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ACOUSTICAL PERFORMANCE AND PHYSICAL PROPERTIES OF NONWOVEN FIBRE; ARENGA PINNATA *(IJUK)* AND NATURAL RUBBERCOMPOSITE

Mathan Sambu, Musli Nizamyahya, Hanif Abdul Latif, Mohamed Nasrul Mohamed Hatta and Mohd Imran Bin Ghazali
Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
E-Mail: mathan_agarathi@yahoo.com

ABSTRACT

ArengaPinnata, a sustainable and eco-friendly material obtained from nature is eligible as alternative for synthetic fibre in sound absorber which is hazardous to human health. This paper discusses the sound absorption properties of this natural fibre. During the processing stage, ArengaPinnata fibres are treated with alkaline treatment individually and mix with various mixingratio of natural rubber (latex). The thickness of each sample is kept constant at 50mm. Method used to measure sound absorption coefficient (α) is the Impedance Tube Method (ASTM E1050-09) which is a standard test method for impedance and absorption of acoustical materials using a tube, two-way microphones and a digital frequency analysis system. The results showed that sound absorption coefficients of Arengapinnatasamples mix with natural rubber were better than the sample without natural rubber as binder. The better sound absorption performance obtained from 80:20, ArengaPinnata and natural rubber mixed sample which gives the value of 0.8 to 0.9 at 1000 Hz and 4000 Hz compare to other mixing ratio samples. Moreover, empirical model proposed by Delany-Bazley are used to support the normal incidence sound absorption result as a preliminary prediction. The physical properties of the ArengaPinnata fibres such as density, porosity, tortuosity and flow resistivity were also been tested. The physical properties results agree that, they significantly influence the acoustical performance. All the outcomes demonstrate that, this selected natural fibre is a promising light and environment-friendly sound absorption material.

Keywords: arengapinnata, natural rubber, sound absorption, Delany-Bazley, physical.

INTRODUCTION

This era`s infrastructure aiming in buildingsrequire controlled sound quality in anindoor living space such as lecture room, theatre hall, musical studio, theatreand even working space such as office and meeting room, where theconventional abrasive and porous acoustic materials are still widely used.Apart from that, the commonly used acoustic material are made by synthetic fibres(Joshi, Shravage, Jain, and Karanth, 2011).Porous filled material that made from synthetic fibres, such as mineral wool isgenerally used for sound insulation and thermal control due to their good performance rank and low cost. Previous surveyor on acoustical material, Francesco Asdrubali stated that most of European building insulation market of value approximately 3.3 billion euros has been estimated to (Asdrubali, 2006);

- Glass wool : 27%
- Stone wool : 30 %
- plastics Foam : 40 %
- Other materials : 3%

This extensively used sound insulation material made of synthetic fibres indeed cause injurious for human health. If this fibres were everinhaled, they can lay down in the lung alveoli, and can cause skin irritation (Lamyaa Abd Al-Rahman, Raja Ishak Raja, 2012).Production of these synthetics materials has been known to release significant amount ofCO_2into atmosphere compared to that sound insulation made from natural materials (Asdrubali, 2006). The character of synthetic also creates another problem in disposition which is harmful to the global environment. Thus outcome with alternative green materials which have not only comparable capability as sound absorbers, but also bio-degradable, sustainable, abundance as well as less health risk are of interest(Reixach *et al.*, 2015).

Concerns on the ability and capability of natural fibres which categories as green material are discovered with several works and were to be enrolled as sound absorber. Researcher Yang employed rice straw-wood particle board to substitute wood. Comparison was made between common industrial plywood and rice straw-wood particle board for analysis. The outcome was that the rice straw-wood particle with lower specific gravity gives better sound absorption at range of 1-8 kHz compared to the plywood (Yang *et al.*, 2004). The potential of waste industrial tea-leaf as an acoustics material also exposed to green recycle environment by (Ekici, Kentli, and Küçük, 2012). The tea-leaf`s acoustical properties significantly increases when backing with a single woven cotton cloth and giving better sound absorption solution. Some studies on coir fiber have also been done to investigate the effect of perforated facing, multiple-layer sequence and the compression on its acoustical performance. Numerical and empirical data was established to support the experimental data. Overall results stated that, coir fibre is has a good acoustical performance naturally and good sound absorption at medium and high frequency range, 1.5 kHz - 5 kHz (Hosseini Fouladi, Nor, Ayub, and Leman, 2010), (Verma, Gope, Shandilya, Gupta, & Maheshwari, 2013).

