of sound energy is measured by a pair of microphones positioned at different points along the interior surface of the tube. The computer's installed analysis software was linked to the LMS SCADAS data acquisition unit (DAQ) for the purpose of analyzing the sound absorption coefficient. To ensure the accuracy of the test outcomes, the sound absorption coefficient for every specimen was evaluated via three iterations of testing.

In addition, the SAC value was also determined using theoretical calculation based on the empirical model, Delany-Bazley model [6, 15] and Maa's theory [13, 16] for natural fiber and BC-MPP, respectively. Meanwhile, for the combination of BC-MPP with backed structure without natural fiber, Helmholtz resonator theory, which includes MPP theory and electrical-acoustical analogy, was employed in measuring the SAC [17]. The results were compared with the experimental result.

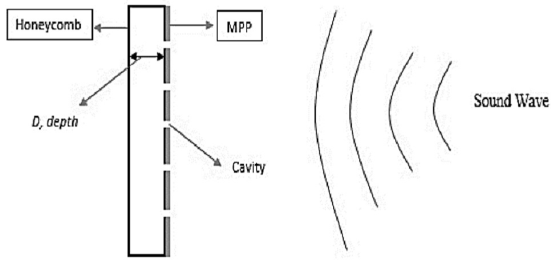

Fig. 7. Helmholtz resonator concept.

2.2.1 Delany-Bazley model

The Delany-Bazley model is commonly used for evaluating acoustic properties of an isotropic and homogeneous porous layer. The determination of the sound absorption coefficient (SAC) relies on several crucial parameters: the acoustic characteristic impedance (Z_c), propagation constant (k), and surface acoustic impedance (Z_s). These parameters can be ascertained through the utilization of Eqs. (1)-(3) [18].

$$Z_c = \rho_0 c_0 \left[1 + 0.057 b^{-0.754} - i\left(0.087 b^{-0.732}\right)\right] \quad (1)$$

$$k = \frac{2\pi f}{c_0}\left[0.189 b^{-0.595} + i(1 + 0.0978 b^{-0.7}\right] \quad (2)$$

$$Z_s = Z_c \coth(k.d) \quad (3)$$

where ρ_o is the air density, c_o is sound speed in the air, f is sound wave frequency, d is porous layer thickness, and $b = \rho_o f/\sigma$ is a dimensionless parameter with $0.01 < b < 1$. This particular model necessitates a sole parameter, which is flow resistivity, denoted as σ, within the interval of $1000 < \sigma < 5000$ N.sm^{-4} and porosity close to 1 [18]. Then the SAC is determined using Eq. (4) [19].

$$\propto = 1 - \left|\frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}\right|^2 . \quad (4)$$

2.2.2 Helmholtz resonator

A Helmholtz resonator is a resonant-type sound absorber composed based on the principle of internal resonance effect. The structure comprises a cavity with walls that exhibit rigidity and a neck that remains open. The resonant-type sound absorber operates on a mechanism like a mass-spring-damper system. In this system, the mass pertains to the air in motion within and surrounding the openings, while the spring relates to the enclosed air within the cavity. When the sound wave propagates and hits the Helmholtz resonator structure, the enclosed air resonates at a single frequency which depends on the volume of the cavity and the geometry of its opening. The illustration in Fig. 7 shows the concept of Helmholtz resonator, such as honeycomb-backed structure. The resonance frequency, F_r, determined by Eq. (5), indicates the maximum frequency absorption which can be tuned by altering the vibrating mass and the stiffness of the air spring of the Helmholtz resonator.

$$F_r = \frac{c_0}{2\pi}\sqrt{\frac{\pi a^2}{(l_0+1.7_a)V}} . \quad (5)$$

V refers to volume of the cavity, l_0 is the length of the neck, c_0 speed of sound of the air and *a* is the cross-sectional area of the opening. The acoustic impedance characteristic of Helmholtz resonator is determined by Eqs. (6)-(11) [17].

