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Research Paper

Sound Absorption Characteristics of Pineapple Leaf/Epoxy Composite

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Natural fibres are attractive as the raw material for developing sound absorber, as they are green, eco-friendly, and health friendly. In this paper, pineapple leaf fibre/epoxy composite is considered in sound absorber development where several values of mechanical pressures were introduced during the fabrication of absorber composite. The results show that the composite can absorb incoming sound wave, where sound absorption coefficients $\alpha_n > 0.5$ are pronounced at mid and high frequencies. It is also found that 23.15 kN/m^2 mechanical pressure in composite fabrication is preferred, while higher pressure leads to solid panel rather than sound absorber so that the absorption capability reduces. To extend the absorption towards lower frequency, the composite absorber requires thickness higher than 3 cm, while a thinner absorber is only effective at 1 kHz and above. Additionally, it is confirmed that the Delany-Bazley formulation fails to predict associated absorption behavior of pineapple leaf fibre-based absorber. Meanwhile, a modified Delany-Bazley model discussed in this paper is more useful. It is expected that the model can assist further development of the pineapple leaf composite sound absorber.

Keywords: natural fibres; pineapple leaf/epoxy composite; sound absorber; absorption prediction model.

1. Introduction

Fibrous porous materials like foam, glass wool, and rock wool are commonly found as sound absorbers in practice due to their performance at mid-high frequencies. Despite this, environmental and health issues are the matter of concern as well as their lifetime. Hence, some alternative fibrous porous materials have been proposed, i.e. porous material made of polyester fibre or recycled polyester fibre (Kino, Ueno, 2008; Lee, Joo, 2003) have been developed in order to replace conventional absorbers. Apart from this, biomass based materials (Asdrubali, 2006a; 2006b) or recycled materials like crumb rubber (Pfretzschner, Rodriguez, 1999; Swift *et al.*, 1999) were also used to develop composite absorbers. The potential of natural fibres have also been explored for the same purpose, e.g. the use of natural fibres such as multi-layer coir fibre (Zulkifli *et al.*, 2008), oil palm empty fruit bunch (Or *et al.*, 2017), coconut coir fibres mixed with cylindrical granular materials (Mamtaz *et al.*, 2017), and kenaf fibres (Lim *et al.*, 2018). Such fibres are gaining attraction due to the enviromental concern related with synthetic materials (Mvubu *et al.*, 2015; Patnaik, *et al.*, 2015) as they are biodegradable hence environmentally friendly.

Some studies were performed to characterise sound absorber made of natural fibres, especially to find out the sound absorption characteristics along with prediction models (Berardi, Iannace, 2015; 2017). Moreover, natural fibres in the form of composites have shown the ability to absorb incoming sound, considering the experimental results where absorption coefficients are 0.7 and higher (Ersoy, Küçük, 2009; Ismail, 2010; Silva *et al.*, 2019).

Fibres extracted from pineapple leaves are attractive to be used for many applications due to their mechanical properties (Arib *et al.*, 2006; Asim *et al.*, 2015; Devi *et al.*, 1997) as well as a source of cellulose (Cherian *et al.*, 2010). Apart from this, pineapple leaves can be useful to alleviate environmental burden as the leaves are typically waste of pineapple plantations.

A few studies have been devoted to investigate the sound absorption properties of pineapple leaf as found in (Putra *et al.*, 2018; Rusli *et al.*, 2019) where good absorption performances were concluded. Meanwhile, many parameters in the composite fabrication process are still lacking intensive studies to discuss their effect on the sound absorption characteristics such as mechanical pressure, temperature, and so on. In this research, composite materials from pineapple leaf natural fibre and epoxy resin are developed as sound absorbers. The sound absorbing performance of these composite panels is evaluated in terms of acoustics and geometry as results of applied mechanical pressure of hot press during fabrication. Moreover, a prediction model of this kind of absorber developed on the basis of Delany-Bazley formulation (Delany, Bazley, 1970) and optimization using empirical data is proposed. It is expected that the model can serve further development of pineapple leaf absorber such as obtaining wide band absorber, perfect absorber, etc.

This paper is organised as follows: in the first section we introduce the trend of the use of natural fibre as well as the research motivation to the development of pineapple leaf based absorber. In Sec. 2, material and methods are described to explain how the absorbers are developed and while evaluation procedures to their performance are presented. In the following section, geometrical and absorption characteristics are presented and analysed. Lastly, some important findings are drawn in the conclusions.

