Evaluating the Thermo-acoustic Performance of Composite Panels Made of Oil Palm Fibers with Latex

Lamyaa A. JAWAD
College of Health and Medical Technology, MTU, Iraq, lamyaeng@gmail.com

Tawfeeq W. MOHAMMED
College of Engineering, Mustansiriyah U, Iraq, tawfeeqwasmi@uomustansiriyah.edu.iq

Abstract: - In this study, composite panels made of natural oil palm fibers (OPFs) mixed with latex are manufactured and tested to evaluate the thermo-acoustic performance of these panels. The involving of OPFs in the manufacturing would be a contribution to green technology and optimal usage due the accumulation of deposits thus non-useful ways of removal wastes by burning. The study has included theoretical and experimental investigation to determine the acoustic absorption coefficient (AAC) of composites made of OPFs with latex. Allard approach is used for calculating the values of AAC theoretically in a range of frequencies between 100 Hz to 5000 Hz. In the experimental works, different composite panels of 20, 30, 40, and 50 mm thickness have manufactured. The measurement of AAC has done using an impedance tube instrument. The results show that the value of AAC has increased by increasing the thickness and bulk density for a certain range. Peak AAC values are pointed at high frequencies (more than 1600 Hz) and they have reached up to 0.8. Where, an improving in the value of the AAC between 10-20% could be obtained by increasing the thickness by 10 mm. However, the experimental values show a slight deviation in contrast to theoretical values by ±20% as a consequent to experimental regards as well as some approximated assumptions.

Keywords: - thermo-acoustic performance, sound absorption, natural fiber, composite, insulation

1. INTRODUCTION

Natural porous materials are widely used as sound absorption materials in noise control engineering. These types of materials consist of various natural fibers such as: oil palm fibers, date palm fibers, coconut fibers, sisal fibers, saw-dust and even hemp [1- 4]. These fibrous materials have many eco-friendly advantages in compare to synthetic materials such as glass fiber, rock wool and polymeric materials [5-7].

Acoustical design focuses upon the requirements to satisfy a comfortable environment free of noise, where excess vibration and fatigue may be induced from acoustical waves that may damage sensitive mechanical systems [8]. Approaches of sound controlling may be classified as active, such as sound transducers, or passive such as acoustic panels. The acoustic panels have the ability in absorbing the sound by increasing the thicknesses or the densities for a certain range. When sound waves travel through the porous panel, the friction has increasing among the pores or fibers, as well as the quick vibrations dissipate the acoustical energy, so the kinetic energy has converted into heat [9-11].

The indication of absorbed acoustical energy by porous materials is represented by the value of acoustical absorption coefficient (AAC). This parameter involves the combined effect of changing both temperature and pressure of the medium as a result of acoustical energy, thus it is well conjugated to the definition of thermo-acoustic effect.

Oil palm is a plant that grows up in tropical and subtropical regions. Oil palm fibers (OPFs), shown in Figure 1, are strings extracted from the empty fruit bunches, and can be used as a reinforcement for many composites. The fibrous characteristics of OPFs encourage the using for many applications of sound insulation and it would be a contribution to green technology [12].

Figure 1. Oil palm fibers

Most sound absorption materials are synthetic materials because of their ease of manufacturing though they have certain risks for lungs and eyes. Hence, researchers have looked into natural materials and agricultural waste to find alternatives. These types of materials have many benefits as they are cheaper, non-abrasive and renewable. Also, organic substances impose less health issues during processing.

Recently, several researchers have investigated the thermo-acoustical performance of natural fibers. The composite of fibers mixed with tea leaf layers and woven textile cloth layers were investigated for sound absorption purpose by Ersoy and Küçük (2009) [13]. Whereas, results of adding 1 cm thick layer of tea leaf is providing sound absorber of the equivalent six layers of woven-textile cloth. Ayub, et al. (2009) [14] investigated the behavior of sound absorption of coir natural fiber theoretically by using Delany-Bazley approach [15]. The study shows by increasing the layers of coir fiber, the sound absorption increased in the low-frequency range and be more helpful in the application. In addition, as the density of the coir fiber increases, the acoustic absorption will increase. Analysis of the compression effects of porous materials made of coir fibers for car acoustical application is presented by Nor, et al. (2010) [16].