Even, jute fibre also has been experimentally investigated of its acoustical performance by (Fatima and Mohanty, 2011). They concluded that jute fibre without any treatment gives better acoustical properties compared to the sample with treatment at 1-4 kHz. Also the flammability is also equivalent to that of the common synthetic fibres.Other than that, a preliminary study on acoustical performance ofmesocarp fibre which are natural fibre obtain from waste of oil palm was investigated previously in Acoustic and Vibration Research Group laboratories, UniversitiTun Hussein Onn Malaysia*(Latif et al.*, 2015). Their study results thatmesocarp has good potential character in acoustical properties when exposed tomedium to high frequency (1.6 kHz - 5 kHz) within the range of 0.7 to 0.90 sound absorption values.

Good acoustical performances are the basis of well-established physical principles; the final material structure, itsporosity and resistivity are the features which are important in acoustic properties. As a prime consideration of acoustic reflection, bulk density of a material is an intimate binding of the particulates thus will be required for sound absorption materials(Delany and Bazley, 1970), (Jones and Kessissoglou, 2015). A study by Koizumi *et al.* (2002) showed the increase of sound absorption value in the middle and higher frequency as the density of the sample increased (Seddeq, 2009).Additional to acoustical performance evaluate, open pores structure where the pores are interconnected is the key to sound absorption as structure increases air flow resistivity and consequently the dissipation of sound energy. Due to that, porous rich materials areused to avoid the resonance of the air cavity. When the cavities of the resonance are not dissolved by damping, sound will go through the partitions easierand will result in poor sound absorption condition (Cox and D'Antonio, 2009).In the case of (Matyka, Khalili, and Koza, 2008) proved that, porosity and tortuosity holds important relation between the acoustical performance and the sample surface. One more useful parameter which determines sound-absorptive and sound-transmitting properties of acoustic materials is the flow resistivity (Joshi *et al.*, 2011). In research by (Rey *et al.*,2013), it is confirmed thatflow resistivity give compatible results and influence the acoustical performance for thin layers of loose granular materials.

In this work, another potential natural fiber to be an alternative for acoustic material, namely ArengaPinnata known as Ijukfibre that mixed with natural rubber, latex which according to author`s knowledge has yet been discovered. The objective of the study is to find the influence of the mixing ratio of natural rubber on the acoustic properties of the composite materials. As aadditional support for the impedance tube result and the fast approximation and pre, Delany-Bazley empirical method was executed. This study is also to explore the interconnection between acoustics and the material's physical properties such as density, porosity, tortuosity, and air flow resistivity which derived towards a better acoustical performance to replace synthetic fibres as sound absorbers.

BACKGROUND OF ARENGA PINNATA AND NATURAL RUBBER

ArengaPinnata

Among the substitute material obtained from green resources, ArengaPinnata, the scientific family name for a kind of sugar palm plant fibre was choose to study their acoustical performance. ArengaPinnata fibre, known as Ijuk, is green natural resources that directly obtain from the trunk of sugar palm.Before the modern era, ArengaPinnata has been widely used in everyday products such as broom, brushes, mat, roof and even as water filter (Mogea, Seibert, and Smits, 1991), (Ismail and Ghazali, 2010). The features of ArengaPinnata fibres such as easily available in low price; strong and durable in any typical environment condition induced it to be used in this study. The previous investigation on ArengaPinnata by (Bachtiar, Sapuan, and Hamdan, 2010) are appropriate for composite material components. As comparable in green fibres, Arengapinnata fiber has moderate tensile strength that almost equal to coir, Kenaf, bamboo in the range of 138.7 - 270 MPa(Ishak, Sapuan, Leman, Rahman, and Anwar, 2011). Recently (Ismail and Ghazali, 2010) stated thatArengaPinnatais also capable as sound insulation material which are made of composite with polyurethane. Tactlessly there is no study on ArengaPinnata mix with natural rubber. Hence this study is toproducesamples made fully by natural resources and to obtain its acoustical performance.