$$Z_{HR} = R_a + j\omega M_a - \frac{j}{\omega c_a} \quad (6)$$

$$R_a = \rho c\left\{16kx^2\left[1+\frac{1}{8x(1+4x^2)}\right]\frac{l}{s}+\frac{k^2}{2\pi}\right\} \quad (7)$$

$$M_a = \rho\left\{\left[\frac{4}{3}-\frac{10}{3(10+x)}\right]\frac{l}{s}\right\} \quad (8)$$

$$C_a = \frac{v}{\rho c^2} \quad (9)$$

$$S = \frac{\pi d_h^2}{4} \quad (10)$$

$$x = \sqrt{\frac{2\eta}{\rho\omega d_h^2}} \quad (11)$$

where R_a and M_a are the acoustic resistance and reactance of the Helmholtz resonator, C_a is the acoustic compliance of Helmholtz, l is the hole distance (neck length) of Helmholtz resonator, *v* is the volume of Helmholtz resonator hollow (cavity), s is the cross-sectional area of the neck, *d* is the diameter of the hole (neck), and $K = \omega/c$ is the wave number. The absorption coefficient is given by the relation,

$$\alpha = \frac{4R_e(Z)}{[1+R_e(Z)]^2+[l_m(Z)]} . \quad (12)$$

2.2.3 Theory of micro-perforated panel (MPP)

Maa's formula is a simple mathematical formula to determine the acoustic performance of MPP. It can be measured by several MPP parameters, such as perforation diameter (*d*), thickness of panel (*t*), distance between perforations (*b*), and the air gap depth (*D*) [20] as shown in Fig. 1. The normalized specific acoustic impedance of MPP structure, Z_{total}, is given by Eq. (13). It consists of the acoustic impedance characteristic of MPP, Z_{MPP}, which is determined by Eqs. (14) and (15) and the acoustic impedance of the air gap behind MPP, Z_D, which is determined by Eq. (16):

$$Z_{MPP\,total} = Z_{MPP} + Z_D \quad (13)$$

$$Z_{MPP} = \frac{8\mu t}{\sigma\rho c r^2}\left(\sqrt{1+\frac{x^2}{32}}+\frac{\sqrt{2}}{16}x\frac{r}{t}\right)+j\omega\left(1+\frac{1}{\sqrt{9+\frac{x^2}{2}}}+1.7\frac{r}{t}\right) \quad (14)$$

$$x = r\sqrt{\frac{\omega\rho}{\mu}};1<x<10 \quad (15)$$

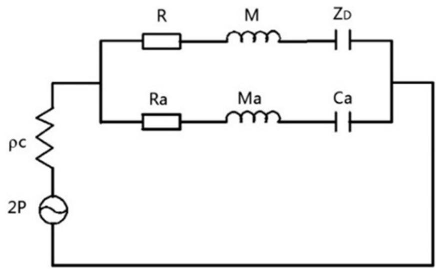

Fig. 8. The equivalent circuit of MPP backed honeycomb structure.

$$Z_D = -jcot\left(\frac{\omega D}{c}\right) . \quad (16)$$

μ is the coefficient of fluid viscosity, t is thickness, σ is perforation ratio that can be calculated by $\sigma = \pi(r/b)^2$, $r = d/2$ is radius of perforation, ρ and c are the density and the speed of sound in the fluid medium, ω is angular frequency of the incident sound wave that can be calculated by $\omega = 2\pi f$ and *D*, is air gap distance normalized by *ρc*. Then, the SAC of MPP structure of normal incidence is determined by Eq. (17):

$$\propto = 1-\left|\frac{Z_{MPP\,total}-1}{Z_{MPP\,total}+1}\right|^2 . \quad (17)$$

2.2.4 Electro-acoustical analogy

The acoustic impedance of MPP backed honeycomb structure system can be derived by impedance-type of electro-acoustic analogy as shown in Fig. 8 [17]. According to this analogy, the normalized specific acoustic impedance of this structure at length *D* from the rigid wall is characterized by acoustic impedance of Helmholtz resonator and the acoustic impedance of MPP as specified by Eq. (18) [17].

$$Z = \frac{Z_{MPP\,total}Z_{HR}}{Z_{MPP\,total}+Z_{HR}} . \quad (18)$$

where Z_{HR} is according by Eqs. (6)-(11) and $Z_{MPP\,total}$, is according to Eqs. (13)-(16).

