

INVESTIGATION ON SOUND ABSORPTION PROPERTIES OF KAPOK FIBERS*

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Abstract Sound absorption properties of natural kapok fibers have been investigated. Kapok fibrous assemblies with different bulk density, thickness, fiber length and orientation were manufactured, and their acoustical performances were evaluated by using an impedance tube instrument. Results show that the kapok fiber has excellent acoustical damping performance due to its natural hollow structure, and the sound absorption coefficients of kapok fibrous assemblies are significantly affected by the bulk density, thickness and arrangement of kapok fibers but less dependent on the fiber length. Compared with assemblies of commercial glass wool and degreasing cotton fibers, the kapok fiber assemblies with the same thickness but much smaller bulk density may have the similar sound absorption coefficients. Theoretical modelling of the acoustical damping performance of kapok fibers shows a good agreement with the experimental data. All the results demonstrate that kapok fiber is a promising light and environment-friendly sound absorption material.

Keywords: Kapok fiber; Hollow structure; Sound absorption coefficient; Bulk density.

INTRODUCTION

Noise pollution has great adverse effects on human health such as hearing impairment, disturbance of rest and sleep, psychophysiological, mental-health and so on^[1]. Therefore, the requirements of human health drive the need to manufacture economical and environment-friendly acoustical materials to control the noise pollution. Traditional acoustical materials generally include fibers, foams, perforated panels, membranes and their composites. Fibrous material is one of the most widely used in various fields, e.g. architecture^[2], automotive industry^[3] and audio equipments^[4] due to its low cost and excellent noise reduction properties. Fibrous sound absorption materials involve natural fibers such as cotton^[5, 6], wood^[7, 8], tea-leaf-fiber^[9], rice straw^[10]; inorganic fibers like glass wool^[11–13]; metal fibers represented by aluminium fiber^[14] and synthetic fibers typically as polypropylene^[15], polyacrylonitrile^[16] and polyester fiber^[17, 18]. Among these fibrous materials, inorganic fibers have potential hazard to the environment and human health; the cost of metal fibers is high; most of the synthetic fibers are not degradable, therefore more and more attention are paid to the environmental-friendly and renewable natural fibers. Koizumi^[19] found that the bamboo fibers had acoustic properties equivalent to those of glass wool and the bamboo fiberboard possessed superior acoustical performance than the plywood with similar density. Ersoy and colleagues^[9] evaluated the sound absorption properties of industrial tea-leaf-fibre waste material. They found that a 1 cm thick tea-leaf-fibre with backing provided the similar sound absorption with that of six layers of woven textile cloth.

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Different from other fibers, kapok fiber has large lumen and thin cell walls, which endow it with extraordinary properties in the field of stuffing, buoyancy and oil-absorbing. The special structure of kapok fiber would also be beneficial for the sound absorption since it increases the chance of friction between sound waves and fibers. Besides, kapok fiber has some ecological characters such as environment-friendly, biodegradable, renewable, safe fiber handling and low energy consumption. It also has excellent chemical stability making it have potential applications in noise reduction field. However, to the best of our knowledge, there are few reports on the acoustical property of the kapok fiber.

The aim of this work is to investigate the acoustical performance of natural kapok fibers and study the relationship between the physical and acoustical characteristics. Kapok fibrous assemblies with different bulk density, thickness, fiber length and orientation were manufactured, and their acoustical performance was evaluated. Comparison with commercial glass wool and degreasing cotton fibers was performed and the sound absorption coefficients of kapok fibrous assemblies were also calculated by employing modified Delany and Bazley's empirical equation. All of these results demonstrate that kapok fiber promises a potential application in noise reduction as a light and environment-friendly acoustical damping material.

EXPERIMENTAL

Materials

Natural kapok fibers were obtained from Qingdao Suitable Pillow Co., Ltd., China. Glass wool was purchased from Beijing Salable Environment Engineering Technologies Co., Ltd., China. Degreasing cotton fibers (Density: 2330 kg/m^3) were supplied by Shandong Caoxian Huanu Medical & Health Material Co., Ltd., China.