Natural rubber (latex)

Natural rubber is an amorphous material among the non-synthetic rubber, but has a very strong matrix due to its strain-induced crystallization(Nunes, 2014). It also contain good mechanical properties that gives the capability to be used as filler or binder(Verma *et al.*, 2013).The primary effects of short fiber reinforcement on the mechanical properties of natural rubber composites include increased modulus, decreased elongation at failure, and greatly improved creep resistance, increased hardness and a substantial improvement in cut, damping and processing economy, tear and puncture (John, Anandjiwala, and Thomas, 2009). Reinforcing the natural rubber with renewable resources, such as plant-based natural fibers, for the production of bio sustainable composite materials can be a potential alternative for synthetic materials. The most widely used natural rubber as filler/binder for natural fibres composites are jute, bagasse, bamboo, coir fiber, oil palm fibre and sisal. On the other hand, widely used synthetic chemical binders arepolyurethane and other paste used by combined together.(Sambu *et al.*, 2015), (Verma *et al.*, 2013), (Geethamma, Kalaprasad, Groeninckx, and Thomas, 2005).

METHODOLOGY

In this paper, two methods were used for acoustical analysis of ArengaPinnata fibrebonded with natural rubber in various ratios atnormal incidence sound absorption. First, the normal incidence results obtainusing Impedance tube is followed by ASTM E1050, two-

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microphone method. As a support for the impedance tube result and for fast approximation, Delany-Bazley empirical method was executed. Before performing these tests, physical properties of the ArengaPinnata fibres such as bulk density, porosity, tortuosity, flow resistivity, and fibres structure character are also investigated.

1. Preparation of ArengaPinnata as absorber sample

The preparations of ArengaPinnata from fibers into absorber sample are allocated into two stages. There are the pre-treatment stage and fabrication stage. In the pre-treatment stage, the long raw fibres are crushed into smaller length to make the fabrication process easier. Then the fibres are washed with clean water to remove any damagedbast and dirt's. After a good wash, the fibers are soaked in alkaline treatment for 24 hours straight to remove its cellulose layer and unwanted properties of the raw fibres. It was then sundried and further heated in the oven,until to evaporate the excess water in the fibers.In the preparation stage, the treated ArengaPinnata fibres are mixed with different composition of binder. The binder used in this procedure is natural rubber obtained from local rubber tree farmin form ofliquid.Using a cylindrical mould, the mixture was place inside and hot-pressed to melt the natural rubber and bond well with the fibres to obtain a cylindrical shape sample pieces. Each produced absorber sample has a diameter of 100mm for low frequency and 28mm in diameter for high frequency to fit in the impedance tube diameter in the sound absorption test as seen in Figure 1. Totally there are four different ratiosof fibers to binder samples are produced such as; 100:0, 80:20, 70:30 and 60:40. All samples are fixed at 50mm thickness as it isalreadybeen proved that thickness of samples has influence on the sound absorption coefficient of the material from previous researcher (Ismail and Ghazali, 2010).

2. Physical measurement

2.1 Bulk density

Previous studies have based their density measures for sample using principle of Archimedes (Voronina and Horoshenkov, 2003). The weight of the dry fibre sample was measured and recorded by placing it on the weighing tray first. Then, the same sample was placed in a net bucket which was then dipped fully inside the water and the weight of the immerse fibre sample were also recorded

Figure-1. Absorber sample of ArengaPinnata.

using Equation.1. Where, W_d is weight of dry sample in gram; $W_s$weight of sample saturated in water and ρ_w density of water.

$$\rho_s = \frac{W_d}{W_d - W_s} - \rho_w \quad (1)$$

2.2 Porosity

Many previous research have declared the important of porosity on calculating the acoustical absorptive properties of porous material(Biot, 1962), (Latif *et al.*, 2015). Direct measurement of the open porosity was performed using the same Archimedes principle of porosity by using Equation.2.