Moreover, Nor, et al. (2010) [17] studied the effectiveness of different factors by using Allard approach [18] for acoustical absorption by the coir fibers. Where, the factors that have more effectiveness in the absorbing behavior are the diameter and the thickness. Yang, et al. (2011) [19] examined the bundled natural fibers that consist of cashmere, goose down, and kapok for absorption coefficients. The internal structures of these natural materials affected the sound absorption measuring such as mass, air gap, and acoustic frequency. The results have shown a good absorption achievement at a low and medium frequencies. While, at higher frequencies the performance deteriorates. Deveikytė, et al. (2012) [20] examined the activity of various combinations of reeds and straw across a band of frequencies. The comparison depended on the thickness, while the density was similar for all samples at a frequency range 100-3000 Hz. The results show the higher the thickness the better the acoustic performance. Khair, et al. (2014) [21] utilized natural bamboo fibers for acoustical absorption application. The result indicated that at very high frequencies (above 3000 Hz), the 2 cm sample was an optimal choice. To improve the absorption coefficient at low frequencies, a procedure can be carried out in the back layer of the sample by increasing the air gaps. Lamyaa (2015) [22] indicated the acoustical performance of innovative natural fibers of date palm fiber by using the Johnson–Allard approach. The increasing of the thickness will increase the acoustical performance. Bulk density has similar effect. Furthermore, the validation of AAC values has done by experimental measurements based on the using an impedance tube. Genc and Koruk (2016) [23] studied the sound absorption, elastic characterizes, and damping of Luffa fibers in the vibro-acoustic behaviors through experimental and theoretical models. The Luffa fibers composite samples have 9 mm thickness, while the ratio of volume fraction of the sample made of Luffa fibers to the epoxy was 0.4. The coefficient of absorption increases gradually with the increasing in the frequency as the outcomes appear at high frequencies. Thilagavathi, et al. (2018) [24] used four composite mats of Luffa fibers with the net of kapok and cotton layer and measured the noise reduction coefficient (NRC). These composites were developed by thermal bonding. The results show that by increasing composite mats thicknesses an increase in the sound absorption is obtained due to the addition of kapok/cotton net. The frequency ranged from 250-2000 Hz, and the NRC value was 0.39 in average.

However, these studies involved the natural fibers to investigate the acoustic performance directly without focusing on the combined effect of thermal-acoustic parameters resultant from the thermo-physical changes in the porous media due to sound energy, which is introduced by the current study. Where, the study has included theoretical analysis combined between the acoustic absorption and corresponding thermal effects hence many thermo-physical properties have been involved. Furthermore, the evaluation of sound absorption of OPFs mixed with latex for different thicknesses, densities and over a band of frequencies has been found depending on the values of AAC that determined theoretically, as well as experimentally for the validation purposes.

2. THEORETICAL ANALYSIS

The study aims to evaluate thermo-acoustical performance of composite panels made of natural oil palm fibers (OPFs) mixed with latex. Acoustic absorption coefficient is the indication parameter, where it is calculated theoretical by an analytical approach and also determined experimentally by measurements. Theoretical values of AAC can be determined by many analytical approaches such as: Delany [15], Allard [18] and Biot [25] which depend on the physical characteristics of fibrous material within a rigid frame modified for acoustic performance. The Allard approach is commonly used by sound engineers and manufacturers due to accuracy and easiness of predicting the acoustic performance of the material by calculating AAC values. The advantage of this approach lies in its ease, where the relations depend on thermo-physical properties of the fibers and frequency analysis in order to calculate the impedance and constant propagation. It can be applied widely for porous materials with ($f\rho_o/\sigma$) ratio ranges between (0.01 – 1) [26-29].

The acoustic absorption coefficient (AAC) is commonly denoted by the symbol (α) and could be calculated by [30]:

$$\alpha = \frac{4\Gamma_1 / \rho_0 C_0}{\left(\Gamma_1 / ((\rho_0 C_0)+1)\right)^2 + \left(\Gamma_2 / \rho_0 C_0\right)^2} \quad (1)$$

where;

Γ1: Real component of surface impedance factor.

Γ2: Imaginary component of surface impedance factor.

C_o: Speed of sound.

ρ_o: Air density.

The speed of sound (C_o) is a function of air temperature and it is given by:

$$C_o = \gamma\, R_g\, T \quad (2)$$

where;

γ: Specific heat ratio.

R_g: gas constant.

T: Air temperature.