Equipments and Methods

Surface morphology of the fibers was observed by a Hitachi S-4300 field emission SEM (Hitachi Japan) operated at 15.0 kV. Kapok fibers were cut off by electric grinder (Hangzhou Electrical Equipment Co., Ltd, China). Kapok fibers were orientated by a double-edged fine-toothed comb and observed under a microscope (Olympus BX51). The density (ρ) of the kapok fiber was measured by using a pycnometer at room temperature, and the measured value of the kapok fiber is 370 kg/m^3 .

Normal incidence absorption of kapok fibrous assemblies was measured by Type SW 466 Impedance Tubes (BSWA Technology Co., Ltd., China) based on the method of ISO10534-2:1998(E) (Acoustics-determination of sound absorption coefficient and impedance in impedance tubes — Part 2: Transfer function method). The acoustical measurement system contains a tube, two microphones and a Frequency Analysis System MC3242 (Fig. 1a). The principle of testing normal incidence absorption of kapok fibrous assemblies is shown in Fig. 1(b). Broadband random sound waves are generated by a loudspeaker at the end of the impedance tube, and then the waves transmit to the surface of sample at the other end. The reflected signals are picked up by the sensors. The sound absorption coefficient is defined as the ratio of the acoustical energy not reflected by sample ($I_{\text{incident}} - I_{\text{reflected}}$) to the acoustical incident energy (I_{incident}). The large tube (60 mm) can measure the sound absorption coefficients in the frequency range of 100–2500 Hz while the small one (30 mm) can give the sound absorption coefficients in the frequency range of 1600–6300 Hz. The sound absorption coefficients in the full frequency range (100–6300 Hz) are the combination of the values measured in the two tubes. The acoustical measurement system can also give the sound absorption coefficient at the one or 1/3 octave frequency. The environmental conditions were included as follows: temperature $T_0 = 30^\circ\text{C}$, pressure $P_0 = 1.01325 \times 10^5 \text{ Pa}$. During the experimental measurement, the samples were all backed by the stiffness wall. The samples for the sound absorption measurement were prepared by compressing the kapok fibers appropriately into cylindrical shapes with a diameter of 6 and 3 cm, respectively. The bulk density of the sample discussed later is defined as the mass per unit volume of the sample (kg/cm^3). It should be noted that the bulk density is referred to the prepared kapok fibrous assembly, which is different from the density of the single kapok fiber. The bulk densities of the samples can be changed accordingly with the different compressing degrees at a fixed thickness, or otherwise the thickness of the prepared samples can be tuned with the bulk density unchanged.

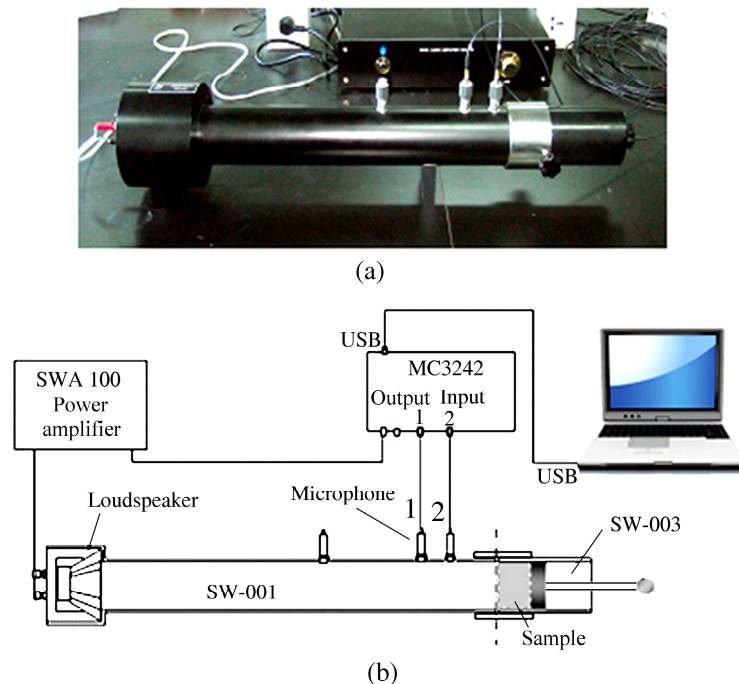


Fig. 1 Photo of the impedance tube (a) and schematic diagram of the acoustical measurement system (b)