$$\phi = \frac{W_d}{W_s} \quad (2)$$

2.3 Tortuosity

Tortuosity is the measurement of the elongation of the passage way through the pores, compared to the thickness of the sample. According fundamental algorithmby (Umnova, Attenborough, Shin, and Cummings, 2005), the tortuosity calculated by using Equation.3.

$$k = \frac{1}{\sqrt{\phi}} \quad (3)$$

2.4 Air flow resistivity

The most critical parameter which used to describe the acoustic absorption character of fibrous material is the air flow resistivity. Those materials in fibrous category are anisotropic and it depends on the air flow direction through the material(Yang *et al.*, 2004). There is a close relationship between air flow resistivity, density and porosity. Apart from that, air flow resistivity, σ was measured experimentally using ISO 9053, Determination of airflow resistivity apparatus σ_{exp} ,whereby steady stream of air flow through a sample of fiber material placed in a tube. The flow resistivity calculated using Equation. 3(Cox and D'Antonio, 2009).

$$\sigma = \Delta p / VL \quad (4)$$

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At Equation. 3 where the Δp indicate pressure decreases over the sample, V is the steady state velocity, and L is thethickness of the sample which is 50mm as measured.

2.5 Morphological characteristics

The possibility for the binder to form the bond at the interface is mainly dependent on the surface morphology and treatment of the fibre(Sreekala *et al.*, 2000). Morphological analysis was accomplished to observe the comparison between topology and fiber pull-out of the samples using Scanning Electron Microscope (SEM) Model JEOL JSM-7600F and Digital Microscope Scan, Model NIKON LV150NL. This advance scanning analyser helps to understand the characteristics before and after samples preparation.

3. Acoustical measurement

3.1 Normal incidence sound absorption coefficient

The measurement of sound absorption coefficient (denoted as (α) was performed in an impedance tube by applying two-way microphone transfer function method according to ASTM E1050-09. The measurement setups for this test are followed as in Figure 2. At the end of the impedance tube, the sample was placed and backed by rigid surface. The amplitude loudspeaker feeds white noise signal into the tube where the incident and reflected sound pressure are recorded by the microphones. Then the data processed to have the absorption coefficient of the sample. Analysercalled 'dBFA' with SCS 8100 software was used as the data acquisition system. The signal processing of the measured data was done using graph plotting tool. With diameter of the tube i.e. 100 mm, the consistent frequency range for this experiment is between set between 90 Hz to 1.8 kHz for low frequency mode. For the high frequency mode, i.e 28mm is the diameter of tube for range of 450 Hz till 7.1 kHz.

Figure-2. Impedance tube.

3.2 Empirical model delany-bazley

The first empirical model equation for equivalent fluids provided by Delany-Bazleyis based by measured on acoustical properties. These model method are applicable for many noise control materials (Jones and Kessissoglou, 2015). Moreover this empirical model is the fastest prediction and effective because the measurement are not dimensionalised (Kirby, 2014). This first empirical model is chosen for this study as it easily considered with few parameters of fibrous materialsuch as bulk density and air flow resistivity. Also, this paper is just the preliminary study based on Delany-Bazley model to make an investigationpracticefor ArengaPinnata fiber bonded with natural rubber and to be a supportive result for the impedance tube result of sound absorption. Considering the effects of porous materials with porosities close to one on acoustic absorption, and can be presented as follows:

$$k_c = k_a \left[1 + 0.0978\left(\frac{\rho_a f}{\sigma}\right)^{-0.7} - j0.189\left(\frac{\rho_a f}{\sigma}\right)^{-0.595}\right] \quad (5)$$

$$Z_c = Z_a \left[1 + 0.057\left(\frac{\rho_a f}{\sigma}\right)^{-0.734} - j0.087\left(\frac{\rho_a f}{\sigma}\right)^{-0.732}\right] \quad (6)$$

$$c_c = \frac{\omega}{k_c}, \;\; \rho^c = \frac{k_c Z_c}{\omega}, f = \frac{\omega}{2\pi} \quad (7)$$

Wherek_a and ρ_a are signified to the wavenumber and the density of air without pressure attenuation respectively. The complex wavenumber and empirical material model`s impedance of Delany-Bazley are k_c and Z_c respectively.It is noted that, the formulation of empirical method shown in Equations. 5-7 is based only on measurement of airflow resistivity, σ which is highly reliant on the chosen fibrous material. Also, these very useful expressions only depend on the (Cox and D'Antonio, 2009). As mention above, this first model is widely acceptable and work well for fibrous material over normalized frequency range of $\rho_a f/\sigma$ from 0.01 to 1. The data was also obtain and stated in Table-1 for this ArengaPinnata study.