The following acoustical parameters are used to find the term (Γ1), as [15]:

$$Z_f = \rho_0 C_0 \left[\left\{1 + C_1\left(\frac{f\rho_0}{\sigma}\right)^{C_2} - i\left[C_3\left(\frac{f\rho_0}{\sigma}\right)^{C_4}\right]\right\}\right] \quad (3)$$

$$\gamma_f = K_0\left\{C_5\left(\frac{f\rho_0}{\sigma}\right)^{C_6} + i\left[1 + C_7\left(\frac{f\rho_0}{\sigma}\right)^{C_8}\right]\right\} \quad (4)$$

$$\Gamma_1 = Z_f\ \coth\left(\gamma_f t_f\right) \quad (5)$$

where;

f: frequency.

σ: Flow resistivity.

K_o: Wave number.

t_f: Thickness of the fibrous panel.

The flow resistivity (σ) is given by:

$$\sigma = 0.490\, \rho_{bulk}^{1.61} / d_f \quad (6)$$

where;

ρ_{bulk}: Bulk density of the panel.

d_f: Diameter of fiber.

The wave number (K_o) could be found by:

$$K_0 = 2\pi f / C_0 \quad (7)$$

The coefficients (C_1-C_8) are given in Table 1.

Table 1. Coefficients used in theoretical approach [15]

C_1=0.0570	C_2=-0.745	C_3=0.0870	C_4=-0.732
C_5=0.1890	C_6=-0.595	C_7=0.0978	C_8=-0.700

In order to find the term (Γ2), some parameters should be founded. Firstly, the modulus (K_f) is calculated by [18]:

$$K_f(\omega) = \frac{\gamma P_0}{\gamma - (\gamma - 1)\left[1 + \frac{8\eta}{j\Lambda'^2\, \Pr^2\, \omega\rho_0}\left(1 + j\rho_0 \frac{\omega \Pr^2 \Lambda'^2}{16\eta}\right)^{\frac{1}{2}}\right]^{-1}} \quad (8)$$

where;

P_o: Atmospheric pressure.

Pr: Prandtle number of air.

η: Air viscosity.

ʌ': Thermal characteristic length.

ω:angular frequency.

The thermal characteristics length (ʌ') is given by:

$$\Lambda' = 1 / (\pi\, d_f\, L) \quad (9)$$

where;

L: Length of fiber.

The stress-strain relationships due to the energy distortion have been developed by Allard [18] and Biot [25] using the coefficients (P, Q and R), as following;

$$P = \frac{4}{3}N + K_b + \frac{(1-\varphi)}{\varphi}K_f \quad (10)$$

$$Q = K_f(1-\varphi) \quad (11)$$

$$R = \varphi K_f \quad (12)$$

where;

N: Shear modulus.

K_b: Bulk modulus.

φ: Substance porosity.

The values of shear modulus (N) and Poisson's ratio (ν) are estimated as 870 MPa and 0.1, respectively [27-29]. The bulk modulus (K_b) is given by:

$$K_b = \frac{2N(\nu+1)}{3(1-2\nu)} \quad (13)$$

where;

ν: Poisson's ratio .

Now, the viscous influence coefficient G(ω) is presented to connect some coupling parameters between the framed material and the air, as following [28]:

$$G(\omega) = \left(1 + \frac{8j\alpha_\infty^2 \eta \rho_0 f\pi}{\sigma^2 \Lambda^2 \varphi^2}\right)^{\frac{1}{2}} \quad (14)$$

where;

α_∞: Tortuosity of porous material. It is given by:

$$\alpha_\infty = \left(\frac{1}{\sqrt{\varphi}}\right) \quad (15)$$

The coupling parameters (ρ_{11}^*, ρ_{12}^* and ρ_{22}^*) are given by:

$$\rho_{11}^* = \rho_{bulk} + \rho_a - j\sigma\varphi^2 \frac{G(\omega)}{2f\pi} \quad (16)$$

$$\rho_{12}^* = -\rho_a + j\sigma\varphi^2 \frac{G(\omega)}{2f\pi} \quad (17)$$

$$\rho_{22}^* = \varphi\rho_0 + \rho_a - j\sigma\varphi^2 \frac{G(\omega)}{2f\pi} \quad (18)$$

where; the inertial coupling (ρ_a) is given by:

$$\rho_a = \rho_0 \varphi (\alpha_\infty - 1) \quad (19)$$

Furthermore, the dynamic stiffness (δ) for flexible solid panels could be calculated by:

$$\delta_1^2 = \frac{\omega^2}{2(PR - Q^2)} \left[\begin{array}{l} P\rho_{22}^* + R\rho_{11}^* - \\ 2Q\rho_{12}^* - \sqrt{\Delta} \end{array} \right] \quad (20)$$

$$\delta_2^2 = \frac{\omega^2}{2(PR - Q^2)} \left[\begin{array}{l} P\rho_{22}^* + R\rho_{11}^* \\ -2Q\rho_{12}^* + \sqrt{\Delta} \end{array} \right] \quad (21)$$

where,

$$\Delta = \left(P\rho_{22}^* + R\rho_{11}^* - 2Q\rho_{12}^*\right)^2 - 4\left(PR - Q^2\right)\left(\rho_{11}^* \rho_{22}^* - \rho_{12}^*\right) \quad (22)$$

