

PERFORMANCE OF WOOD COMPOSITES WITH NATURAL FIBER AS SOUND ABSORBER OF BUILDING MATERIALS

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Abstract

Natural fibers are an alternative to reduce the use of synthetic materials in acoustic products. Such fibers have the benefits of being inexpensive, environmentally benign, biodegradable, and safe for human health. The influence on sound absorption coefficient of different natural fibers including rubberwood, coconut coir, and oil palm empty fruit bunches was investigated. The samples were composed of three kinds of natural fibers, three different fiber sizes, and two different kinds of adhesives. The porosity values of the samples were found in the range of 4.58-8.84% whereas the lowest water absorption value was found on the sample with rubberwood fiber in the range of 57.62-127.83%. Impedance tube testing was used for the sound absorption tests following ISO 10534-2. The experimental result revealed that the natural fibers have good performance associated with the fiber length. The longer fiber performs the better sound absorption than that of the short fiber. All kinds of natural fiber plates tested had sound absorption of 50% above 3.5 kHz whereas the oil palm fiber gave the highest absorption coefficient at 95%. The fiber size fraction approved that those fibers could improve the peak values of sound absorption. The small fiber size gave higher peak values than that of the large fiber size. The type of adhesive influences sound absorption coefficient on the sample with small fiber size (80 mesh) than that of the large fiber size (40 mesh). The output of this study reveals the waste plant fibers could adopt to develop sound absorber building materials.

Keywords: Sound absorption, Natural fiber, Oil palm fiber, Coconut Coir, Rubberwood fiber

Introduction

According to the World Health Organization (WHO), noise pollution is ranked second as an environmental cause of health problems. That report also presents effects of noise pollution on human health, as it contributes to ischemic heart disease, chronic high annoyance, and chronic high sleep disturbance. Furthermore, exposure to loud noises for an extended period of time (sound levels above

100 dB) might lead to permanent hearing loss. (Kukreja, 2021). One method to control noise pollution is to reduce the noise level by using an acoustic material, and this is an important element in the industrial noise control systems (Pedroso *et al.*, 2017). Such materials are common in buildings for controlling the quality of acoustics in rooms. Acoustic materials are generally divided

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into two categories, namely sound absorbers and sound insulation. The common acoustic materials are made from synthetic materials such as plastic foam, glass wool, and rock wool, which have desired acoustic properties (Tiuc *et al.*, 2016; Cao *et al.*, 2018). However, a prior study indicates that these synthetic materials can negatively impact human health and environment (Stone *et al.*, 2020). Recently, researchers have reported that natural fibers have the least impact on human health and environment, while having good acoustic performance. In addition, natural fibers can have equally good acoustic performance as the synthetic materials, rock wool, and polyurethane foam (ALRahman *et al.*, 2013; Berardi and Iannace, 2015; Putra *et al.*, 2018; Cherradi *et al.*, 2021).

The acoustic performance of natural fiber was investigated in relation to material properties, sample specification, and test arrangement. Natural fibers from different plant species were characterized for their material properties in prior studies that have reported density, fiber diameter, porosity, and air flow resistivity. However, these properties of natural fibers depend on the type of natural fiber. Various natural fibers have been reported to give good sound absorption in the range from middle to high frequencies, namely kenaf fiber, corn husk, coconut coir, date palm fiber, and wood fiber (ALRahman *et al.*, 2013; Berardi and Iannace, 2015; Ganesan and Karthik, 2016; Berardi *et al.*, 2017; Lim *et al.*, 2018; Tang *et al.*, 2018). However, few studies were found in the literatures to compare the characteristic of different fiber under the same factor. Furthermore, the sample specifications are known to affect the acoustic performance. For example, increasing density of the sample could increase its sound absorption. Prior researches have also proven that increasing thickness of the sample increases its sound absorption (Xiang *et al.*, 2013; Chin *et al.*, 2018; Lim *et al.*, 2018). Additionally, a higher density of the sample could increase sound absorption coefficient due to an increasing amount of adhesive (Berardi and Iannace, 2017; Taban *et al.*, 2020). However, regarding the type of adhesive, its potential effects on sound absorption coefficient were not addressed in the literature reviewed. Therefore, the main objective of this current study was to characterize the behavior of natural fibers in the sound absorption under the same density and thickness conditions. The natural fibers tested, collected from local industry in Thailand as waste materials, are rubberwood sawdust, coconut coir, and oil palm empty fruit bunches. In addition, the effects of fiber size of the natural fiber on sound absorption coefficient were also assessed. Regarding the adhesive added in the sample,