RESULT AND OBSERVATION

Physical properties analysis

The first step was to obtain the physical properties of ArengaPinnta mixed with various ratio of natural rubber which are presented in Table-1. The table shows an increase inArengaPinnatadensity from 30.32 kg/m^3 to the highest density of94.42 kg/m^3 as the binder mixing ratio increase from 100:0 to 60:40. This clearly states that higher ratio of binder results in higher density of ArengaPinnata. This result agree to that fact that samples having different density will give different behaviouron sound absorption, meanwhile the fibrous material`s porosity is influenced by the density of the specific material or sample (Mahzan and Zaidi, 2010). On the porosity column in Table-1, each sample`s porosity are stated.

Table-1. Physical properties of ArengaPinnata fiber that mix with natural rubber.

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Mixing ratio		Density (kg/$\mathbf{m^3}$)	Porosity	Tortuosity	Air flow resistivity, σ ($\mathbf{NSM^{-4}}$)
ArengaPinnata	Natural rubber				
100	0	300.32	0.85	1.09	11382.67
80	20	632.17	0.76	1.15	16546.47
70	30	824.93	0.71	1.18	27891.93
60	40	941.42	0.65	1.24	32675.76

Referring to that, values of porosity is inversely proportional to the ratio of natural rubber mixed with ArengaPinnata fibre. Where, 100:0 of samplein the highest value of porosity. High porosity value indicates that the pores and micro gaps are more random. With 80:20 ofArengaPinnatafibre innatural rubber mix, it allows more gaps to exist compare to samples that holding in 60:40 of natural rubber as binder. This is due to the fact that higher ratio of binder covers up and dissolves the pores and micro gaps inside the samples. Prior studies that have noted the importance of porosity state that fabrication of nonwoven type sample have a high sound absorption coefficient; porosity should increase along the propagation of the sound wave. As for the physical character such asdensity, porosity and airflow resistivity are the inbound parameters which playsan important role in acoustical performance. Fromthe obtained result that presented at Table-1 it can observe that there are some relationsin between these three parameters. In all the prepared ArengaPinnata fiber samples, increase in bulk density of the sample results an increase in flow resistivity and a reduction in porosity where the lower numerical value of flow resistivity gives best absorption.This is in agreement to the fact that, in all ordinary forms of porous sound absorbing materials, the viscous resistance or know as flow resistance of air in the porous material has an important influence on the sound absorption mechanism(Cox and D'Antonio, 2009).It alsorevealsthat the pore and structure of the samples are increasing as the natural rubber binder usage getslower. When more pores and gaps appears in the structure, airflow or viscous also get thrown in to plays their role. The same incident occurs when sound wave pass throw the sample and dissolves between the gaps.

The morphological observation under scanning electron microscope (SEM) and microscope scan wereillustrated in Figure-3. Where, Figures 3(a) and 3(b) displays the pre-treated and untreated of ArengaPinnatawhile Figures 3(c) and 3(d) shows the Digital Microscope Scan photographs of prepared samples' surfaces upon different reforms.As can be detected from the image 3(a) and (b), alkaline treatmentanalysis reveals that it will remove the impurities and smoothness the surface of ArengaPinnata fibres. It alsohelps by creating better interlocking between binder and the fiber. This is a strong evidence for the physical microstructural changes occurred to the ArengaPinnata samples surface. The shiny gummy-look in Figure-3(c) is the image of natural rubbers bonded well with ArengaPinnata fibre. Sample in Figure-3(c) has more pores and micro gaps compare to (d) which is bonded with melted natural rubberthat creates better interlock in the structure. The higher the ratio of natural rubber in the sample, the stronger the bond gets. But this also causes the samples to be poorin acoustical performance because the pores and micro gaps are already filled up by the natural rubber.