The media of propagation waves were utilized to extract four values of property impedance according to transfer in either air or framework, as following:

$$Z_i^a = \left(R + \frac{Q}{\mu_i}\right)\frac{\delta_i}{\varphi\omega} \quad i = 1, 2 \quad (23)$$

$$Z_i^f = (P + Q\mu_i)\frac{\delta_i}{\omega} \quad i = 1, 2 \quad (24)$$

where;

$$\mu_i = \frac{P\delta_i^2 - \omega^2 \rho_{11}^*}{\omega^2 \rho_{12}^* - Q\delta_i^2} \quad i = 1, 2 \quad (25)$$

Finally, the surface impedance (Γ_f) is a function of properties of both incident and reflected pressure waves in porous materials, as following:

$$\Gamma_f = -j \frac{\left(Z_1^f Z_2^a \mu_2 - Z_2^f Z_1^a \mu_1\right)}{D} \quad (26)$$

where,

$$D = (1 - \varphi\mu_2)\left[Z_1^f - (1-\varphi)Z_1^a \mu_1\right]\tan \delta_2 t_f + (1 - \varphi + \varphi\mu_1)\left[Z_2^a \mu_2 (1-\varphi) - Z_2^f\right]\tan \delta_1 t_f \quad (27)$$

Equation (26) can be re-written as:

$$\Gamma_f = j\,\Gamma_2 \quad (28)$$

Hence, the term (Γ2) is extracted as:

$$\Gamma_2 = -\frac{\left(Z_1^f Z_2^a \mu_2 - Z_2^f Z_1^a \mu_1\right)}{D} \quad (29)$$

3. EXPERIMENTAL WORK

The experimental work included the collecting of OPFs locally, grinding the row material and peeling to tiny strings. The fibers should be heated to 150 °C for 6 hours to improve the dimensional stability and to treat the hydrophilic issues [31]. Composite panels then have manufactured by mixing the fibers with the latex as a cohesive material. Several samples of 20, 30, 40, and 50 mm thicknesses are formed with different diameters, as shown in Figure 2. The whole process of the manufacturing and the tests was done according to ISO10534-2.

Figure 2. Samples manufactured in this study, 100 mm diameter and 28 mm diameter for each panel thickness

The experimental tests have developed to demonstrate actual values of AAC for the panels. The measurements have done at Noise and Vibration Laboratory, UTHM University, Malaysia. An impedance tube instrument was used to test the samples, as shown in Figure 3.

Figure 3. Impedance tubes and setup system

The impedance instrument has two tubes. Large tube (100 mm) used to measure AAC at low frequencies (100-1200 Hz), and a smaller tube (28 mm) used with higher frequencies (more than 1600 Hz). Thus, the selected samples have two circular shapes to fit the diameters of the impedance tubes. Other tools used were: computer, noise generator, loud speakers, audio amplifier, microphones and power supply. Each test was repeated three times to confirm the measurements data where the time that required acquiring the absorber‘s spectrum by the instrument took approximately 10 s with a resolution of 3.13 Hz. A calibration process [32, 33] has been utilized for GRAS-42 AB microphone at calibrations sensitivity of 114 dB at 1 kHz. Random set of individual fibers have taken to measure the dimensions of the fibers, as shown in Table 2, using electronic microscopy of 50X magnification.

Table 2. Features for selected individual fibers

Feature	Average value
Diameter	0.28 mm
Length	32.43 mm
Volume	1.9 mm^3

Figure 5 show photos for some selected fibers. Moreover, the bulk density for each panel has measured also, as shown in Table 3.