2. Material and methods

2.1. Composite fabrication

Schematic diagram of composite panel fabrication is shown in Fig. 1 while Fig. 2 shows several pictures to illustrate composite panel fabrication process. Pineapple leaf fibre was obtained from a local market in Blitar, Indonesia. Epoxy resin and hardener are water based, from Mortar, Germany. The pineapple fibre was cut in 1 cm length using scissors and paper cutter set. Epoxy resin and hardener mixture were obtained by mixing 10 g epoxy resin, 10 g hardener, and 100 ml distilled water. The mixture was then poured to 100 g pineapple fibre and blended until both are evenly distributed. For obtaining the composites, the mixture was then poured to an aluminum mold with $24.5 \times 18 \times 1$ cm^3 size and then hot-pressed at 100°C for 3 hours. In this research, composite panels were made for three varied applied forces: 1, 3, and 5 kN. After the hot-pressing step, the composite panels were cured in an oven at 105°C for 24 hours.

The composite panels were made for different applied pressure are listed in Table 1. Note that the thickness of 1 kN samples have two variations due to the use of two different mold sizes, size A: $25.5 \times 18.6 \times 3.5$ cm^3 and size B: $24.5 \times 18 \times 1$ cm^3.

Table 1. Thickness and density of composite panels prepared using different pressure.

Composite panel name	Force [kN]	Pressure [kN/m^2]	Thickness D [mm]	Density ρ [g/cm^3]
Sample 1A	1	23.15	9.03	0.258
Sample 1B		24.71	5.50	0.515
Sample 2	3	69.44	3.44	0.837
Sample 3	5	115.74	3.07	0.907

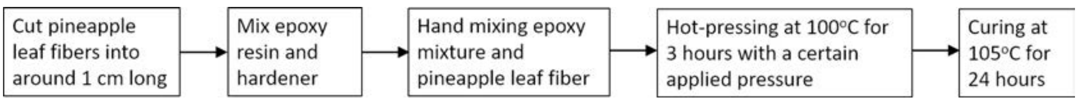


Fig. 1. Pineapple leaf/epoxy composite panel fabrication steps.

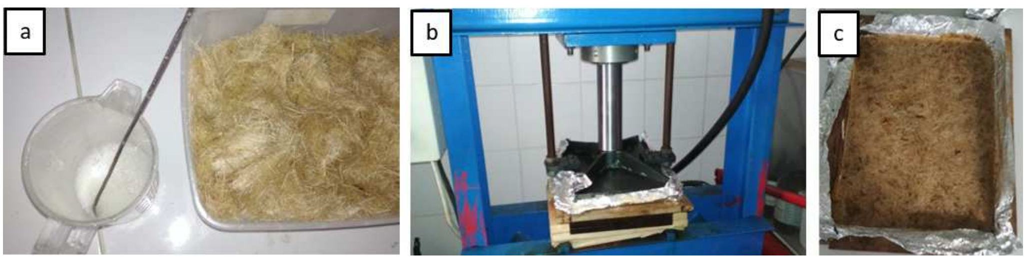


Fig. 2. Illustration of: a) epoxy and pineapple leaf fibre before mixing, b) hot pressing of epoxy and fibre mixture, c) finished composite panel.

2.2. Morphological characteristics

In this study, the porous size distribution of each composite panel or fibre diameter were observed using SEM. Having these parameters allows us to predict static air flow resistivity (σ) of the composite using formula proposed by Bies and Hansen (1980) as follows

$$\sigma d^2 \rho^{-1.53} = 3.18 \cdot 10^{-9}, \tag{1}$$

where ρ is the bulk density in kg/m^3 and d is the diameter of fibre in meters. Note that Eq. (1) is valid for uniform cross-sectional glass fibre with diameter of less than 15 μm. The binder content is disregarded.

2.3. Acoustic characteristics

For acoustic characteristics, the absorption coefficient of composite panels was measured using the impedance tube according to ISO 10534-2 (ISO, 1998) with measurement configuration as shown in Fig. 3. In principle, white noise was generated by a loud speaker and travelling along the tubes with diameters of 3 cm and 10 cm for covering sound absorptions of 64 Hz – 1.6 kHz and 1 kHz – 6.3 kHz respectively. Considering the tube diameter, plane wave conditions hold by which cross-section modes were absent. The reflection coefficient R can be obtained by combining transfer function of the incoming wave pressure p_1 measured at microphone positions H_I as well as that of the reflected wave pressures p_r measured at the same position H_R and transfer function of the total pressure at microphone 1 and 2 H_{12} as follows:

$$R = \frac{H_{12} - H_1}{H_R - H_{12}} e^{jk_0 2x_1}, \tag{2}$$

where k_0 is the wavenumber and $2x_1$ is the compensator distance from the surface sample to the microphone.