RESULTS AND DISCUSSION

Effect of Hollow Structure on the Sound Absorption Property

Kapok fiber is different from other natural fibers for its large lumen and thin cell walls. As shown in Fig. 2(A), the outer diameter of the kapok fiber is about 15–23 μm and the thickness of the wall is less than 1 μm . The large hollow structure endows the kapok fiber a porosity of more than 80%. For a comparison, the degreasing cotton fiber shows a compressed morphology (Fig. 2B). The structure parameters of the kapok fiber are listed in Table 1. This large hollow structure is beneficial for acoustical energy dissipation. As shown in Fig. 2(C) (curves a and b), the kapok fiber has a better sound absorption performance than the degreasing cotton fiber at the similar bulk density (8.3 kg/m^3) throughout the entire range of sound frequencies. Besides, it also exhibits that kapok fiber has much smaller bulk density than that of degreasing cotton fiber when they obtain almost comparable sound absorption behavior (curves a, c and d). The reasons can be explained as follows: first, the large and straight hollow structure increases the frictional resistance between sound waves and kapok fibers, resulting in energy dispersion of the waves. Second, the special structure of the kapok fiber makes air vibrations of the waves transfer to fiber vibrations more easily since the density of the kapok fiber is much smaller than that of the degreasing cotton fiber. As a result, compared with the degreasing cotton fiber, kapok fiber converts the acoustical energy into the mechanical energy more efficiently. Third, air compression and expansion of the sound waves might occur not only among but also in kapok fiber tubes, and the acoustical energy dissipates due to the thermal diffusion, while it is generated only among degreasing cotton fibers as compared.

Table 1. Structure parameters of the kapok fiber

Outer diameter (μm)	Thickness of the wall (μm)	Length (mm)	Porosity (%)	Average density (kg/m^3)
15–23	0.7	10–25	84–99	370

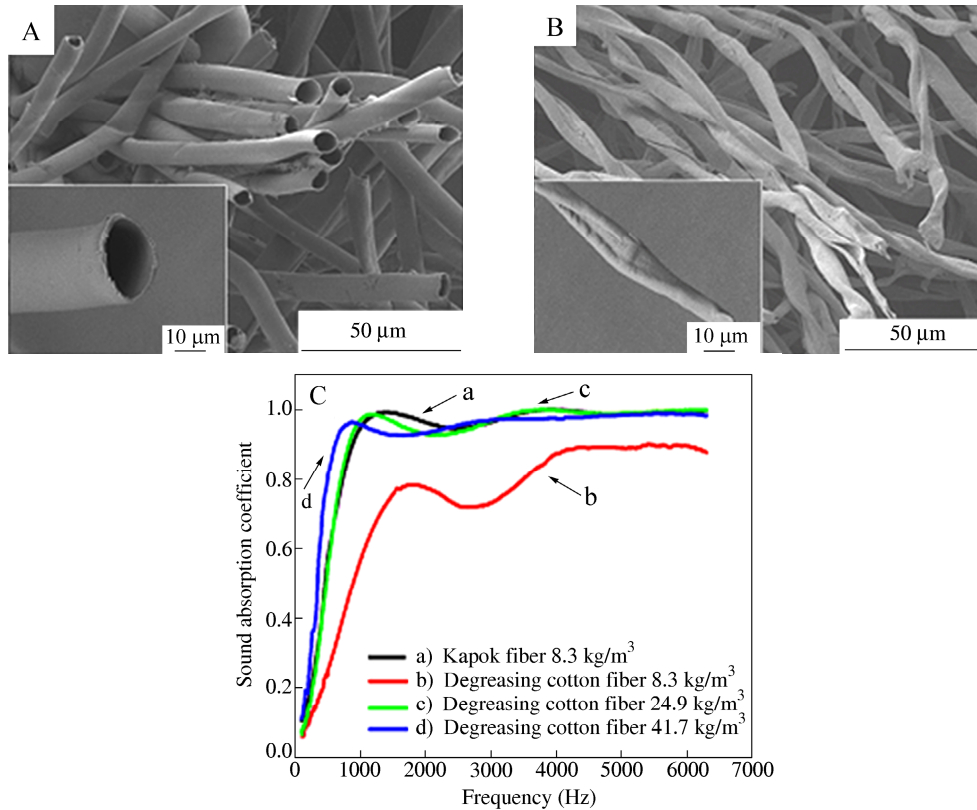


Fig. 2 SEM images of kapok fibers (A) and degreasing cotton fibers (B); (C) sound absorption behavior of kapok fibers and degreasing cotton fibers

