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Enhancement of sound absorption of coir fiber using thin layer of kapok fibers

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ABSTRACT
Natural fiber materials are often favored as a replacement to synthetically made sound absorbers due to its comparable sound absorption properties as well as in the effort to reduce the environmental issue. However, studies are weighted heavily on evaluating the performance of a single or composite fiber and only few studies focused on the multi-layer fiber. In this paper, the sound absorption performance of multi-layer coir and kapok fibers is presented. The kapok fiber is used as the assisting layer element for the coir fiber. A combination of coir fibers with different layer thicknesses and with additional 2 mm thick kapok layer shows significant improvement of the absorption bandwidth. It is also found that the kapok fiber layer placed in between the coir fiber layers show the best improvement of the absorption frequency bandwidth.

摘要
天然纤维材料由于其可比的吸声性能以及减少环境问题的努力,通常被青睐作为合成吸声材料的替代品. 然而, 研究主要侧重于评估单纤维或复合纤维的性能, 只有少数研究集中于多层纤维. 本文介绍了多层椰壳纤维和木棉纤维的吸声性能. 木棉纤维用作椰壳纤维的辅助层元件. 具有不同层厚度和附加2mm厚木棉层的椰壳纤维的组合显示出吸收带宽的显著改善. 还发现, 放置在椰壳纤维层之间的木棉纤维层显示出吸收频率带宽的最佳改善.

KEYWORDS
Noise; sound absorber; natural fiber; coir fiber; kapok fiber; sound absorption

关键词
噪音; 吸音器; 天然纤维; 木棉纤维; 声音吸收

Introduction

The manufacturing and decomposition process of synthetic sound absorbers are often associated with environmental pollution and hazardous to humans. Replacement of these materials is focused on the use of green product, which are abundance, biodegradable and has mechanical and acoustical advantages. It is also as an initiative to some new building regulations to increase sustainability. In particular, natural fiber harvested from plant (seed, bast, leaf, fruit, stalk, grass/reed and wood) is among the discussed terms of material to produce new sound absorber (Yang et al. 2020).

Natural fiber although proven to have good mechanical and thermal properties, it still displays some lack such as poor interface bonding, thermal instability, poor water- and fire-resistant (Abdullah et al. 2018; Dilfi et al. 2018). Physical, mechanical, and chemical treatment are therefore used to eliminate the poor characteristics. Loose fibers are commonly hold by building an enclosure composed by porous materials or perforated panel. While alkaline treatment or composite structure made from adding bio-degradable resin (latex, PP or PVA) is the most common chemical modification (Chen et al. 2016; Olcay and Kocak 2021; Tan et al. 2015), adding recycle materials also can improve the strength and acoustical characteristics of fibrous sound absorber.

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Raw kenaf investigated by Lim et al. (2018) shows absorption coefficient $\alpha \approx 0.86$ above 1500 Hz. Samples of 40 and 50 mm thick samples also have identical absorption to commercial rockwool of 45 mm thick. On the other hand, by increasing thickness and bulk density of kenaf bonded with polyvinyl alcohol together with fabrics layering shows good absorption coefficient at mid-to-high frequency for random and normal incidence measurements. Statistical results exhibit positive correlation to Johnson–Champoux–Allard (JCA) model by modifying the absorber thickness (Taban et al. 2020). Also, experimental work on bamboo shows an excel performance of $\alpha > 0.7$ at 1500 Hz in transverse position compared to the axial and cross-transverse arrangements of the hollow structure (Putra, Khair, and Nor 2015).

Abdullah et al. (2013) studied rice paddy panicle bonded with carboxymethyl cellulose achieved high absorption coefficient above 2000 Hz, but the bonding material is found to be abrasive. Thus, in Putra et al. (2013), polyurethane was used as a replacement. The study demonstrated high and wide frequency range of absorption coefficient above 1500 Hz by adding polyester fabrics as the sample enclosure. The use of fabric as the enclosure was also studied by Tang, Liu, and Yan (2020). Contrary of using resin to execute bonding, Olcay and Kocak (2021) used recycle rice husk as a reinforcement to polyurethane foam. It was found that with 5% fiber by weight composition of treated rice husk using NaOH, the absorber was able to produce noise reduction rating (NRC) of 0.41.