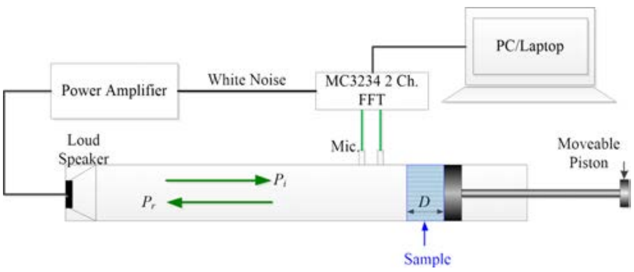


Fig. 3. Schematic diagram of sound absorption measurement using impedance tube.

Finally, the normal sound absorption coefficients α_n of the absorber are obtained through

$$\alpha_n = 1 - |R|^2. \tag{3}$$

The measurement of each microphone configuration was carried out for around 120 s to obtain a steady state response. The data at overlapping frequency were averaged so that absorption coefficients were obtained for 64 Hz to 6.3 kHz.

2.4. Sound absorption model

A simple model as a function of flow resistivity parameter is employed to benchmark the experimental results. For this, a least fitting model of Delany-Bazley is considered by which the characteristic impedance Z_c and complex wave number k_c can be defined as follows (Delany, Bazley, 1970):

$$Z_c = \rho_0 c \left[1 + c_1 \left(\frac{\rho_0 f}{\sigma}\right)^{-c_2} - jc_3 \left(\frac{\rho_0 f}{\sigma}\right)^{-c_4}\right], \tag{4}$$

$$k_c = \frac{\omega}{c} \left[c_5 \left(\frac{\rho_0 f}{\sigma}\right)^{-c_6} - jc_7 \left(\frac{\rho_0 f}{\sigma}\right)^{-c_8}\right], \tag{5}$$

where ρ_0 is the density of air, c is the sound speed in air, ω is the angular frequency, f is the frequency, and c_i $(i = 1, \ldots, 8)$ are the numerical constants. The values of c_i are obtained through optimisation approach by adopting the Nelder-Mead simplex method and the following the procedure in (Nelder, Mead, 1965) is applied to minimise the cost function of squared difference between the measured absorption coefficients and corresponding predicted absorption coefficients.

The surface impedance of a porous material backed up by an impervious layer can be defined by making use of Z_c and k_c in Eqs (4) and (5) as

$$Z_s = -jZ_c \cot(k_c D), \tag{6}$$

where D is the absorber thickness.

The normal sound absorption coefficient α_n is thus obtained as follows:

$$\alpha_n = \frac{4\mathrm{Re}(Z_s)}{(1 + \mathrm{Re}(Z_s))^2 + (\mathrm{Im}(Z_s))^2}. \tag{7}$$

3. Results and analysis

3.1. SEM observation

SEM observation results of composite panels can be seen in Fig. 4, where the yellow lines indicate the pore size and the blue lines indicate the fibre diameter. The pore size and fibre diameter values distribution for composite panels are listed in Table 2, showing a large value of distribution range that indicates a high degree of non-uniformity on the fibre diameter and pore size of these composite panels. The non-uniformity is due to the fact that it is difficult to distribute the epoxy evenly throughout the fibres. Moreover, some of the fibres are originally attached to one another such as the fibre marked by red arrows in Fig. 4a. However, these SEM results clearly show that with the increase of applied pressure, the porosity of composite panels