the effects of alternative adhesives on sound performance were scoped. Two types of adhesives were chosen including urea formaldehyde as a toxic adhesive and sucrose and citric acid as non-toxic adhesives. This study aims to primitive adhesive as toxic material to compare with the non-toxic material as sucrose and citric acid. The comparison is approved to provide the choice of adhesive used in acoustic materials.



Figure 1. The natural fibrous raw materials

Materials and Methods

Materials

The natural fiber samples were collected from local industry in Thailand as waste materials from different industries. These wastes included natural fibers from rubberwood, coconut, and oil palm. The rubberwood sawdust came as waste from the furniture industry (Songkhla, Thailand). Coconut coir and oil palm empty fruit bunch fibers were supplied from a local fertilizer factory (Nakornsrihammarat, Thailand) and a palm oil extraction mill (Nakornsrihammarat, Thailand), respectively. The appearances of these materials are shown in Figure 1. The natural fibers were comminuted to smaller particles in a blender. The particles were then sieved to three size classes, below 420, 250, and 177 μm (40, 60, and 80 mesh) as displayed in Figure 2. The urea formaldehyde was purchased from k.kosmik Co., ltd. (Bangkok,

Thailand) and sucrose mix and citric acid were supplied by Intereducation Supplies Co., Ltd. (Bangkok, Thailand), and Vidhyasom Co., Ltd. (Bangkok, Thailand), respectively, for use as adhesives.

The fabrication of samples

Prior to compounding, all the natural fibers were dried in an oven at 110°C for 8 h. The

formulation of sound absorber composites was chosen from previous studies (Anisuzzaman *et al.*, 2014; Umemura *et al.*, 2015) and is shown in Table 1. The natural fiber was mixed with adhesive in a mixer. The particle mixtures were formed into panels by using a compression machine at 110°C for 10 min. The bulk density and thickness of the sample were held constant. The bulk density is defined as the mass of the natural fiber mix with adhesive, m , divided by the total volume of the cylindrical shaped sample V , and denoted by $\rho_{bulk} = m/V$. The density of the sample was kept constant at 150 kg/m³. After fabrication, the samples were tested again with the method of weighing by volume. The bulk density value of all samples has fallen within the range of ± 15 kg/m³ from the calculated bulk density. The thickness of the natural fiber samples was manipulated by selecting thickness of the rectangular die as 4 mm. Finally, the samples were cut into specimens for sound absorption testing according to ISO 10534-2 (2001), with diameters of 33 and 98 mm, as shown in Figure 3.

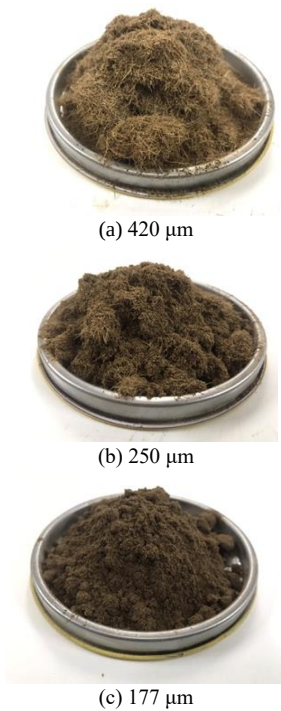


Figure 2. Sieved size fractions of oil palm fiber

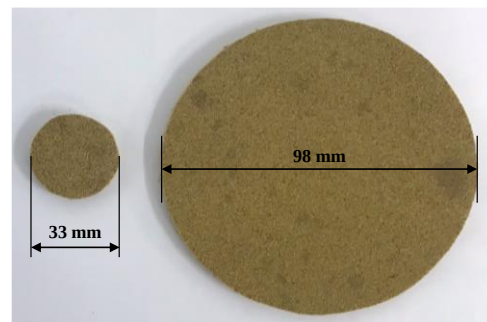
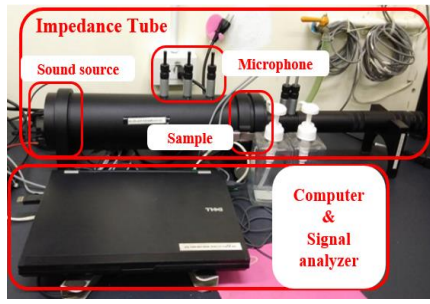