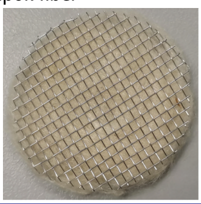
Arenas et al. (2020) studied esparto grass originated from Pakistan (Type 1), Tunisia (Type 2), and Egypt (Type 3). Air flow measurement on esparto grass of equivalent dimension of Type 1 arranged parallel to impedance tube wall indicates higher resistance than Type 2 and Type 3 undergo cold compress. This gave a first peak of absorption close to unity at 500 Hz. Another study of natural fiber is corn husk investigated by Tang et al. (2018). Although common fiber tends to absorb low frequency sound with increasing thickness, corn husk is shown to be less effective. However, with controlled air backing, 2 or 3 layers of corn husk fiber showed acceptable sound absorption coefficient. Additionally, hemp (Glé et al. 2013), rice straw (Zunaidi et al. 2017), and broom fiber (Iannace, Ciaburro, and Trematerra 2020) are other raw fibers that have been studied for sound absorbers.

Absorber made from pure composition of kapok is rarely seen due to the lack of moldability characteristics of its strand. However, having excellent hollowness than other natural fibers and the possibility to strengthen it using thermoplastic starch makes it as promising sound absorber (Prachayawarakorn et al. 2013). Veerakumar et al. (2012) measured the sound absorption of kapok polypropylene composite. In general, all samples exhibited good NRC rating for frequency of 250 Hz −2000 Hz. The highest absorption achieved by 30:70 of uncompressed kapok polypropylene ratio due to the high bulk density. The same pattern is followed by composite of kapok and saw dust bind with water-based glue (Shaharudin 2016). Xiang et al. (2013) found kapok with low bulk density has a better absorption than degreasing cotton or glass wool.

Liu, Yan, and Zhang (2016) explored a 90/10 weight ratio of kapok-hollow polyester nonwoven composite by focusing on two low-frequency ranges. The nonwoven composite with smaller pore diameter increased absorption performance at 100–1000 Hz by boosting of friction between air and outer wall of kapok. For a system with double-layer nonwoven composite with different pore diameter, absorption improved mainly due to the impedance matching effect.

Generally, research on the fiber sound absorption characteristics is in great extent. While coir fiber is widely known to form a multi-layer with other material such as a perforated panel, it is still rarely coupled with other fiber in a layering manner. Moreover, in the author's knowledge, there is still a limited discussion on the sound absorption characteristics of the kapok fiber. This study is aimed as the brief description on the sound absorption performance of coir fiber assisted by the kapok fiber. Coir and kapok fiber samples were molded to several thickness and densities before they were tested in an impedance tube. This study presents the effect of thickness, air gap, and position of kapok fiber on sound absorption performance of the coir fiber.

Table 1. Sample properties.

Sample	Notation	Thickness, mm	Density, kg/m^3
Coir fiber 	C1 C2 C3	10 20 30	175.38
Kapok fiber 	K1 K2	2 2	29.23 58.50

Sample preparations and measurement

Sample preparations

The coir fiber samples were fabricated by cutting a 10 mm thick weaved mat obtained from a local manufacturer to a circular shape of 33 mm diameter. Three thickness of coir samples used in the measurements are: 10 mm, 20 mm, and 30 mm. Samples of 20 mm and 30 mm are made by stacking two and three 10-mm-thick samples, respectively. No mechanical force was used in the process to assemble coir–coir fiber or coir–kapok fiber. Slight pressure was applied to eliminate air gap between the sandwich layers.