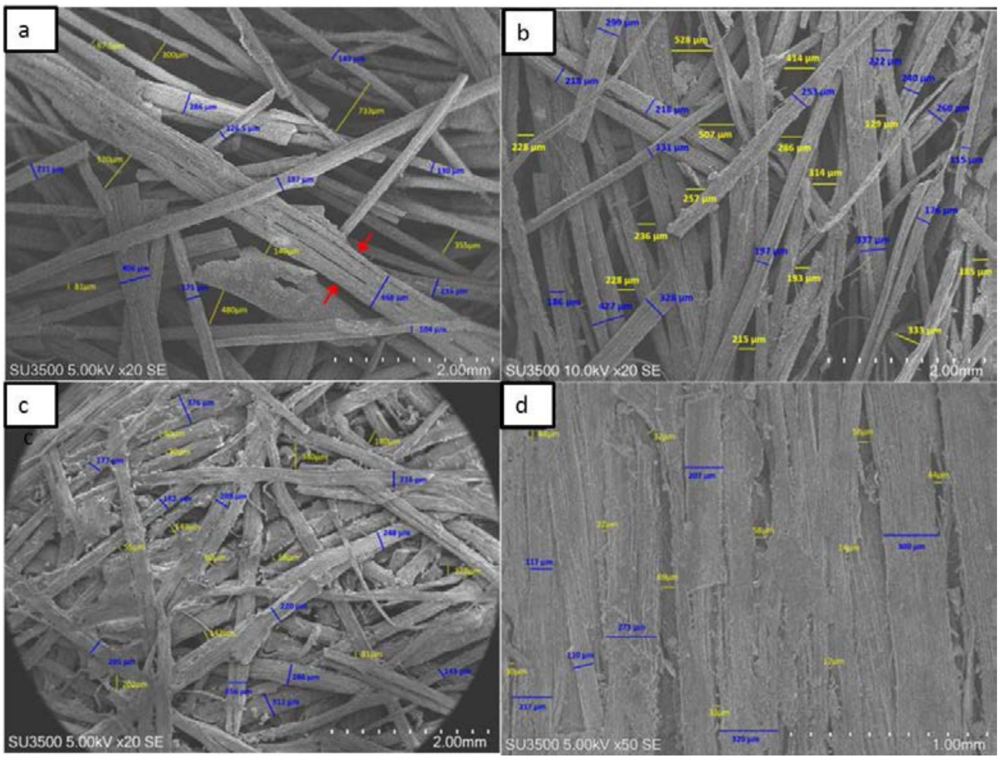


Fig. 4. SEM observation results of: a) sample 1A, b) sample 1B, c) sample 2, d) sample 3. Yellow lines indicate pore size and blue lines indicate fibre diameter.

Table 2. Pore and fibre diameter size distribution based on SEM observation results.

Composite panel name	Thickness D [mm]	Pore size [μm]	Fibre diameter [μm]	Average air flow resistivity $\overline{\sigma}$ [$\mathrm{N \cdot s/m^4}$]
Sample 1A	9.03	334.6 ± 235.8	216.3 ± 110.3	332.73
Sample 1B	5.50	389.5 ± 119.4	240.5 ± 81.9	774.93
Sample 2	3.44	121.6 ± 89.2	266.7 ± 105.8	1324.80
Sample 3	3.07	38.3 ± 18.0	223.7 ± 79.8	2129.29

is decreasing. The pore size distribution is also getting better with increasing applied pressure, indicated by decreasing value of deviation range as shown in Table 2. This is because higher applied pressure can help to distribute the epoxy more evenly throughout the panel.

Using Eq. (1) as an initial approximation, bulk density calculation, and fibre diameter data obtained by SEM; it is concluded that the flow resistivity σ of samples considered in this research is 332.73 $\mathrm{N \cdot s/m^4}$ up to 2129.29 $\mathrm{N \cdot s/m^4}$ as indicated in Table 2. Again, the calculations of flow resistivities were performed by omitting the presence of binder in the composite panels.

3.2. Sound absorption performance

The sound absorption measurement result for a single layer absorber with the thickness of 0.5 cm can be seen in Fig. 5. It is clear that most of sound absorption coefficients α_n are lower than 0.5 for the case of sample 3 and sample 5, except for that of sample 1A and 1B

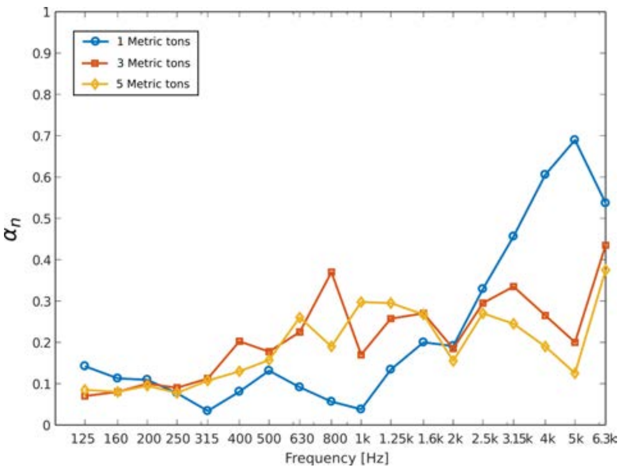


Fig. 5. Sound absorption coefficients of the composite panels prepared using 23.15 $\mathrm{kN/m^2}$, 69.44 $\mathrm{kN/m^2}$ and 115.74 $\mathrm{kN/m^2}$ pressure.

where $\alpha_n > 0.5$ at high frequencies. The variation of mechanical pressure applied during fabrications affects the flow resistivity as this determines sample density as well as perforation properties. Moreover, these results also indicate that the composite panel prepared using 23.15 kN/m^2 pressure is a good sound absorbing candidate while the composite panels prepared using higher pressure (69.44 kN/m^2 and 115.74 kN/m^2), tend to have more solid surface so that the reflectance factor is dominant. Hence, lower applied pressure is preferable to produce a lower density composite panels as this leads to a higher sound absorption coefficient.