Figure 3. The samples for sound absorption testing

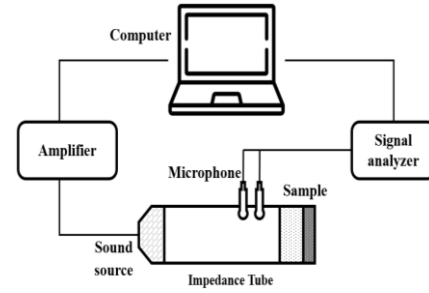
Table 1. Formulation of the sample

The sample code*	Natural fiber	Fiber size	Type of adhesives
10UF90RW40	Rubberwood	420 µm	Urea formaldehyde 10 wt%
15S5C80RW40		(40 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90RW60		250 µm	Urea formaldehyde 10 wt%
15S5C80RW60		(60 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90RW80		177 µm	Urea formaldehyde 10 wt%
15S5C80RW80	Coconut	(80 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90CC40		420 µm	Urea formaldehyde 10 wt%
15S5C80CC40		(40 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90CC60		250 µm	Urea formaldehyde 10 wt%
15S5C80CC60		(60 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90CC80	Oil palm	177 µm	Urea formaldehyde 10 wt%
15S5C80CC80		(80 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90OP40		420 µm	Urea formaldehyde 10 wt%
15S5C80OP40		(40 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90OP60		250 µm	Urea formaldehyde 10 wt%
15S5C80OP60		(60 mesh)	Sucrose 15 wt% with citric acid 5 %
10UF90OP80		177 µm	Urea formaldehyde 10 wt%
15S5C80OP80		(80 mesh)	Sucrose 15 wt% with citric acid 5 %

*The sample code summarized the formulations, such as the code 10UF90RW40 was consisted of 10 wt% urea formaldehyde, 90 wt% rubberwood flour 40 mesh.



(a) Sound absorption testing setup



(b) A schematic diagram of sound absorption testing

Figure 4. Sound absorption testing

Sound absorption testing

The experimental setup followed ISO 10534-2 (2001), using an impedance tube as shown in Figure 4. The diameters of the impedance tubes were 33 and 98 mm for measuring sound absorption coefficients in the frequency range of 500-6,400 Hz due to the constraints of diameter tube, size, and sensitivity of the microphone (Lim *et al.*, 2018). The sample was located at the end of the tube, while a speaker that generated white noise was at the other end of the tube. Five replicates of each sample formulation were tested. Sound absorption testing machine and diagram are shown in Figure 4.

Morphological analysis

The interfacial morphology and arrangement of the natural fibers in the sample structures were assessed by imaging with a digital microscope. The surfaces were prepared by cutting the sample in cross sections to see the content and arrangement of inner material, with a magnification of 5 $\times$.

Physical testing

The porosity and water absorption were characterized with five replicates of each sample formulation in table 1.

Water absorption testing

The water absorption is an important element of physical properties of the sample. It is a known fact that the water absorption test is conducted on dry mass of sample before dip and soak in the water in order to have a saturated mass of sample. The sample was basically dried in the oven at 80°C for 12 h. After that, it was soaked in the water at room temperature for 24 h. The water absorption (W_a) is calculated following in the Equation (1).

$$W_a = (W_w - W_d)/W_d \quad (1)$$

whereas W_w is the water-saturated mass and W_d is the dried mass. The water absorption values will be used to calculate the porosity of the samples.

Porosity properties

The porosity is the percentage of void space in the sample. The porosity value, n , is calculated in terms of dry bulk density, ρ_b , and the particle density, ρ_m , following in the Equation (2).

$$n = 100(1 - (\rho_b/\rho_m)) \quad (2)$$

whereas ρ_b and ρ_m are defined as the dried mass, W_d , divided by the volume of sample, V , and the volume of the particles, V_s , respectively. Therefore, the water absorption value could convert to porosity values to identify the characteristic of sample.