The kapok fiber samples were fabricated from loose kapok fibers obtained also from a local market. After it has been weighted, the loose strand was then carefully mold manually to approximate a 2-mm-thick layer with the same diameter as the coir sample. Thin steel wire mesh was attached on the kapok sample surface to retain the shape and thickness. The attached wire mesh was ensured to have no effect on the overall sound absorption of the fiber. The details of the sample are summarized in Table 1.

Sound absorption measurement

Measurement of normal incidence absorption coefficient was obtained using the impedance tube method according to ISO 10534–2 : 2001. Figure 1(a) shows the schematic diagram of the 33 mm diameter impedance tube. Both acoustic microphones were calibrated before the measurement. RT Photon+ was used as the signal analyzer. The normal incidence sound absorption coefficient is calculated by

$$\alpha = 1 - |r|^2 \tag{1}$$

where r is the reflection coefficient as detailed in ISO 10 534 - 2: 2001. On the account of equipment limitation and the tube diameter, the frequency analysis is fixed from 500 Hz to 4500 Hz. Full setting of the measurement is shown by the schematic diagram in Figure 1(b).

Results

The results shown in the subsequent sections show the measured sound absorption performance of the coir fiber with the aid of thin kapok layer. Throughout the analysis in this paper, good sound

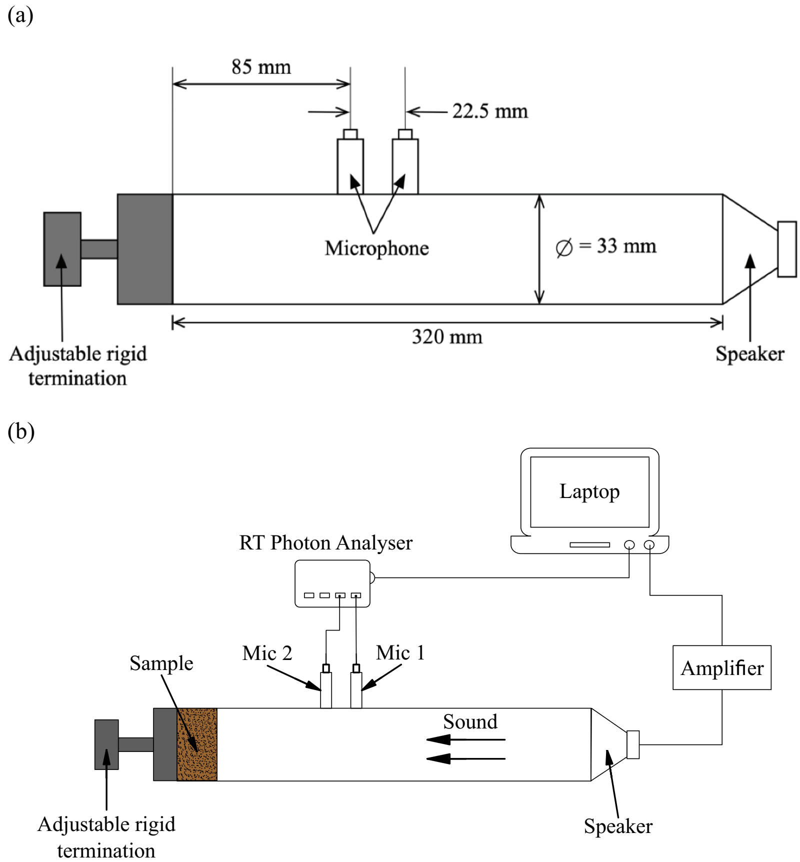


Figure 1. (a) impedance tube schematic diagram and (b) impedance tube measurement setup.

absorption is indicated with half power absorption where $\alpha \geq 50$.The absorption coefficient value of 0.5 is denoted as α_{50}.