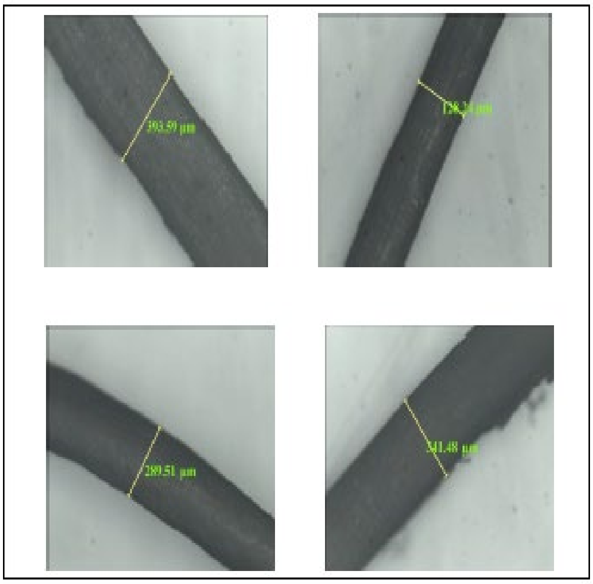

Figure 5. SEM images for some individual fibers

Table 3. Bulk densities for the selected panels

Thickness (mm)	Bulk density (kg/m^3)	Mixing ratio (OPFs:Latex:Air)
20	120	20:10:70
20	160	30:10:60
20	200	40:10:50
30	205	40:10:50
40	210	40:10:50
50	210	40:10:50

4. RESULTS AND DISCUSSIONS

The values of AAC for selected composite samples determined theoretically and experimentally at different thicknesses, densities and frequencies, as shown in Figures 6-11.

The results show that AAC values have increased due to the increase in the thickness, where the absorption increases as colliding wave goes longer path through the material, thus losses its energy due to dissipative effect of viscosity and thermal losses within the material. In general, the AAC values improved by 10-20 % for each 10 mm layer added. On the other hand, the increasing in the bulk density of the panel improves the AAC values by 5-15 % for each 40 kg/m^3 added. The behavior of the results for both theoretical and experimental works is very similar because of using adequate range of thicknesses and densities.

Furthermore, the values of AAC are varied directly with the sound frequency passed through the sample. In low frequencies (100-1200 Hz), there is a kind of linear relationship between the AAC and the frequency, where the AAC value increased with the frequency until a peak value of: 0.36, 0.44, 0.59 and 0.61 for 20, 30, 40 and 50 mm, respectively. Take into account that in the theoretical result, the linear relationship may extend up to 2500 Hz. However, in low frequencies, the comparison between AAC values is not well recognized and that is attributed to the high acoustic resistance which already leads to diminish sound transmission. In high frequencies (more than 1600 Hz), there is a fluctuating cyclic relationship between the AAC and the frequency, where the peak values of AAC were: 0.63 at 3200 Hz for 20 mm thickness, 0.67 at 3600 Hz for 30 mm thickness, 0.71 at 3300 Hz for 40 mm thickness and 0.78 at 3400 kHz for 50 mm thickness.

The comparison between calculated values of AAC with that obtained experimentally show differences by ±20%. The discrepancies between experimental and analytical values are due to the fluctuation in the theoretical values that extracted from several resources, where they involved different conditions or assumptions in the analysis. Other reasons are due to the experimental data collected by the impendence tube, where the switching between large tubes, assigned for low frequencies, and small tube, assigned for high frequencies, created unexpected sharp notch in the AAC value after combining the whole data from both tubes. Furthermore, the low values of flow resistivity (<4000 Ns/m^4) and porosity (<< 1) of the samples may add another reason for extra error [34].