It is instructive to further investigate sound absorption of a thicker panel which is fabricated using 23.15 to 24.71 kN/m^2 pressure or around 1 kN metric. For this, several composite panels with thickness of 0.5 cm and 1 cm were stacked together in order to get overall panel thickness to increase. It can be seen from Fig. 6 that high absorption coefficients extend to lower frequency as the thickness increases. For the thickness of 3 cm, the absorption coefficients higher than 0.8 are present above 800 Hz, while half-absorption bandwidth can be found around 630 Hz and above. Moreover, the sound absorption coefficients tend to increase after certain frequency. That tendency can be also observed for the absorption coefficients after 2.5 kHz and 3.15 kHz for the cases of the 3 cm thick panel and 2 cm thick panel respectively. This is so as the absorber thickness is equal to one-quarter sound wavelength in which maximum particle velocity exists at the absorber's surface so that sound absorption works efficiently. This kind of situation is hardly seen for the case of 0.5 cm and 1 cm thick panels where considerable dips are found after the presence of high absorption coefficients. This comes about as the maximum particle velocity is expected around 17 kHz and 8.5 kHz associated with 0.5 cm and 1 cm thick panel, which is beyond the frequency range of measurement of interest.

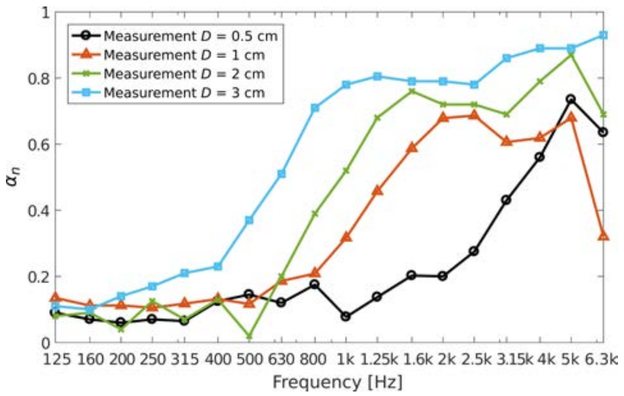
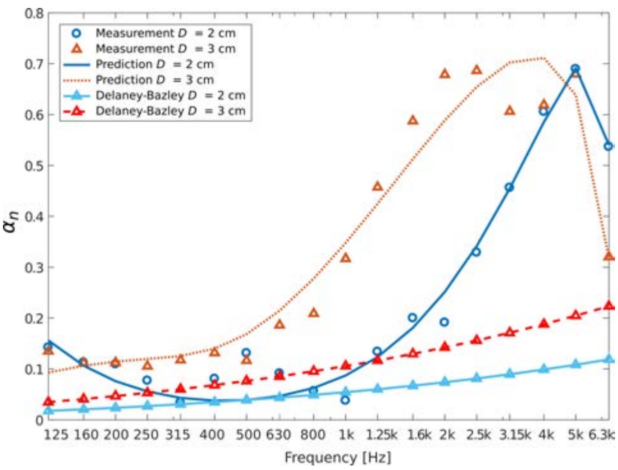


Fig. 6. Sound absorption coefficient comparisons for $D = 0.5$ cm, $D = 1$ cm, $D = 2$ cm, $D = 3$ cm.

3.3. Optimised prediction model

A prediction model is developed to calculate sound absorption coefficients of the pineapple leaf absorbers. It is obtained by fitting the measurement data with Eqs (4) and (5) where c_i values are optimised using the Nelder-Mead simplex method (Nelder, Mead, 1965). The optimisation procedures follow the same approach as found (Arenas *et al.*, 2014; Prasetiyo *et al.*, 2018). In this study c_i value optimisations were performed according to empirical data of 24.71 kN/m^2 absorber with different thickness designated by samples I, II, III, and IV, while flow resistivity data were taken from Table 2. Figure 7 presents a comparison between the measurement results and the prediction ones, while the c_i values are listed in Table 3. The results are in good agreement but the c_i values have a wide range where each of c_i values are dependent on the absorber's thickness. Moreover, the c_i values also different a lot as compared to that of Delany and Bazley model. It can be seen that the use of Eqs (4) and (5) with numerical constants suggested by the Delaney-Bazley as indicated in Table 3 is not in agreement with the measurement results. That means the pineapple

a)



b)