Results and Discussion

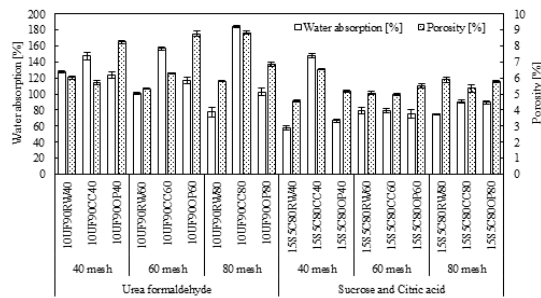
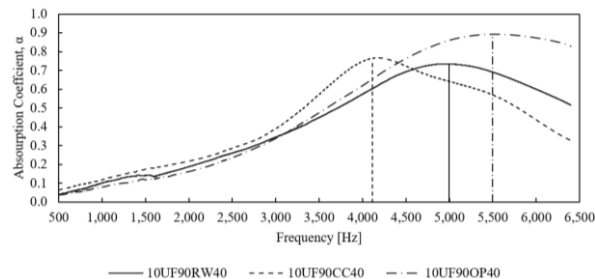
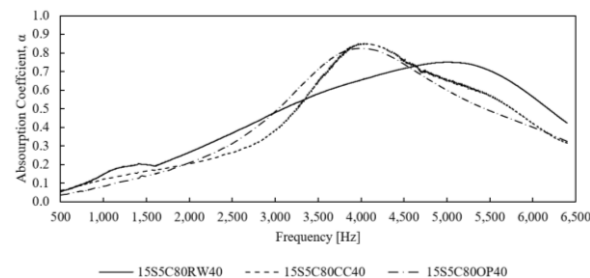
The results of samples were reported regarding to effect of natural fiber types, fibers size fraction, and adhesive types on sound absorption coefficient. This allows us to deduce the relation of physical properties such as water absorption and porosity to the sound absorption coefficient as shown in Table 2 and Figure 5. The porosity values of the composites with rubberwood fiber, coconut coir, and oil palm fiber are found in the range of 4.58-6.02%, 4.98-8.83%, and 5.19-8.84%, respectively whereas the water absorption values of the composites with rubberwood fiber, oil palm fiber, and coconut coir are in the range of 57.62-127.83%, 66.57-123.37%, and 79.05-184.01%, respectively. The effect of water absorption and porosity is discussed in the sequential parameters of this study.

Effect of natural fiber type

The sound absorption coefficients of samples prepared with different natural fibers, from rubberwood, coconut, and oil palm, were obtained from the ratio of incident energy and absorbed energy for different frequencies, as shown in Figure 6. The results reveal that all the fibers gave good sound absorption coefficients ($\alpha > 0.5$) at middle to high frequencies (3,000-6,000 Hz).

Table 2. The samples for sound absorption testing

The sample code	Porosity [%]	Water absorption [%]
10UF90RW40	6.02	127.83
15S5C80RW40	4.58	57.62
10UF90RW60	5.32	100.82
15S5C80RW60	5.06	79.84
10UF90RW80	5.90	77.38
15S5C80RW80	5.81	74.63
10UF90CC40	5.73	147.19
15S5C80CC40	6.55	147.84
10UF90CC60	6.29	156.88
15S5C80CC60	4.98	79.05
10UF90CC80	8.83	184.01
15S5C80CC80	5.35	90.61
10UF90OP40	8.84	123.37
15S5C80OP40	5.19	66.57
10UF90OP60	8.76	117.33
15S5C80OP60	5.50	75.11
10UF90OP80	6.86	102.77
15S5C80OP80	5.78	89.69

**Figure 5. Porosity and water absorption values****(a) Sound absorption coefficients with urea-formaldehyde adhesive****(b) Sound absorption coefficients with sucrose and citric acid mix as adhesive****Figure 6. Comparison of sound absorption coefficients with various natural fibers (40 mesh fraction)**