3. Results

3.1 Sound absorption characteristic of bio-composite microperforated panel

The sound absorption characteristic of BC-MPP (sample 1) was obtained to observe the improvement on SAC when the BC-MPP was attached to the backed structure filled natural fiber. Both theoretical measurement and the experiment result of SAC were considered. Fig. 9 shows the comparison of SAC of BC-MPP between experimental result and theoretical measurement from Maa theory. Based on the experimental results, the BC-MPP absorbs almost 90 % of sound energy at frequency 1350 Hz, while the theoretical result shows a slight lower peak of SAC value with 83 % of sound energy absorb at frequency 1420 Hz. This is due to the viscosity coefficient of air maybe being inconsistent for the calculation SAC and experimental test. The viscosity of air depends on the surrounding temperature. The average room temperature is assumed to be 23 °C used in the theoretical modeling calculation. The correlation coefficient between the theoretical model and experimental measurement data is obtained at 0.91, and thus the SAC measurement using Maa theory showed good agreement with the experiment results and it is considered reliable and validated.

3.2 Sound absorption characteristic of bio-composite micro-perforated panel with honeycomb backed structure

For BC-MPP mounted with honeycomb structure, the SAC is determined by electro-acoustical analogy (Eq. (18)) and compared with the experimental value (sample 2) as shown in Fig. 10. The result shows that the peak of SAC value of BC-MPP backed honeycomb structure provided by theoretical calculation is lower than the experimental result that is 0.70 at frequency 1680 Hz and 0.80 at frequency 1925 Hz, respectively. The peak of absorption also shifted to a lower frequency when using the theoretical calculation. The comparison with Fig. 9 indicates that the SAC and the effective absorption of BC-MPP have decreased and shifted to the higher frequency with the attachment of honeycomb backed structure. The correlation coefficient value between the theoretical model and experimental data is 0.88.

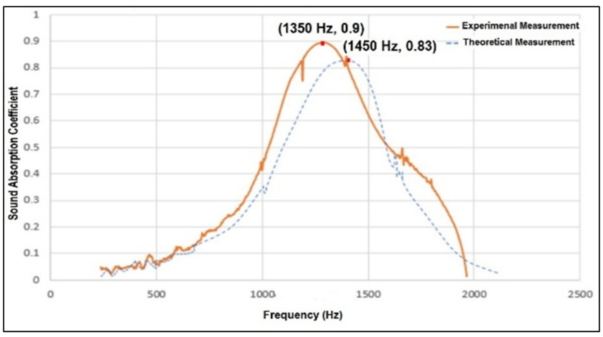

Fig. 9. Comparison of sound absorption coefficient of BC-MPP through experiment and Maa theory.

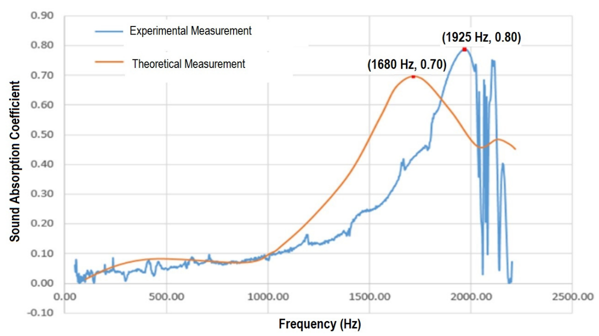

Fig. 10. SAC for BC-MPP backed honeycomb structure by theoretical measurement and experiment.

3.3 The sound absorption coefficient of natural fiber using Delany-Bazley model.

SAC of natural fibers used in this study was calculated according to Delany-Bazley model. Fig. 11 shows the SAC of kapok, loofah and coconut coir in the range of frequency 0-1000 Hz. The highest SAC value of kapok, loofah and coconut coir was obtained by 0.78 at frequency 787 Hz, 0.71 at frequency 700 Hz and 0.65 at frequency 600 Hz, respectively. Fig. 11 also shows that kapok fiber has the highest SAC value throughout the frequency followed by loofah and coconut coir. This is due to the porosity of kapok fiber being higher than coconut fiber and loofah, which relate to the bulk density and diameter size of kapok fiber. According to Ref. [21], kapok fiber having lower bulk density than the others' natural fibers contributes higher SAC performance per unit mass (normalized SAC). The smaller diameter of fiber increases the interior pores and contact areas with air molecules, resulting in more excellent sound energy dissipation [22].