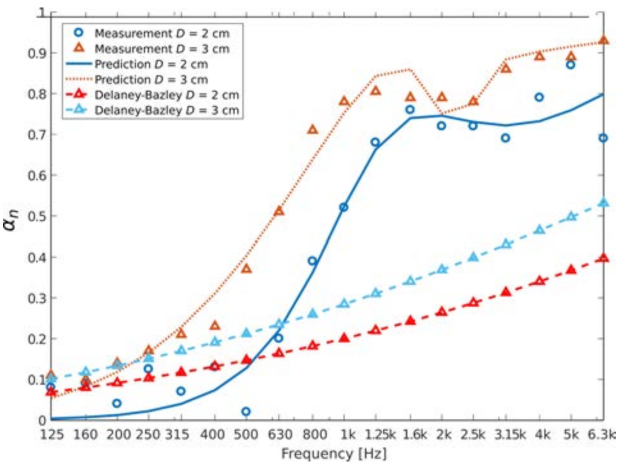


Fig. 7. Sound absorption coefficient of 23.15 kN/m^2 absorber with different thickness: a) sample 1A and 1B; b) sample 2 and sample 3.

Table 3. Numerical constants c_i obtained using the Nelder-Mead simplex method for 23.15 kN/m^2 and 24.71 kN/m^2 samples.

Sample	Thickness D [cm]	Numerical constants							
		c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
I	0.5	0.036	–1.042	0.482	–0.274	–0.413	–0.725	0.069	2.664
II	1	0.182	2.713	0.164	–0.837	–3.624	0.432	0.137	3.001
III	2	0.253	2.165	5.790	2.059	–1.328	0.446	0.287	0.236
IV	3	0.251	1.145	1.289	0.344	–1.209	–0.131	0.005	–3.340
Delany-Bazley		0.078	0.623	0.074	0.66	0.0987	0.700	0.189	0.595

leaf composite absorbers developed here have different characteristics and properties compared to the fibrous absorbent material in (Delany, Bazley, 1970).

To test the sensitivity of model to the flow resistivity, we introduce a different value of the flow resistivity σ and the results compared to that of σ = 774.93 N·s/m^4 which is set to 700 N·s/m^4 for this comparison purpose. As it can be seen from Fig. 8, the prediction results with 700 N·s/m^4 can produce a good result at low and mid frequencies but fail to match the peak at 5 kHz; root means square error RMSE = 0.0471. The situation is much worse for the lower σ result, and better results are found for a higher σ, see the results for 2000 N·s/m^4 in which RMSE of 0.0265 is pronounced. Hence, the results indicate that the optimised model is affected by σ value. However, σ value must be selected with a great care as the empirical data for the case of 0.5 cm thick panel do not cover the effective absorption frequency range.

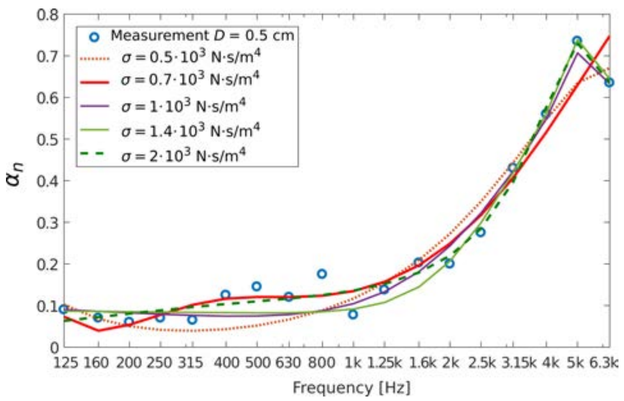


Fig. 8. Sound absorption comparison for different flow resistivity values for the case of 0.5 cm thick panel.

A similar fashion is also found for a 3 cm thick case where $\sigma = 3 \cdot 10^3$ N·s/m^4 produces the lowest RMSE that is 0.027. Meanwhile, lower or higher flow resistivities result in greater errors as shown in Fig. 9, although the use of flow resistivity ranging from $1 \cdot 10^3$ N·s/m^4 to $3 \cdot 10^3$ N·s/m^4 has slightly different errors. Note that the flow resistivity tends to increase for this case as a result of greater thickness than that of sample I.