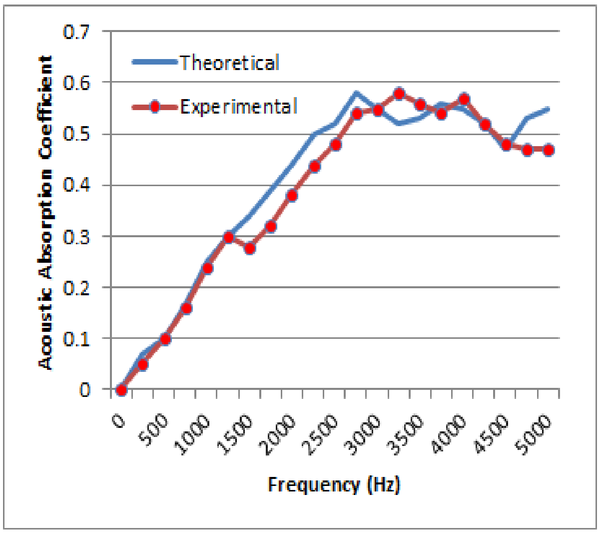

Figure 6. AAC for 20 mm, 120 kg/m^3 sample

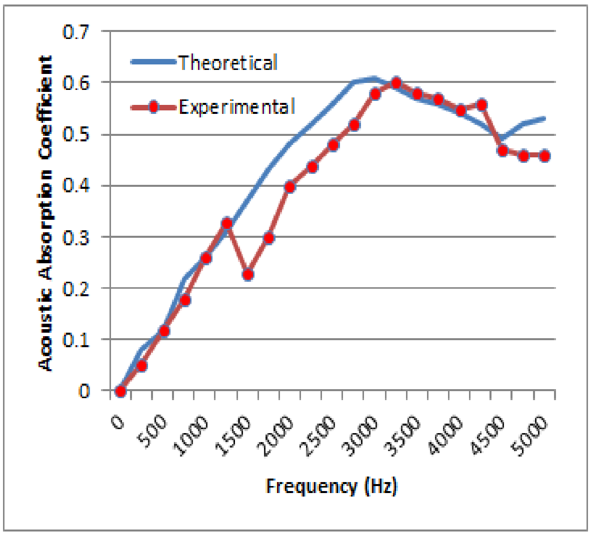

Figure 7. AAC for 20 mm, 160 kg/m^3 sample

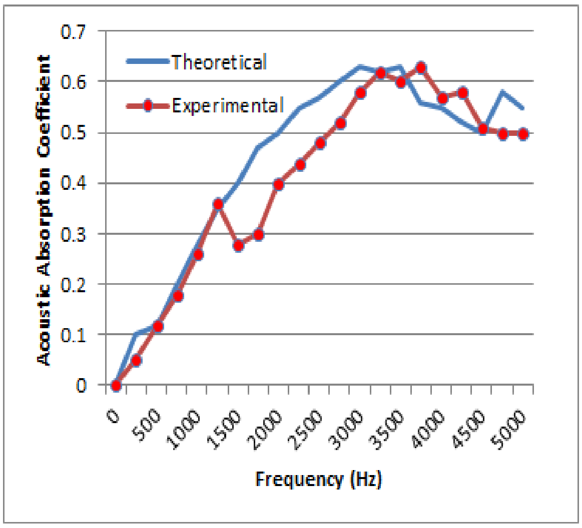

Figure 8. AAC for 20 mm, 200 kg/m^3 sample

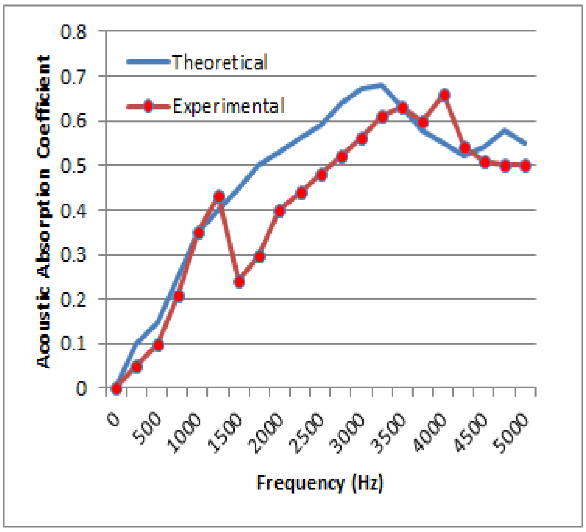

Figure 9. AAC for 30 mm, 205 kg/m^3 sample

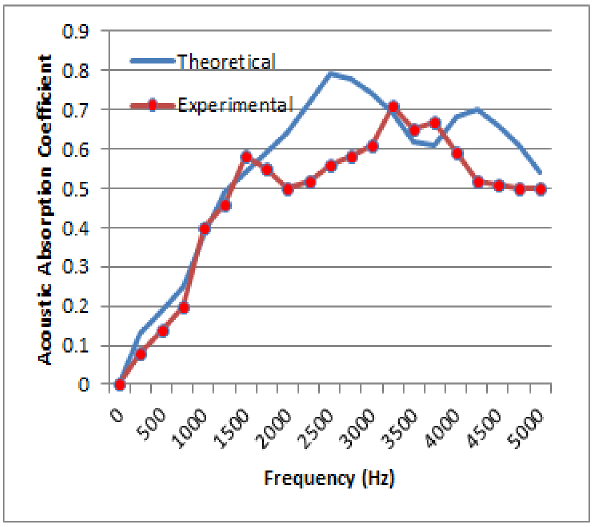

Figure 10. AAC for 40 mm, 210 kg/m^3 sample

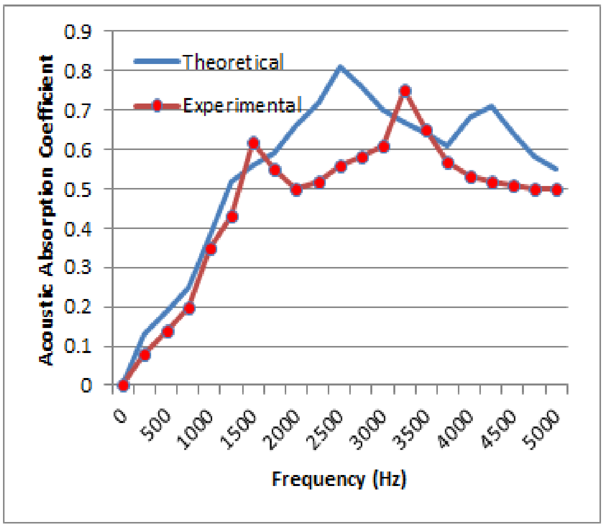

Figure 11. AAC for 50 mm, 210 kg/m^3 sample

5. CONCLUSIONS

The study seeks to evaluate thermo-acoustic performance of composite panels made of oil palm fibers and latex. The reference parameter, AAC, has been calculated theoretically by modified Allard approach and depending on the thermo-physical properties of the fibers and the medium. The study involved experimental works for validation purposes, where many samples have been manufactured with different thicknesses and densities. The results show that the value of AAC has increased by increasing the thickness and bulk density for a certain range. The increasing in the value of the AAC was between 10-20% for each increasing in the thickness by 10 mm. On the other hand, the increasing in the bulk density of the panel improves the AAC values by 5-15 % for each 40 kg/m^3 added. However, these results are conclusive for certain combination of materials under limited conditions and concentration ratios.

ACKNOWLEDGMENTS

Authors are grateful to Noise and Vibration Laboratory, Faculty of Mechanical and Manufacturing Engineering - UTHM University (Malaysia) for facilitation of the laboratory works. Grateful is extended as well for encouraging of completing this work by College of Health and Medical Technology-Middle Technical University and College of Engineering - Mustansiriyah University (Iraq).

REFERENCES

[1] Lamyaa J., Tawfeeq M., An investigation into practical values of sound transmission loss across natural Luffa fibers, *Epitoanyag, Journal of Silicate Based and Composite Materials*, Vol. 72, No. 3, 2020, pp. 106-109.