3.4 Sound absorption characteristic of bio-composite micro-perforated panel with honeycomb back structure filled with natural fiber

Fig. 12 shows the SAC performance of BC-MPP with backed structure of honeycomb filled with kapok (sample 3) and coconut coir (sample 4), and BC-MPP with loofah (sample 5) in the range of frequency 0-2000 Hz. From the graph, the attachment of natural fiber at the back of BC-MPP improved the SAC up to 0.99. The SAC value achieves 0.99 at frequency 640 Hz, 800 Hz and 930 Hz, respectively, for sample BC-MPP with loofah, sample BC-MPP with honeycomb backed structure filled with kapok, and sample BC-MPP with honeycomb backed structure filled coconut coir. As compared to Fig. 10, the insertion of natural fiber inside the honeycomb hole shifted the peak of sound absorption frequency to the lower frequency. It is also

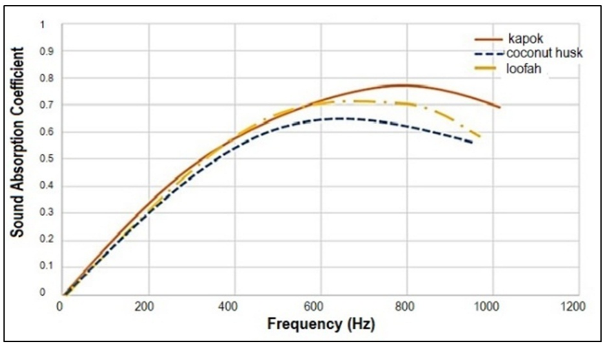

Fig. 11. Sound absorption coefficient of various natural fibers used in this experiment according to delany-bazley model

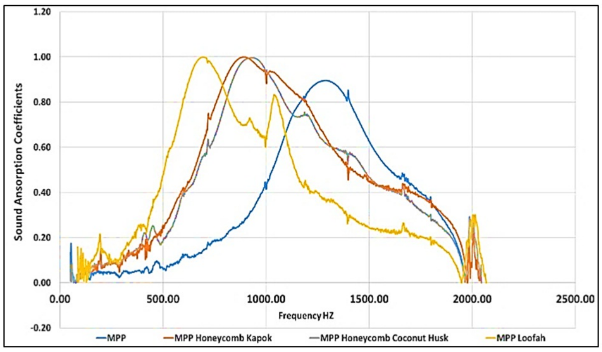

Fig. 12. Sound absorption coefficient of BC-MPP backed honeycomb structure filled natural fiber.

shown that the attachment of natural fiber either attached directly or filled inside the hole of honeycomb structure had widened the effective sound absorption frequency. BC-MPP with honeycomb backed structure filled kapok provided the widest range of effective absorption frequency from 450 Hz to 1750 Hz.

4. Conclusions

A BC-MPP backed honeycomb structure with natural fibers was successfully fabricated and used for SAC analysis. The findings from the experiment indicate that the introduction of natural fiber at the back of BC-MPP, either through insertion in the hole of the backed structure (BC-MPP with kapok and coconut husk) or direct attachment (BC-MPP with Loofah), resulted in a significant increase in the SAC value to nearly 0.99 as compared to BC-MPP alone. The highest peak values were observed at 930 Hz, 800 Hz, and 640 Hz for each respective BC-MPP with coconut husk, BC-MPP with kapok, and BC-MPP with loofah. The SAC peak was also seen to have shifted towards a lower frequency bandwidth and slightly broader in the presence of natural fiber compared to BC-MPP without it. The comparison of BC-MPP inserted with kapok and coconut husk into the backed structure's cavity also leads to a wider effective region of SAC than the BC-MPP attached with loofah. The experimental results also yield a higher SAC value compared to the theoretical model for both BC-MPP and BC-MPP backed structure.

Acknowledgments

This work is supported by Final Year Research Project under the Faculty of Mechanical Engineering and Technology and Faculty of Civil Engineering and Technology, Universiti Malaysia Perlis. We thank Universiti Malaysia Perlis for providing the necessary laboratory facilities for this work.

Nomenclature

BC-MPP : Bio-composite micro-perforated panel
Hz : Hertz
SAC : Sound absorption coefficient
% : Percent
$N.sm^{-4}$: Newton second per square meter per square meter

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