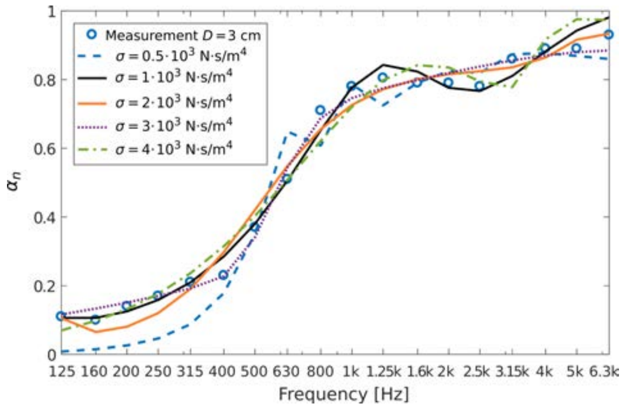


Fig. 9. Sound absorption comparison for different flow resistivity values for the case of 3 cm thick panel.

4. Conclusions

Fibrous porous absorbers along with their associated prediction model have been developed using pineapple leaf fibres composite. The measurement results confirmed that pineapple leaf fibre composite has a potential to be used as a sound absorber, which is indicated by $\alpha_n > 0.5$ at mid and high frequencies. The absorbing performance depends on the mechanical pressure during fabrication and its thickness. It is found that 23.15 kN/m^2 pressure is suitable to use in absorber fabrication while a higher pressure leads to a solid panel rather than a sound absorber. Moreover, the 2 cm thick absorber with the density of 0.258 g/cm^3 up to 0.515 g/cm^3 can deliver absorption capability at frequency of 1 kHz and above, while for lower frequencies can only be achieved by the 3 cm thick absorber or above. Additionally, an optimised prediction model based on the Delany-Bazley formulation can produce reasonable results, particularly at mid and high frequencies. It is useful to further develop pineapple leaf/epoxy composite based panel absorber by having such a prediction model.

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References

1. Arenas J.P., Rebolledo J., del Rey R., Alba J. (2014), Sound absorption properties of unbleached cellulose loose-fill insulation material, *BioResources*, **9**(4): 6227–6240.

2. Arib R.M.N., Sapuan S.M., Ahmad M.M.H.M., Paridah M.T., Khairul Zaman H.M.D. (2006), Mechanical properties of pineapple leaf fibre reinforced polypropylene composites, *Materials, Design*, **27**(5): 391–396, doi: 10.1016/j.matdes.2004.11.009.

3. Asdrubali F. (2006a), Green and sustainable materials for noise control in buildings, *9th International Congress on Acoustics*, Madrid, 2–7 September 2007.

4. Asdrubali F. (2006b), Survey on the acoustical properties of new sustainable materials for noise control, *Proceedings of Euronoise 2006*, *Structured Session Sustainable Materials for Noise Control*, Vol. 92, Tampere, Finland, 30 May – 1 June.

5. Asim M. *et al.* (2015), A review on pineapple leaves fibre and its composites, *International Journal of Polymer Science*, **2015**, 16 pages, doi: 10.1155/2015/950567.

6. Berardi U., Iannace G. (2015), Acoustic characterization of natural fibres for sound absorption applications, *Building and Environment*, **94**: 840–852, doi: 10.1016/j.buildenv.2015.05.029.

7. Berardi U., Iannace G. (2017), Predicting the sound absorption of natural materials: Best-fit inverse laws for the acoustic impedance and the propagation constant, *Applied Acoustics*, **115**: 131–138, doi: 10.1016/j.apacoust.2016.08.012.

8. Bies D.A., Hansen C.H. (1980), Flow resistance information for acoustical design, *Applied Acoustics*, **13**(5): 357–391, doi: 10.1016/0003-682X(80)90002-X.

9. Cherian B.M., Leao A.L., de Souza S.F., Thomas S., Pothan L.A., Kottaisamy M. (2010), Isolation of nanocellulose from pineapple leaf fibres by steam explosion, *Carbohydrate Polymers*, **81**(3): 720–725, doi: 10.1016/j.carbpol.2010.03.046.

10. Delany M.E., Bazley E.N. (1970), Acoustical properties of fibrous absorbent materials, *Applied Acoustics*, **3**(2): 105–116, doi: 10.1016/0003-682X(70)90031-9.

11. Devi L.U., Bhagawan S.S., Thomas S. (1997), Mechanical properties of pineapple leaf fibre-reinforced polyester composites, *Journal of Applied Polymer Science*, **64**(9): 1739–1748, doi: 10.1002/(SICI)1097-4628(19970531)64:9<1739::AID-APP10>3.0.CO;2-T.