The absorption coefficients with the alternative natural fibers (below 177 micron fraction) with urea-formaldehyde as the adhesive are displayed in Figure 6(a). It appears that the oil palm fiber gave the highest peak in sound absorption coefficient reaching 0.9 at 5,500 Hz, whereas the coconut coir and rubberwood fiber gave peak values around 0.8 at 4,100 Hz and 0.7 at 5,000 Hz, respectively, which is in a good agreement with previous studies showing that natural fibers such as oil palm fiber and coconut gave peaks reaching 0.9 at 4,000 Hz and 0.7 at 4,200 Hz, respectively (ALRahman *et al.*, 2013; Berardi and Iannace, 2015; Or *et al.*, 2017; Cherradi *et al.*, 2021). Figure 6(b) shows the results for the natural fibers of the coarsest 40 mesh fraction, when bonded with sucrose and citric acid. It was found that the oil palm fiber gave the highest sound absorption coefficient, while the pattern of sound absorption coefficient was similar with all types of adhesives as shown in Figure 6(a) and 6(b). The result also showed an influence of the highest porosity value on the sound absorption of oil palm fiber as found in Table 2. In addition, both oil palm fiber and rubberwood fiber gave the highest peaks of sound absorption coefficient at high frequencies, whereas the highest value with coconut coir was observed in the middle frequencies. This is associated with the characteristics of these natural fibers.

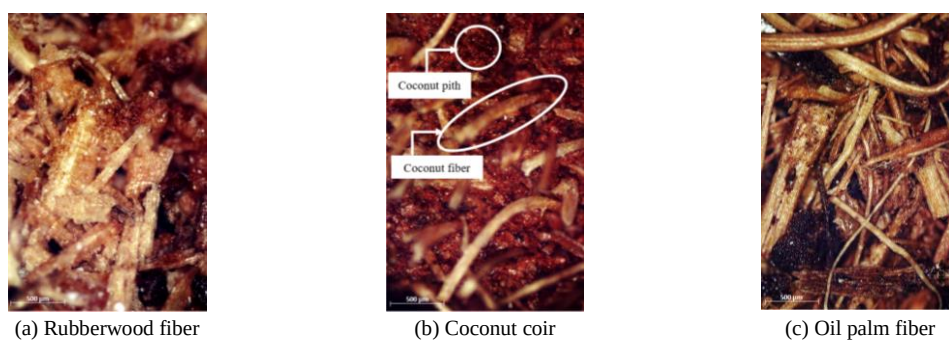


Figure 7. Different natural fibers with urea formaldehyde adhesive (magnification 5×)

Representative samples of each fiber type are shown in Figure 7. It is apparent that the coconut coir consists of coconut pith and coconut fiber as seen in Figure 7(b), whereas rubberwood fiber and oil palm fiber contain only fiber. Therefore, the presence of pith in coconut coir increases the contact surfaces on each fiber, and influences the sound absorption properties (Berardi and Iannace, 2015). In Figure 7(a) and 7(c), it can be seen on comparing oil palm fiber and rubberwood fiber that the former fibers are longer. The long fibers gave a more complex structure than the short fibers. The porous material, theoretically, has many macropores and micropores that are interconnected void space inside the material. This can be viewed as a complicated channel system with many solid frames and capillaries (Peng, 2017). This causes the sound absorption by oil palm fiber to be higher than that by the rubberwood fiber.

Effects of fibers size fraction

A comparison of sound absorption coefficients between the different fiber sizes of rubberwood fiber; 420, 250, and 177 μm , is shown in Figure 8(a). The peak sound absorption coefficient for 420 μm fraction is 0.7 at 5,000 Hz, whereas the 177 μm fiber size gave peak value 0.9 at 3,500 Hz. It is observed that the sound absorption coefficient decreased with size of rubberwood fiber particles, the peak frequency of absorption coefficient increased from middle to high frequency.

Figure 8(b) shows sound absorption coefficients for samples with oil palm fiber at 420 μm peaking at 0.89 and 5,300 Hz. When the fiber size was decreased to 177 μm , the peak was at 0.9 and 3,800 Hz. It seems that the trend in peak of

sound absorption coefficient is similar for oil palm fiber and for rubberwood fiber, as regards effects of fiber size. The trend of sound absorption with an effect of fiber size is also agreed well with the trend of porosity that decreasing fiber size of coconut coir from 420 to 177 μm increases the porosity value from 5.73 to 8.83 resulting to have better sound absorption. In addition, Figure 8(c) shows the sound absorption coefficients with coconut coir of sieve sizes 177 and 420 μm . The 177 μm size fraction gave the higher sound absorption coefficient peaking at 0.95 and 3,800 Hz.