Effect of Bulk Density on the Sound Absorption Property

Bulk density is an important parameter that noise control engineers often concern about. Variable bulk densities may result in different behavior of noise reduction since the bulk density has great influence on the porosity of fibrous assemblies. The porosity, σ , of kapok fibrous assembly is calculated as follows:

$$\sigma = \left(1 - \frac{\rho_1}{\rho_2} \right) \times 100 \quad (1)$$

where ρ_1 is the bulk density of kapok fibrous assembly (kg/m^3) and ρ_2 is the density of kapok fiber (kg/m^3).

Sound absorption coefficients of kapok fibrous assemblies with different bulk densities at one octave frequencies had been measured. The results listed in Table 2 show that the average noise absorption coefficient of kapok fibrous assemblies increases from 0.627 to 0.646 when the bulk density increases from 8.3 kg/m^3 to 25.0 kg/m^3 . Continuously increasing the bulk density leads to the decrease of sound absorption coefficients since every fibrous acoustic damping material has an optimal range of bulk density for obtaining best noise reduction behavior. The decrease in sound absorption coefficients is due to the dense packing of fibers leading to the reduction of porosity and the increase of reflection of sound waves by the materials.

We can also explain this phenomenon by using the impedance matching concept. The kapok fibrous assemblies have good acoustical damping performance only when the acoustic impedance of air and the assemblies are matched. As the latter one relates to the bulk density, an optimal impedance matching can be realized when the bulk density is about 25.0 kg/m^3 . Further increase in bulk density will lead to the impedance mismatching between air and the kapok assemblies, resulting in the decrease of the sound absorption coefficients. Thus, kapok fibrous assemblies are expected to use as efficient acoustical damping materials with an optimal bulk density *ca.* 25.0 kg/m^3 .

Table 2. Noise absorption coefficient of kapok fibrous assemblies with different bulk densities

Bulk density (kg/m ³)	Thickness (mm)	Porosity (%)	Sound absorption coefficient						Average sound absorption coefficient
			125 (Hz)	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)	
8.3	60	97.7	0.117	0.164	0.570	0.948	0.964	0.999	0.627
25.0	60	93.2	0.220	0.374	0.542	0.827	0.930	0.984	0.646
42.0	60	88.7	0.238	0.298	0.636	0.662	0.861	0.965	0.610
58.0	60	84.2	0.188	0.243	0.304	0.520	0.727	0.903	0.481

Effect of the Thickness on the Sound Absorption Property

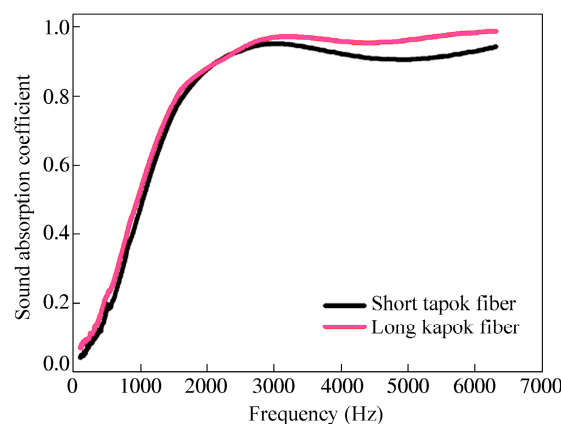
The sound absorption coefficients of kapok fibrous assemblies increase with their thickness, as shown in Table 3. For the same bulk density (range: 5–20 kg/m³), the average sound absorption coefficients of kapok fibrous assemblies with a thickness of 40 mm is by 29%–70% larger than that of the assemblies of 20 mm thick. The tendency is in agreement with the results of a previous study^[20], the thicker the material, the better the noise absorption behavior, particularly for the low frequency sounds. This is because the sound waves in the low frequency transmit mostly through thicker materials and they are absorbed along the air path and through the materials^[21].