Effect of thickness

Thick absorber is known to have a proportional relationship with low-frequency range between 100 Hz and 2000 Hz due to the quarter wavelength effect. However, as a consequence of a tight space required, such as in automotive application, thicker absorbers are usually unfavorable. Hence, to minimize increasing the acoustic panel thickness, adding another thin layer of a different fiber (with different acoustic impedance) to increase the absorption frequency bandwidth is of interest.

Figure 2 shows the effect of adding only 2 mm thick kapok layer in front of the coir fiber layer. In Figure 2(a), for 10 mm thick, pure coir fiber layer, α_{50} is at around 4000 Hz. By adding the kapok layer (C1 + K1), the sound absorption increases significantly and α_{50} is shifted to 2000 Hz indicating significant improvement of the absorption frequency bandwidth. With the same thickness, but with greater density of the kapok layer (C1 + K2), further improvement is obtained with α_{50} starts at 1000 Hz.

The same phenomenon is shown for the thicker coir layer in Figure 2(b). It can be seen that when the density of the kapok layer is increased, the peak frequency shifts to lower frequency due to change in flow resistivity and tortuosity. Improvement is obtained for lower frequency, but in consequence, it reduces the absorption above the peak frequency. This can also be observed in Figure 2(c).

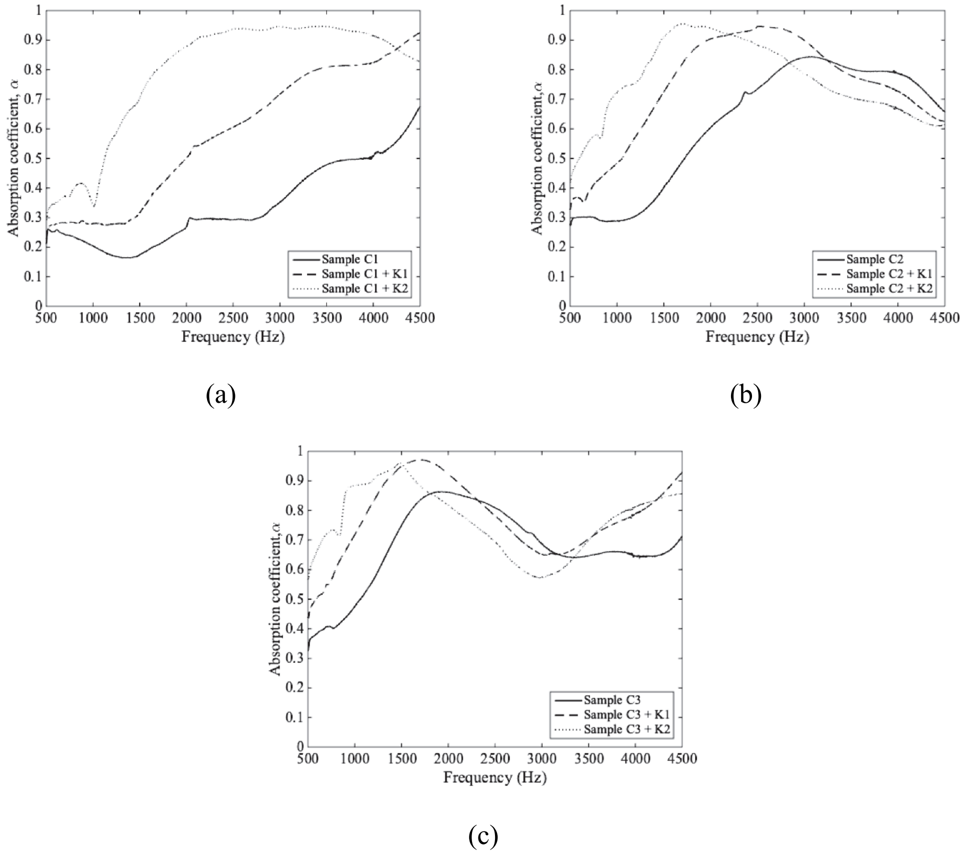


Figure 2. Sound absorption coefficient for coir fiber thickness of (a) 10 mm (C1), (b) 20 mm (C2), and (c) 30 mm (C3) with and without the addition of kapok fibers (Sample K1 and K2).