[2] Hadeel M., Tawfeeq. M., Thermal insulation performance of wood-plastic composite panels as alternative to Alucobond cladding sheets for buildings, *Journal of Engineering and Sustainable Development*, Vol. 24, No. 2, 2020, pp. 425-433.

[3] Abdel-Hakim A., Awad E., El-Nemr, K., El-Basheer T., Impact of gamma radiation and multi-walled carbon nanotubes on the mechanical and acoustical properties of reinforced sisal fiber/polyester resin composites, *Radiation Physics and Chemistry*, Vol. 189, 2021, 109768.

[4] Abdel-Hakim A., El-Basheer T. Abd El-Aziz A., Afifi, M, Acoustic, ultrasonic, mechanical properties and biodegradability of sawdust/recycled expanded polystyrene eco-friendly composites, *Polymer Testing*, Vol. 99, 2021, 107215.

[5] Ravindran A., Investigation of inverse acoustical characterization of porous materials used in aircraft noise control application, Thesis, Wichita State University, 2007.

[6] Wang C., Torng J., Experimental study of the absorption characteristics of some porous fibrous materials, *Applied Acoustics*, Vol. 62, No. 4, 2001, pp. 447-459.

[7] El-Wakil A., Abd-Elbasseer M., El-Basheer T., Mechanical and acoustical properties of Eichhornia crassipes (water hyacinth) fiber-reinforced styrene butadiene rubber, *Polymer Composites*, Vol. 42, No. 8, 2021, pp. 3732-3745.

[8] El-Basheer T., Shawky H., Measurement and limits of vibration affecting the sensitive equipments of some metrological laboratories, *Euronoise,* Vol. 11, 2018, pp. 2637-2644.

[9] Rajiv P., Rajkishore N., Acoustic Textiles, Springer, 2016.

[10] Anand N., Kiran M., Varadarajulu K., Influence of density on sound absorption coefficient of fibre board, Scientific Research Publishing, *Open Journal of Acoustics*, No. 7, 2017, pp. 1-9.

[11] Kisku G., Bhargava S., Assessment of noise level of a medium scale thermal power plant, *Indian Journal of Occupational and Environmental Medicine*, Vol. 10, No. 3, 2006, pp. 133-139.