Table 3. Sound absorption coefficients of kapok fibrous assemblies with different thickness and bulk densities

Bulk density (kg/m ³)	Thickness (mm)	Sound absorption coefficient						Average sound absorption coefficient
		125 (Hz)	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)	
5	20	0.059	0.078	0.105	0.170	0.344	0.674	0.238
5	40	0.078	0.107	0.186	0.411	0.764	0.883	0.405
10	20	0.067	0.082	0.127	0.297	0.619	0.918	0.352
10	40	0.081	0.126	0.308	0.714	0.977	0.963	0.528
15	20	0.065	0.090	0.160	0.413	0.785	0.996	0.418
15	40	0.107	0.143	0.397	0.864	0.984	0.959	0.576
20	20	0.071	0.094	0.185	0.549	0.893	0.997	0.465
20	40	0.109	0.204	0.443	0.905	0.946	0.979	0.598

Effect of Fiber Length on the Sound Absorption Property

To investigate the influence of fiber length on the sound absorption property, kapok fibers were cut with the length reduced from 10–25 mm to 0.5–5 mm. Figure 3 shows that the acoustical performances of the kapok assemblies of long and short fibers are comparable to each other except a slight decrease in sound absorption coefficients for short kapok fibers at high frequencies, indicating that the sound absorption property of kapok fibers shows little dependence on the fiber length.

**Fig. 3** Sound absorption behavior of kapok assemblies with long and short kapok fibers
Thickness: 30 mm; Bulk density: 10 kg/m³

Effect of Fiber Orientation on the Sound Absorption Property

Photos of oriented and randomly packed kapok fibers are shown in Figs. 4(a) and 4(b), respectively. The microscope images (Figs. 4c and 4d) reveal that the fibers orient along the the direction of the sound source while in the natural assemblies the fibers are randomly packed. Figure 4(e) exhibits that the sound absorption property of randomly packed kapok fibrous assembly is superior to that of the oriented one. One reason is due to that random packing of kapok fibers increases the possibility for sound waves to interact with kapok fibers, leading to the more dissipation of acoustical energy than that of oriented fibers. The other is maybe that more entanglements exist in the randomly packed assembly, which causes strong friction between the fibers.