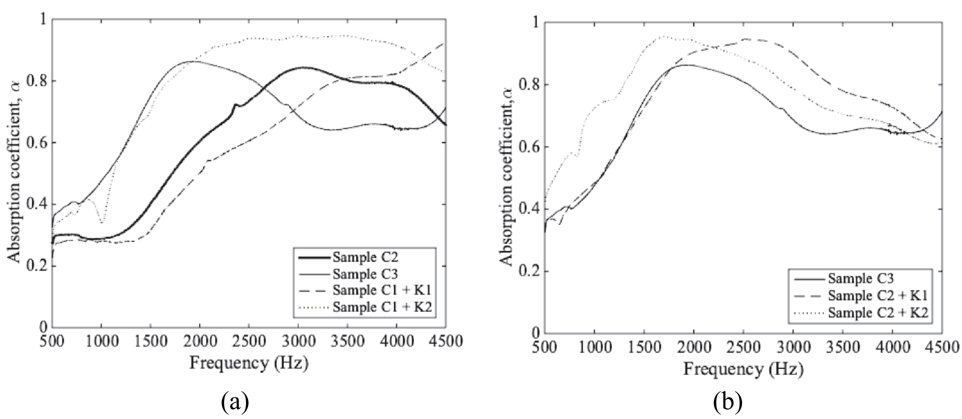


Figure 3. Comparison of coir fiber sound absorption coefficient.

Other comparisons have been made from different coir fiber samples as shown in Figure 3. It shows sound absorption coefficient which is obtained from a single layer coir fiber and compared to the thinner coir fiber added with kapok fiber layer. Although the thicker absorber is always referred to have highest absorbing power, the layering technique with different fiber type shows the contrary as

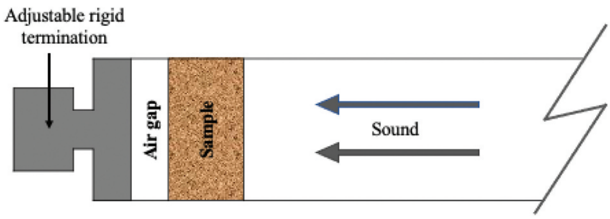


Figure 4. Arrangement of sample with the addition of air gap inside the impedance tube.

seen by sample C1 + K2 ($t = 22$ mm) where it has high absorption coefficient which is almost uniform above 2000 Hz compared to sample C2 ($t = 20$ mm) or sample C3 ($t = 30$ mm) without the kapok fiber layer.

The presence of two different acoustic impedances from two materials improves the sound absorption. The acoustic impedance is determined by five macroscopic properties, namely, the porosity, tortuosity, flow resistivity, viscous characteristic length, and thermal characteristic length. The porosity has been well known as the main important contributor for sound absorption performance. However, for most fibrous materials, the porosity is usually more than 0.8 (regarded as high porosity material) and in this study, small discrepancies of porosity between the coir and kapok fibers will not significantly affect the sound absorption.