Figure 9 presents the sound absorption coefficients in relation to fiber sizes tested with sucrose and citric acid adhesive. All cases of natural fibers with sucrose and citric acid adhesive gave good sound absorption coefficients in the middle frequency range ($\alpha > 0.5$). Figure 9(a) displays sound absorption coefficients in relation to fiber size of oil palm fiber. The oil palm fiber 177 μm size fraction gave sound absorption coefficient peak at 0.95 and 4,300 Hz. Likewise, the rubberwood fiber and coconut coir in Figure 9(b) and 9(c) display similar trends in sound absorption coefficient.

Finally, the results in Figs. 7 and 8 shown the effects of natural fiber size fraction on the sound absorption coefficient. Decreasing fiber size increased sound absorption coefficient because of a larger number of fibers to increase the surface contact area and density as displayed in Figure 10. Theoretically, increasing the number density of fibers in the sample at a constant density and thickness increases the contact area in a porous material (Nor *et al.*, 2010; Othmani *et al.*, 2016; Mamtaz *et al.*, 2017), and increases the sound absorption coefficient.

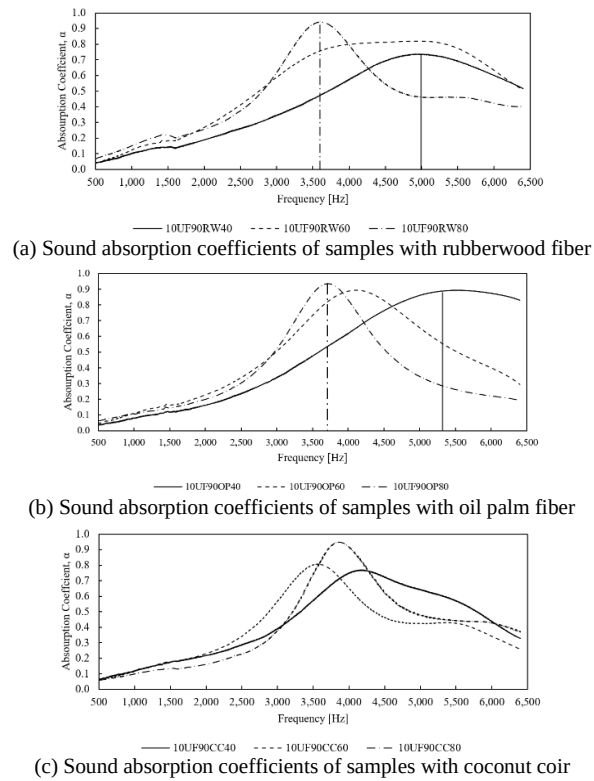


Figure 8. Comparison of sound absorption coefficients with various natural fibers (40 mesh fraction)

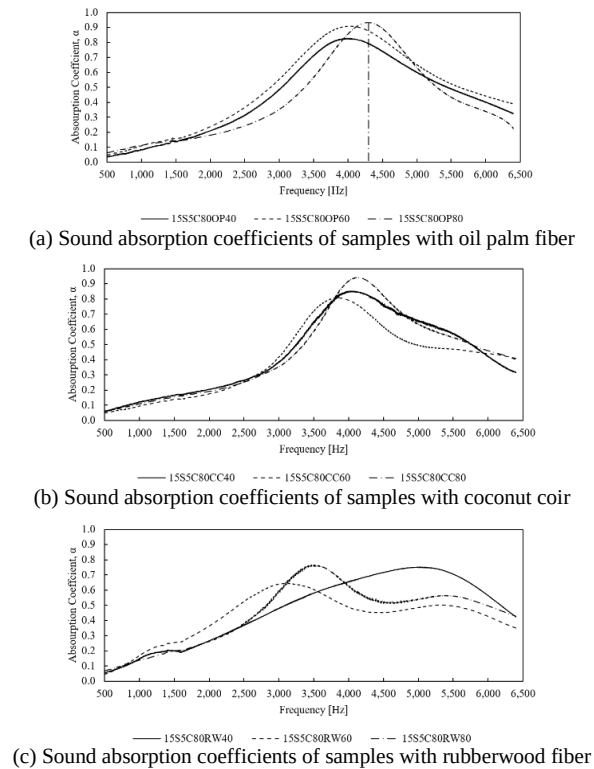


Figure 9. Comparison of samples with different fiber size fractions, with citric acid adhesive