[12] El-Basheer T., Youssef R., Mohamed H., NIS method for uncertainty estimation of airborne sound insulation measurement in field, *International Journal of Metrology and Quality Engineering*, Vol. 8, No. 19, 2017.

[13] Ersoy S., Küçük H., Investigation of industrial tea-leaf fibre waste material for its sound absorption properties, *Applied Acoustics*, Vol. 70, No. 1, 2009, pp. 215-220.

[14] Ayub M., et al., Analysis on sound absorption of natural coir fiber using Delany-Bazley model, *Proceedings of the International Conference on Mechanical Engineering*, Bangladesh, 26 Dec., 2009.

[15] Delany M., Bazley E., Acoustical properties of fibrous absorbent materials, *Applied Acoustics*, Vol. 3, No. 2, 1970, pp. 105-116.

[16] Nor M., et al., Effect of compression on the acoustic absorption of coir fiber, *American Journal of Applied Sciences*, Vol. 7, No. 9, 2010, pp. 1285-1290.

[17] Nor M., et al., Effect of different factors on the acoustic absorption of coir fiber, Journal of Applied Sciences, No. 10, 2010, pp. 2887-2892.

[18] Allard J., Atalla N., Porous materials with perforated facings, Chapter in the book: Propagation of Sound in Porous Media, Springer, 2009.

[19] Yang S., Yu W., Pan N., Investigation of the sound-absorbing behavior of fiber assemblies, *Textile Research Journal*, Vol. 81, No. 7, 2011, pp. 673-682.

[20] Deveikytė S., Mažuolis J., Vaitiekūnas P., Experimental investigation into noise insulation of straw and reeds, *Science–Future of Lithuania/Mokslas–Lietuvos Ateitis*, Vol. 4, No. 5, 2012, pp. 415-422.

[21] Khair F., et al., Preliminary study on bamboo as sound absorber, *Applied Mechanics and Materials*, Vol. 554, 2014, pp. 76-80.

[22] Lamyaa J., Factors effecting acoustic properties of date palm fiber, Thesis, University Technology Malaysia, 2015.

[23] Genc G., Koruk H., Investigation of the vibro-acoustic behaviors of Luffa bio-composites and assessment of their use for practical applications, *23rd International Congress on Sound and Vibration*, Greece, 10-14 July, 2016.

[24] Thilagavathi G., Krishnan S., Muthukumar N., Investigations on sound absorption properties of Luffa fibrous mats, *Journal of Natural Fibers*, Vol. 15, No. 3, 2018, pp. 445-451

[25] Biot M., Generalized theory of acoustic propagation in porous dissipative media, *Journal of the Acoustical Society of America*, Vol. 34, No. 9A, 1992, pp. 1254-1264.

[26] Ayub M., Zulkifli R., Fouladi M., Amin N., Jailani M., A study on the acoustical absorption behavior of coir fiber using Miki model, *International Journal of Mechanical and Materials Engineering*, Vol. 6, No. 3, 2012, pp. 343-349.

[27] Hosseini F., Ayub M., Nor M., Analysis of coir fiber acoustical characteristics, *Applied Acoustics*, Vol. 72, No. 1, 2011, pp. 35-42.

[28] Attenborough K., Models for the acoustical characteristics of air filled granular materials, *Acta Acust*, No. 1, 1993, pp. 213-226.

[29] Dazel O., Numerical methods for the Biot theory in acoustics, University of Maine, Laboratory of Acoustics - UMR CNRS 6613, 2011.

[30] Dunn I., Davern W., Calculation of acoustic impedance of multi-layer absorbers, *Applied acoustics*, Vol. 19, No. 5, 1986, pp. 321-334.

[31] Chung H., Park Y., Yang S., Kim H., Han Y., Chang Y., Yeo H., Effect of heat treatment temperature and time on sound absorption coefficient of Larix kaempferi wood, *J. Wood Sci.*, No. 63, 2017, pp. 575–579.

[32] Hussein T., Calibration and uncertainty estimation for the reference sound source in reverberation room, *Romanian Journal of Acoustics and Vibration*, Vol. 17, No. 2, 2020, pp. 118-127.

[33] Mahmoud A., Shawky H., Youssef R., El-Basheer T., Mohamed H., Uncertainty calculations of pressure sensitivity on one inch microphones using pressure field method at NIS, In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, August 2015.

[34] Komatsu T., Improvement of the Delany-Bazley and Miki models for fibrous sound-absorbing materials, *Acoustical Science and Technology*, Vol. 29, No. 2, 2008, pp. 121-129.

.