12. Ersoy S., Küçük H. (2009), Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties, *Applied Acoustics*, **70**(1): 215–220, doi: 10.1016/j.apacoust.2007.12.005.

13. Ismail L., Ghazali M.I., Mahzan S., Zaidi A.M. (2010), Sound absorption of arenga pinnata natural fibre, *World Academy of Science, Engineering and Technology*, **43**: 804–806.

14. ISO (1998), *Standard 10534-2 Acoustics – Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes – Transfer Function Method.*

15. Kino N., Ueno T. (2008), Evaluation of acoustical and non-acoustical properties of sound absorbing materials made of polyester fibres of various cross-sectional shapes, *Applied Acoustics*, **69**(7): 575–582, doi: 10.1016/j.apacoust.2007.02.003.

16. Lee Y., Joo C. (2003), Sound absorption properties of recycled polyester fibrous assembly absorbers, *Autex Research Journal* , **3**(2): 78–84.

17. Lim Z.Y., Putra A., Nor M.J.M., Yaakob M.Y. (2018), Sound absorption performance of natural kenaf fibres, *Applied Acoustics*, **130**: 107–114, doi: 10.1016/j.apacoust.2017.09.012.

18. Mamtaz H., Foula M.H., Nuawi M.Z., Narayana Namasivayam S., Ghassem M., Al-Atabi M. (2017), Acoustic absorption of fibro-granular composite with cylindrical grains, *Applied Acoustics*, **126**: 58–67, doi: 10.1016/j.apacoust.2017.05.012.

19. Mvubu M., Patnaik A., Anandjiwala R.D. (2015), Process parameters optimization of needle-punched nonwovens for sound absorption application, *Journal of Engineered Fibres and Fabrics*, **10**(4): 47–54, doi: 10.1177/155892501501000415.

20. Nelder J.A., Mead R. (1965), A simplex method for function minimization, *The Computer Journal*, **7**(4): 308–313, doi: 10.1093/comjnl/7.4.308.

21. Or K.H., Putra A., Selamat M.Z. (2017), Oil palm empty fruit bunch fibres as sustainable acoustic absorber, *Applied Acoustics*, **119**: 9–16, doi: 10.1016/j.apacoust.2016.12.002.

22. Patnaik A., Mvubu M., Muniyasamy S., Botha A., Anandjiwala R.D. (2015), Thermal and sound insulation materials from waste wool and recycled polyester fibres and their biodegradation studies, *Energy and Buildings*, **92**: 161–169, doi: 10.1016/j.enbuild.2015.01.056.

23. Pfretzschner J., Rodriguez R.M. (1999), Acoustic properties of rubber crumbs, *Polymer Testing*, **18**(2): 81–92, doi: 10.1016/S0142-9418(98)00009-9.

24. Prasetiyo I., Desendra G., Hermanto M.N., Adhika D.R. (2018), On woven fabric sound absorption prediction, *Archives of Acoustics*, **43**(4): 707–715, doi: 10.24425/aoa.2018.125164.

25. Putra A., Or K.H., Selamat M.Z., Nor M.J.M., Hassan M.H., Prasetiyo I. (2018), Sound absorption of extracted pineapple-leaf fibres, *Applied Acoustics*, **136**: 9–15, doi: 10.1016/j.apacoust.2018.01.029.

26. Rusli M., Irsyad M., Dahlan H., Gusriwandi, Bur M. (2019), Sound absorption characteristics of the natural fibrous material from coconut coir, oil palm

fruit bunches, and pineapple leaf, *IOP Conference Series: Materials Science and Engineering*, **602**, 012067, doi: 10.1088/1757-899x/602/1/012067.

27. Silva C.C.B.D., Terashima F.J.H., Barbieri N., Lima K.F.D. (2019), Sound absorption coefficient assessment of sisal, coconut husk and sugar cane fibres for low frequencies based on three different methods, *Applied Acoustics*, **156**: 92–100, doi: 10.1016/j.apacoust.2019.07.001.

28. Swift M.J., Bris P., Horoshenkov K.V. (1999), Acoustic absorption in re-cycled rubber granulate, *Applied Acoustics*, **57**(3): 203–212, doi:10.1016/S0003-682X(98)00061-9.

29. Zulkifli R., Mohd Nor J., Mat Tahir M.F., Ismail A.R., Nuawi M. (2008), Acoustic properties of multi-layer coir fibres sound absorption panel, *Journal of Applied Sciences*, **8**(20): 3709–3714, doi: 10.3923/jas.2008.3709.3714.