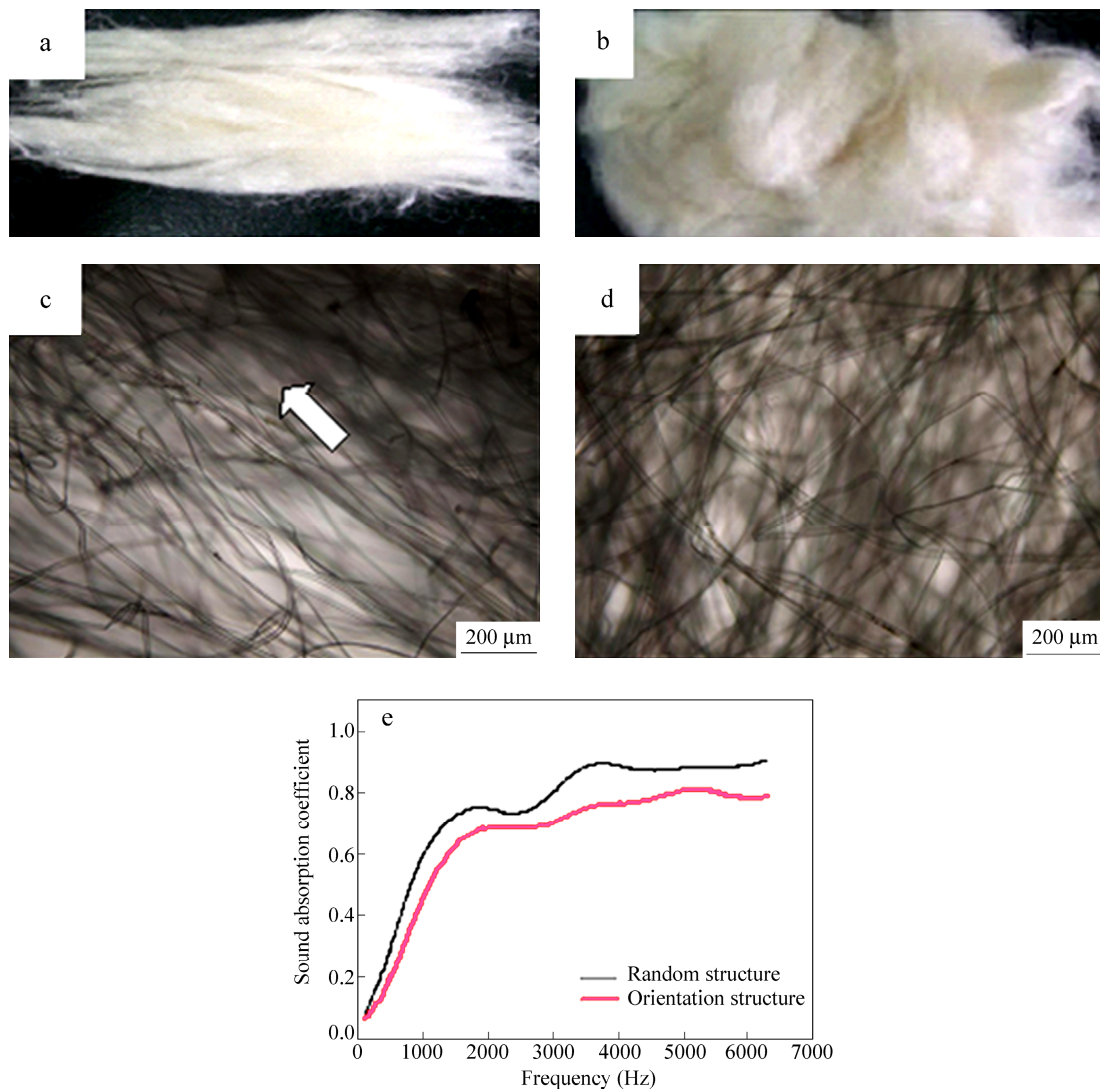


Fig. 4 Photos of the oritentional (a) and random structure (b) of kapok fibrous assemblies; (c) and (d) the macroscope images of (a) and (b), respectively (The arrow in c indicates the oritention direction.); (e) comparison of kapok fibrous assemblies with random and oritention structures in sound abosrpiton behavior (Bulk density: 2.6 kg/m³; Thickness:75 mm)

Comparison between Glass Wool and Kapok Fibers

Glass wool is one of the most commonly used acoustical damping materials in architecture, although it is suspected to have a risk in the enviroment and human health^[22]. The glass wool is a solid fiber with a diameter in

the range of 2–50 μm and a bulk density of 54 kg/m^3 , as shown in Fig. 5(A). The sound absorption coefficients of the samples exhibited in Fig. 5(B) demonstrate that kapok fibers have much smaller bulk density (curve b, 10 kg/m^3) than that of the glass wool (curve a, 54 kg/m^3) when they obtain approximate acoustic damping behavior. The sound absorption performance of kapok fibers of 15 kg/m^3 over 1500 Hz is much better than that of glass wool with bulk density of 54 kg/m^3 . Clearly the special structure of the kapok fiber (such as large lumen, thin cell walls) are more effective for acoustical energy dissipation.