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

Figure-3. Scanning electron micrographs of the ArengaPinnatafibre surfaces (a) Untreated fibres, (b) Pre-treated, digital microscope scan (c) Without binder natural rubber, (d) With binder natural rubber.

Acoustical properties analysis

Sound absorption coefficient of ArengaPinnata bind with natural rubber*:* Result ofsound absorption coefficients of ArengaPinnatafibres bonded with natural rubber were graphically show in Figure-4, which are measured from the impedance tube test on four variousratio of mixingthat covers from low to high frequencies. In this study, the mixing ratiovaries from 100:0, 80:20, 70:30 and 60:40 but all samples have constant thickness of 50mm. The 100:0of natural rubber samples which is pure fibre prepared without binder gives a result of wave pattern that covers up to both mid-low and

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high frequency. At 1300Hz and above 4200Hz frequency, it achieves nearly 0.9 in sound absorption coefficient. Although this is a good coefficient value, still in low frequency below 1000Hz, the value is slower in moving towards better coefficient compare to samples bonded with natural rubber. The samples thatare bonded with binder give a very good absorption coefficient results. The natural rubber mixed porous samples shows more than 0.8 in absorption coefficient value even lower frequency, 1000Hz. Among the three ratio mixed samples, which is 80:20, 70:30 and 60:40; 80:20 of natural rubber mixture gives the high absorption with distinct peaks with an absorption coefficient value of 0.98 that appeared around 1000 Hz. Henceit can conclude that with 80:20 of the binder, the sample has a good airflow resistivity and porosity which also stated in Table-1.This proves that ArengaPinnata fibre bonded with natural rubber is capable to be used in sound absorber application.

Empirical Model Delany-Bazleyprediction comparison: This verification using empirical model Delany-Bazley was carried out to compare the experimental results of impedance tube method for 100:0 and 80:20 of mix samples only. This is due to the fact that 80:20sample gives the better acoustical performance and high potency in absorption coefficient value compare to other two ratios of60:40 and 70:30 while 100:0of binder gives the exact acoustical character of pureArengaPinnata fibre. The prediction and experimental result for both samples are plotted together in Figures 5(a) and 5(b). According the graph in Figure 5(a) and 5(b), the experimental measuredplots falls fairly well with empirical prediction graph. Empirical result of 80:20 has more similaritywith the experimental result compares to the 100:0graphs. However, the results also show that empirical model plot is unable to predict the resonance peak at exact frequency. This may be due to the frame resonance and also, Delany-Bazley model did not consider bulk modulus of elasticity. However the empirical results achievesameperformance value of sound absorption coefficient with experimental result for both samples100:0 and 80:20. This shows that Delany-Bazley modelis capable to be usedto identify the preliminary founding of acoustical performance before proceeding to experimental stage whichrequiresmore cost and time.