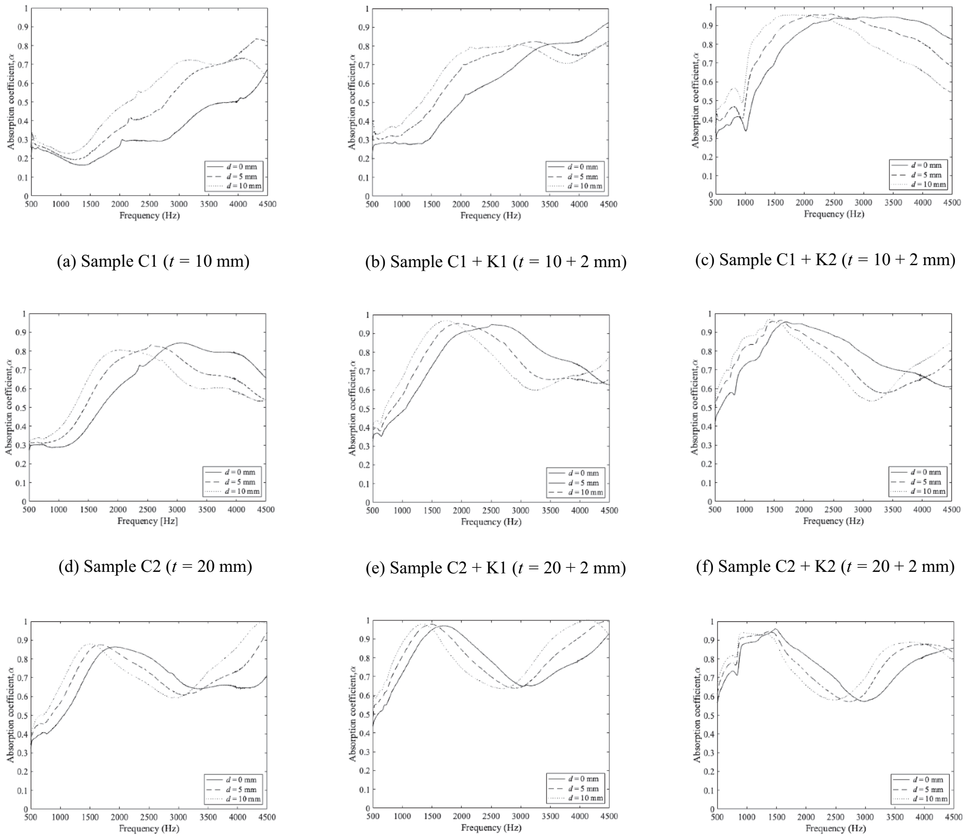
Effect of air gap

The sound absorption performance of the samples is further studied by introducing an air gap of 5 and 10 mm between back surface of the sample and the adjustable rigid termination for both with and without the presence of kapok fiber as illustrated in Figure 4. The air gap provides an extra medium for sound dissipation through multiple reflection between the rigid termination and the back of the sample, that is mostly related to Helmholtz resonance. In this system, the sample fiber acts as a mass while the air inside an air gap has similar behavior to a spring, thus a mass spring resonance relation is created.

The results of absorption are shown in Figure 5. As it is anticipated, adding more air gap between the composite sample and adjustable rigid backing increase the absorption toward low-frequency region (Arenas et al. 2019) shown across all the samples with different thicknesses. This is because of the increase of overall thickness provided by the air gap that is favorable for the dissipation of longer wavelength. The dips around frequency 2000–3000 Hz are obvious in Figures 5(g) –(i). These are the antiresonance effect which is prominent at higher frequency due to the increase of total thickness (combination of sample thickness and air gap) that reduces the total stiffness reactance (Allard and Atalla 2009). This dip will be more noticeable when the sample thickness to air gap depth shown a great ratio since it behavior is closer to a thin resistive absorber as shown in Figures 5(g) –(i).

From Figure 5, it can also be observed that regardless the parametric variation of coir and kapok fibers, the effect of the air gap is "linear," which means the air gap has no favorable effect to either combinations of the sample fibers.

Adding air gap is a common practice to reach target of sound absorption coefficient at lower frequency. Because a part of the sound absorber structure can be replaced by air, consequently less fiber is required compared if a thicker panel with full fibers is used. Fewer fiber means reduction in the cost for materials and overall cut of the production cost. Figure 6 represents this statement where sample C2 + K2 added with 10-mm air gap sound performance is almost reaching unity around 1500 Hz to its equivalent thickness of sample C3 + K2. Both conditions have total thickness of 32 mm.