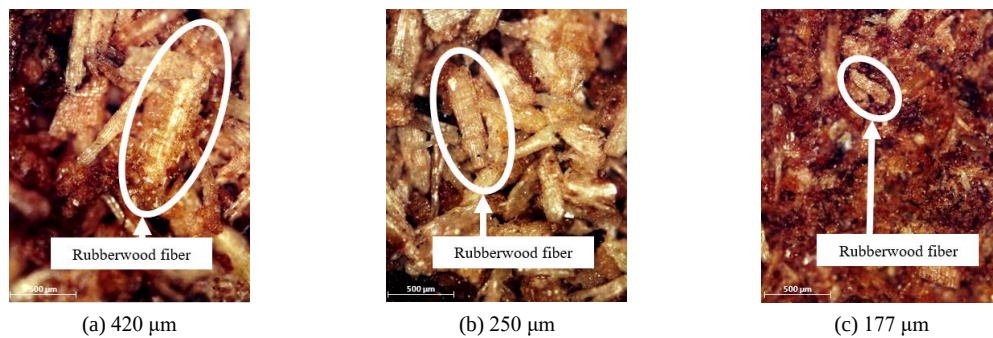


Figure 10. Rubberwood fibers of the different fiber size fractions in samples with urea formaldehyde adhesive (magnification 5×)

Effects of adhesive type

The influence on the sound absorption coefficient of different type of adhesive including urea formaldehyde and a combination of sucrose and citric acid was assessed. The sound absorption coefficients of the composite sample with fiber size of 40 mesh are shown in Figure 11. It is noticed that rubberwood fiber gives similar results with urea formaldehyde as with sucrose and citric adhesive, as seen in Figure 11(a). Likewise, in Figure 11(b) the sound absorption coefficient of coconut coir is also similar with urea formaldehyde as with sucrose mixed with citric adhesive. However, the oil palm fiber with sucrose and citric acid adhesive reached $\alpha > 0.5$ in the frequency range 3,100-5,400 Hz, whereas with urea formaldehyde could observe $\alpha > 0.5$ in the frequency range 3,600 - 6,400 Hz. This might be the fact that the fiber was coated by the cured adhesive, resulting to decrease an effect of different adhesive on the sound absorption properties of the samples. The result is in a good agreement with the study of Mamtaz *et al.* (2017) stating that the binder additive has a less significant effect on a performance of acoustic material.

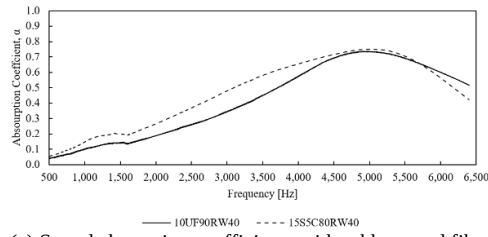
For the fiber size of 80 mesh, the sound absorption coefficients are shown in Figure 12. It was observed that the rubberwood fiber with urea formaldehyde reached the sound absorption peak value at $\alpha = 0.95$ whereas a mix of sucrose and citric acid reached the peak at $\alpha = 0.78$. Nevertheless, the coconut coir and oil palm fiber were found to have similar peak values at $\alpha = 0.95$. The oil palm fiber and coconut coir with a combination of sucrose and citric acid adhesive reached $\alpha > 0.5$ in the frequency range 3,400 - 5,800 Hz and 3,700 - 5,300 Hz, respectively whereas with urea formaldehyde could observe $\alpha > 0.5$ in the frequency range 3,300–4,800 Hz and 3,000 - 4,500 Hz, as can be seen in Figure 12(b) and 12(c). This implies that the different type of adhesive had the higher effect on the sound absorption coefficient at the fiber size of 80 mesh than that of the value of fiber sizes of 40 mesh.