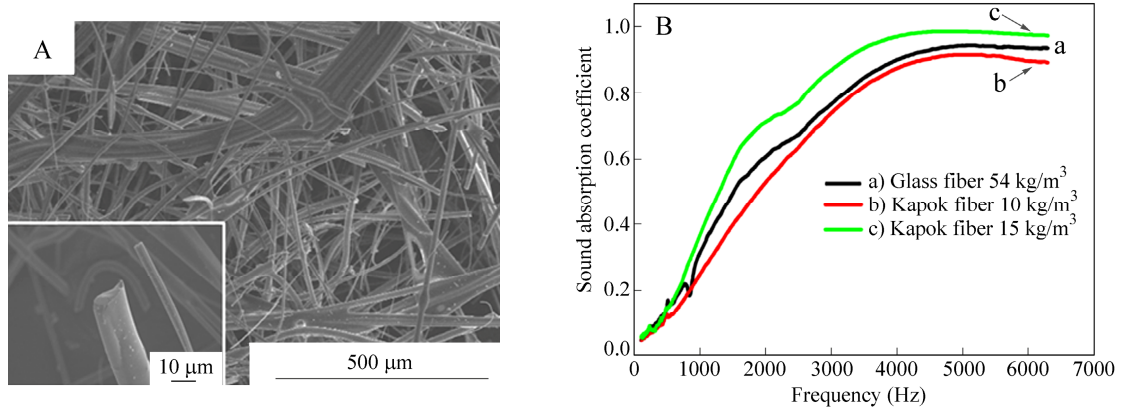


Fig. 5 SEM images of glass wool (A) and the sound absorption coefficients of glass wool and kapok fibrous assemblies with a thickness of 17.4 mm (B)

The Theoretical Modelling of Acoustical Performance for Kapok Fibers

According to the Bies and Hansen's model^[23], the value of flow resistivity can be expressed as a function of bulk density and fiber diameter:

$$rd^2\rho_m^{-K_1} = K_2 \quad (2)$$

where r is the air flow resistivity (Pa s/m^2), ρ_m is the bulk density (kg/m^3) and d is the mean fiber diameter (m). For glass fiber $K_1 = 1.53$ and $K_2 = 3.18 \times 10^{-9}$. Bies and Hansen also pointed out that the Eq. (2) was suitable for the fibers with uniform diameter ($< 15 \mu\text{m}$) and negligible binder content. Garai and coworkers^[24] modified the equation in order to fit polyester fibers with larger and more dispersed diameter. They changed the Eq. (2) into another form:

$$r = A\rho_m^B \quad (3)$$

Compared to Eq. (2), $A = K_2(d)^{-2}$, $B = K_1$, A and B are free parameters in Eq. (3). In this paper, the modified power-law relations-new impedance model (NMI model) proposed by Garai and Pompili^[24] was used to calculate the sound absorption coefficients of kapok fibers. The expressions are as follows:

$$Z_R = \rho_0 c_0 \left[1 + C_1 \left(\frac{\rho_0 f}{r} \right)^{-C_2} \right] \quad (4)$$

$$Z_I = -\rho_0 c_0 \left[C_3 \left(\frac{\rho_0 f}{r} \right)^{-C_4} \right] \quad (5)$$

$$\alpha = \left(\frac{2\pi f}{c_0} \right) \left[C_5 \left(\frac{\rho_0 f}{r} \right)^{-C_6} \right] \quad (6)$$

$$\beta = \left(\frac{2\pi f}{c_0} \right) \left[1 + C_7 \left(\frac{\rho_0 f}{r} \right)^{-C_8} \right] \quad (7)$$

where Z_R is the real part of the characteristic acoustic impedance, Z_I is the imaginary part of the characteristic acoustic impedance, α is the real part of propagation constant γ , β is the imaginary parts of the propagation constant γ , ρ_0 is the air density and f is the frequency. For a rigid backed fibrous layer of thickness l , characteristic acoustic impedance can be obtained using the equations as follows:

$$Z_l = (Z_R + iZ_I)[\coth(\alpha + i\beta)l] = Z_{lR} + iZ_{lI} \quad (8)$$

$$\alpha_n = \frac{4Z_{lR}\rho_0 c_0}{|Z_{lI}|^2 + 2\rho_0 c_0 Z_{lR} + (\rho_0 c_0)^2} \quad (9)$$

The parameters C_1 to C_8 in NMI models are listed in Table 4. The air flow resistivity of kapok fibers could be calculated from the Eqs. (4) to (9) using the sound absorption coefficients, frequency, bulk density, thickness and C_1 to C_8 , then the power-exponential fitting method is used to calculate A and B in Eq. (3). The results are $A = 221.35$ and $B = 1.63$. We used the value of A and B to obtain the air flow resistivity with different bulk densities, and calculated the sound absorption coefficients of kapok fibrous assemblies with different bulk densities at the thickness of 60 mm. Results show a good agreement with the experimental curve with a small fitting average relative errors between the theoretical and experimental values, demonstrating the modified model is suitable to predict the sound absorption coefficients of kapok fibers with different bulk densities (Fig. 6).