(a) Sample C1 (t = 10 mm) (b) Sample C1 + K1 (t = 10 + 2 mm) (c) Sample C1 + K2 (t = 10 + 2 mm)

(d) Sample C2 (t = 20 mm) (e) Sample C2 + K1 (t = 20 + 2 mm) (f) Sample C2 + K2 (t = 20 + 2 mm)

(g) Sample C3 (t = 30 mm) (h) Sample C3 + K1 (t = 30 + 2 mm) (i) Sample C3 + K2 (t = 30 + 2 mm)

Figure 5. Effect of air gap to the sound absorption coefficient for varied thickness coir with and without the addition of kapok fiber.

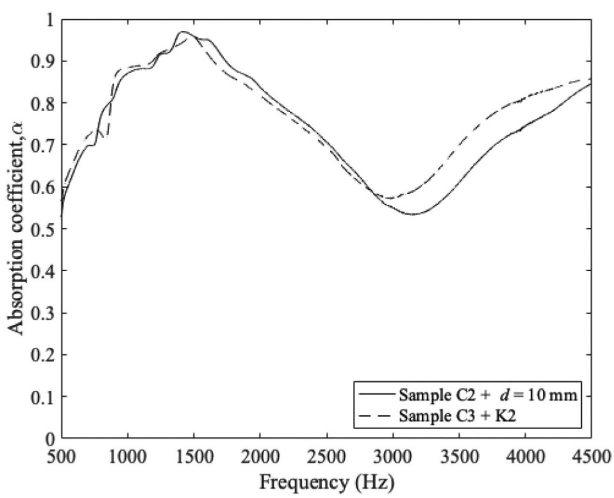
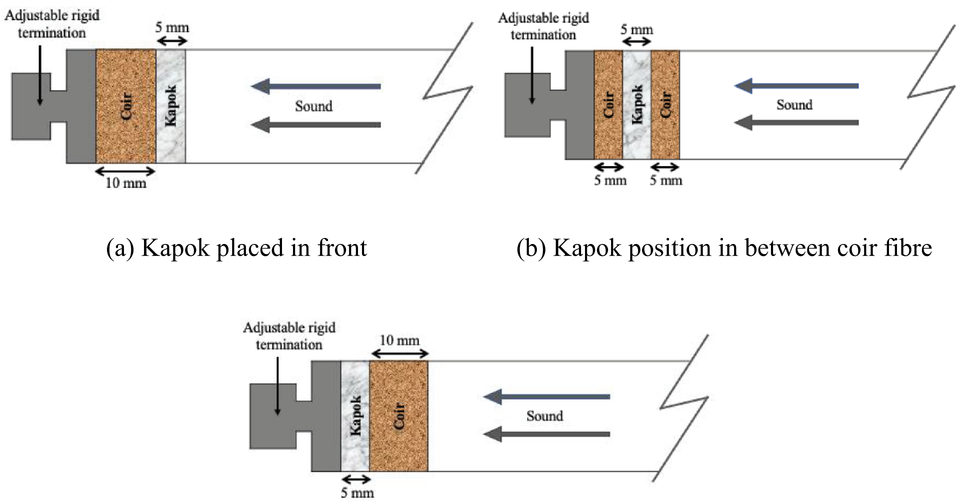


Figure 6. Comparison of sound absorption coefficient for equivalent thickness for the condition of full fiber thickness and fiber added with air gap.



(a) Kapok placed in front

(b) Kapok position in between coir fibre

(c) Kapok place at the back

Figure 7. Variation of kapok fiber layer positions.

Effect of kapok fiber position

The effect of kapok on coir sound absorption performance is further investigated by observing various placements of the kapok fiber sample. For this purpose, only sample C2 of coir fiber and sample K2 for kapok fiber are utilized for the experimental setup. The total thickness of the combined sample throughout the experiment is 22 mm. Three possible placements of kapok fiber are used: (a) on the front, (b) in between, and (c) on the back of the coir fiber sample. The front position indicates the surface closer to sound source and the back position is closer to adjustable rigid termination. As stated in the methodology, sample C2 is made by combining two identical 10 mm thick coir samples. For this setup, C2 is divided carefully so the kapok sample can be inserted in between. There is no air gap included in this measurement. Figure 7 illustrates the arrangement of the kapok sample.