Another notable observation is the fact that the added adhesives affect the porosity properties and

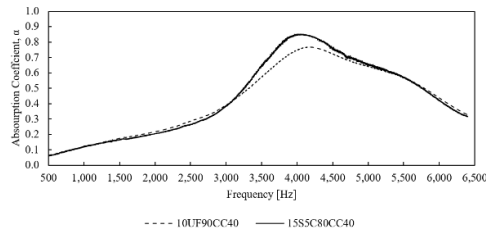
water absorption behavior of the composite sample due to double bonded structure of the sucrose and citric acid as an adhesive whereas urea-formaldehyde has single and double bonds (Wibowo *et al.*, 2021). When the composite sample is soaked in water, the strength of the single and double bonds is lower than that of the double bonds, resulting in the weaker bonding. Therefore, the composite sample with urea-formaldehyde as an adhesive presents poor moisture resistance (de Castro *et al.*, 2021) and has higher percentage of water absorption than that of the composites with sucrose and citric acid as an adhesive.

Conclusions

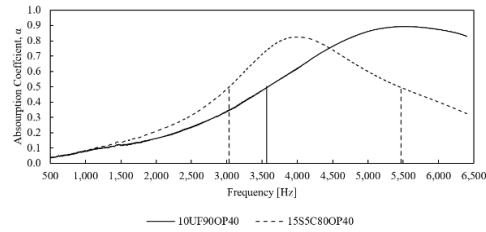
This study reported on the use of natural fibers from agricultural wastes for making sound absorbing materials. The experimental results showed that the all studied natural fibers gave an overall good acoustic performance in sound absorption coefficient of 0.5 above 3.5 kHz. The fiber size has high impact on sound absorption coefficient. The longer size of fiber has more complexity arrangement than that of the shorter fiber. The increasing of complexity arrangement of fiber increases the sound absorption coefficient. The oil palm fiber was found to have the highest absorption coefficient at range 0.5 above 3.5 kHz. In addition, the effects of fiber size fraction indicate that it can be manipulated to improve the sound absorption. Small sized fiber particles gave more absorption than large sized fiber particle fraction. The effects of adhesive type were assessed between urea formaldehyde and mix of sucrose and citric acid, and there was influence on sound absorption coefficient at small fiber size, whereas at large fiber size was little impact on this property. Finally, the innovative aspect of this study was demonstrating that waste plant fibers, such as in rubberwood sawdust, are suitable for making acoustic products. The results of this study could be applied in developing sound absorber building materials.



(a) Sound absorption coefficients with rubberwood fiber

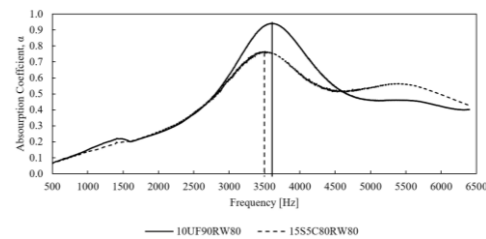


(b) Sound absorption coefficients with coconut coir

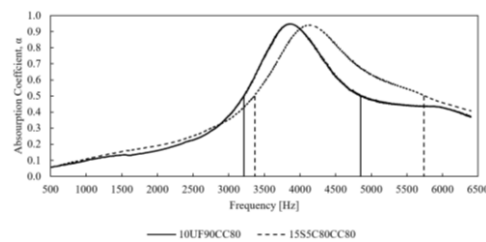


(c) Sound absorption coefficient value of oil palm fiber

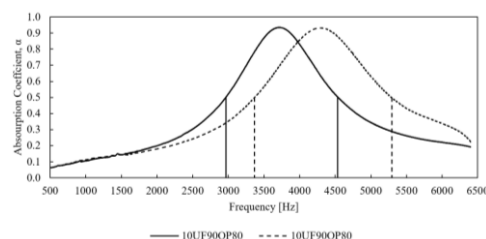
Figure 11. The comparison of two adhesives with fiber size below 40 mesh fraction



(a) Sound absorption coefficients with rubberwood fiber



(b) Sound absorption coefficient value of coconut coir



(c) Sound absorption coefficient value of oil palm fiber

Figure 12. The comparison of two adhesives with particle above 80 mesh fraction

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