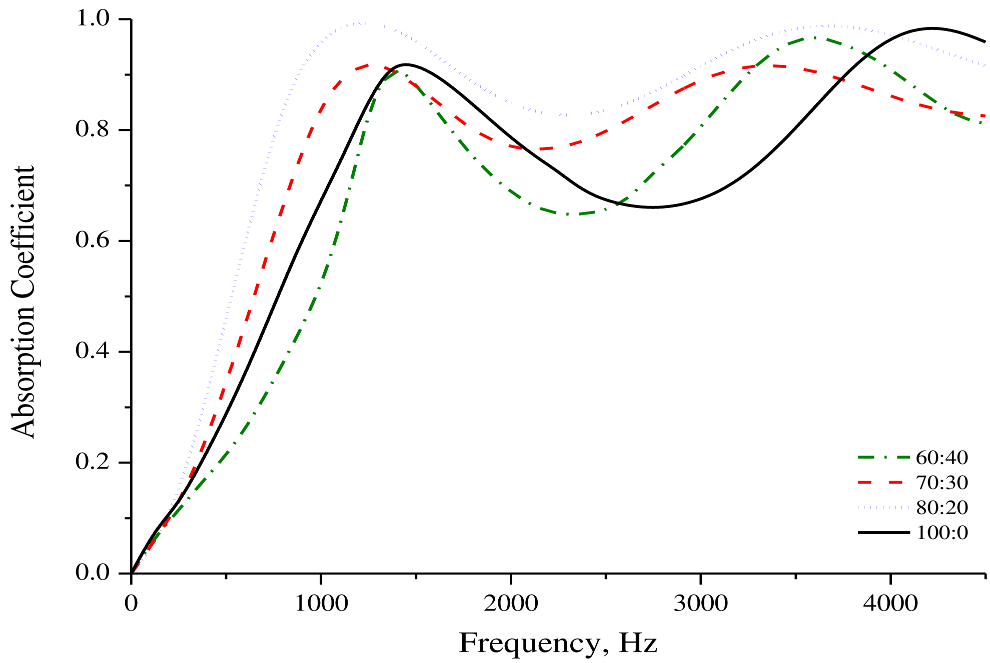
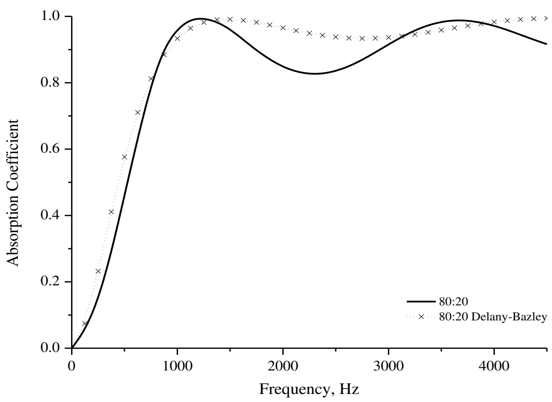


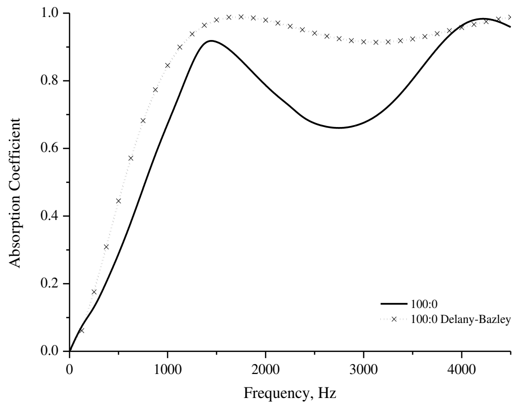
Figure-4. Acoustic absorption coefficient of ArengaPinnata fibre binds with natural rubber on 50mm thickness.

CONCLUSIONS

In this investigation, the sound absorption coefficients of ArengaPinnatafibre mixed with natural rubber as binder have been tested. Analyses from this study give an overall knowledge about the factorsthat influence and able to enhance the absorption of ArengaPinntafiber. The results are discussed in term of physical and acoustical properties. This indicates that both play an important role in the improvement of sound absorption. The effect of density and porosity of this porous material made from natural fibre distinctly promotes acoustic absorption with decreasing natural rubber`s binder mixing.80:20 of mixture is a better sound absorbent compares to 60:40 of mixture. But increasing the ratio of binder with ArengaPinnata fibre increases the airflow resistivity value and slightly moves the absorption peak towards lower frequencies. These results reveals that more strategically designed layers and configurations of ArengaPinnata fiber could increase the sound absorption value effectively.

An empirical model by Delany-Bazley for theoretical prediction also has been obtained. It can justify the overall trend of the ArengaPinnata fibre`s absorption spectrum. But this is just a preliminary assumption to understand the normal incidence of ArengaPinnata fibre`s acoustical performance. For more better prediction of overall absorption including the frame resonance, more sophisticated with additional physical measurements model like Johnson-Allard(Allard, 1992)can be used. It will be carried to future works.





(a) 14.7%

Figure-5. Acoustic absorption coefficient of experimental and empirical model prediction on ArengaPinnata binds with natural rubber, *(a)* Result of 100:0 mixing sample (b) Result of 80:20 mixing sample

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(b) 7.5%

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