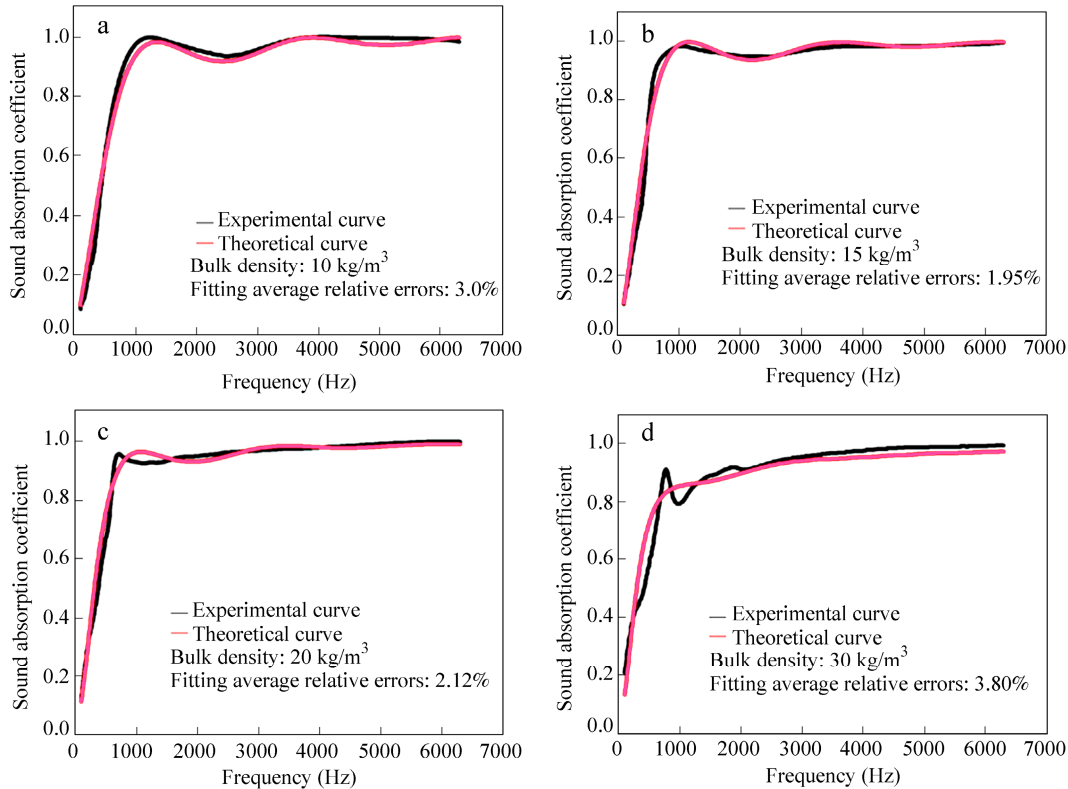


Fig. 6 Comparison of the theoretical and experimental sound absorption curves of 60 mm thick kapok fibrous assemblies with different bulk densities (a) 10 kg/m³, (b) 15 kg/m³, (c) 20 kg/m³ and (d) 30 kg/m³

Table 4. The parameters C_1 to C_8 in NMI models

Parameters	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
NMI model	0.078	0.623	0.074	0.660	0.159	0.571	0.121	0.530

CONCLUSIONS

The acoustical properties of kapok fibers have been evaluated. Results show that the kapok fiber has good acoustical damping performance due to its hollow structure. The sound absorption behavior of kapok fiber assemblies is significantly affected by the bulk density, thickness and arrangement of kapok fibers but less dependent on the fiber length. Compared with assemblies of glass wool and degreasing cotton fibers, the kapok fiber assemblies with much smaller bulk density may have similar acoustical properties. The theoretical modeling shows a good agreement with the experiment results. All the results demonstrate promising application of the natural kapok fibers in the noise reduction field.

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