The recorded sound absorption coefficient is plotted in Figure 8 for the respective change of kapok positions. The overall performance of this setup has a good absorption at mid-to-high frequency owing $\alpha >$ 0.5 above 1500 Hz, although rapid decrement above 2000 Hz is observed if kapok layer is placed in the front. The sample with the kapok fiber on the back shows the least increment compared to a single layer but still in good sound absorption above 1500 Hz. Overall, the in-between position has greater bandwidth of absorption of $\alpha > 0.5$ from 1000 Hz. Especially above 2000 Hz, the absorption coefficient is almost flat around 0.9. Sound wave entering sound absorber is dissipated thoroughly inside the sound absorber. Theoretically sound wave will be reflected and transmitted between multiple mediums existing in its surrounding, where in this case they are the fibrous medium (combined coir and kapok fiber sample) and the rigid back, each has different characteristic impedance determining the absorption coefficient.

Kapok has the highest hollow structure and among the lightest microchemical fiber increases the chances of air–fiber and fiber–fiber viscous frictions (Xiang et al. 2013). With the kapok sample in the middle of the coir layer, the sound energy penetrated the sample has two–time contact incident with kapok fiber. The first contact is with the sound after it is transmitted from the first coir layer, and the second contact is with the sound reflected by the second coir layer. So the process of absorption is greater inside the fibers particularly for shorter wavelength of sound (high frequency). This bouncing of sound energy in the middle of the sample explains why the kapok in between the coir layers has better sound absorption across the frequency range as shown in Figure 8. Meanwhile for kapok in front of the coir layer, more low frequency of sound is absorbed due to the thicker layer of the coir fibers.

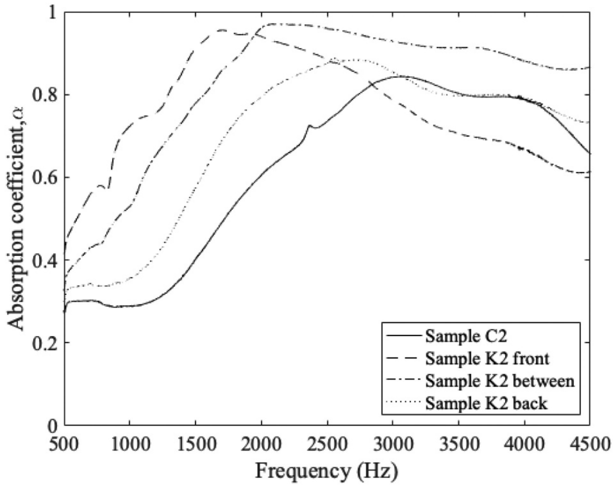


Figure 8. Sound absorption performance of coir sample with varied kapok positions.

Conclusion

The sound absorption of a multi-layer coir and kapok fibers has been presented. The thin kapok fiber layer is used as the assisting layer to enhance the absorption of the coir fiber as the main fiber of the absorber. It is found that the coir–kapok combination is able to give an equivalent absorption performance with the thicker sample of pure coir fibers. The density of the kapok fiber can be controlled to improve the sound absorption. It is also found that the position of the kapok layer in between the coir fiber layers provides better absorption frequency bandwidth, although slightly improved low-frequency range can be obtained by placing the kapok fiber on the front layer. With respect to the coir–kapok variations, the air gap has no specific effect to further improve the sound absorption. The improvement is similar with that for a single layer. This study can be extended with additional thin kapok layer or a sample with mixed coir and kapok fibers (non-layering arrangement).

Disclosure statement

No potential conflict of interest was reported by the authors.

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