Recent Advances in the Sound Insulation Properties of Bio-based Materials

Xiaodong Zhu,[a,b] Birm-June Kim,[c] Qingwen Wang,[a] and Qinglin Wu [b,]*

Many bio-based materials, which have lower environmental impact than traditional synthetic materials, show good sound absorbing and sound insulation performances. This review highlights progress in sound transmission properties of bio-based materials and provides a comprehensive account of various multiporous bio-based materials and multilayered structures used in sound absorption and insulation products. Furthermore, principal models of sound transmission are discussed in order to aid in an understanding of sound transmission properties of bio-based materials. In addition, the review presents discussions on the composite structure optimization and future research in using co-extruded wood plastic composite for sound insulation control. This review contributes to the body of knowledge on the sound transmission properties of bio-based materials, provides a better understanding of the models of some multiporous bio-based materials and multilayered structures, and contributes to the wider adoption of bio-based materials as sound absorbers.

Keywords: Bio-based material; Acoustic properties; Sound transmission; Transmission loss; Sound absorbing; Sound insulation

*Contact information: a: Key Laboratory of Bio-based Material Science and Technology (Ministry of Education), Northeast Forestry University, Harbin 150040, China; b: School of Renewable Natural Resources, LSU AgCenter, Baton Rouge, Louisiana; c: Department of Forest Products and Biotechnology, Kookmin University, Seoul 136-702, Korea. * Corresponding author: qwu@agcenter.lsu.edu (Qinglin Wu)*

INTRODUCTION

Noise reduction is a must, as noise has negative effects on physiological processes and human psychological health. The crowded and active nature of modern society is making noise control engineering increasingly important. Effective noise control can be achieved with a comprehensive understanding of sound phenomenon. For sound to be produced, three components are needed: a sound source, a medium, and a detector. The sound source is a vibrating body that produces a mechanical movement or sound wave. The medium, such as air, transfers the mechanical wave. The detector, such as an ear, detects the sound wave. Accordingly, noise control can be achieved by three means. Primary methods include alterations at noise and vibration sources. Secondary methods include modifications along the sound propagation path, and tertiary methods deal with sound receivers. Primary methods are constrained by technical and economical parameters, while tertiary methods necessitate that each receiving person is treated individually. This makes the secondary methods that include vibration isolation, noise barriers, noise absorption, and dissipative silencing relatively practical and cost-efficient (Kuttruff 1995).

The acoustic energy that is incident on the object is converted into reflected acoustic energy, energy loss, and transmitted acoustic energy. The ratio of reflected acoustic energy to incident energy is defined as the reflectivity, and the ratio of the sum of energy loss and transmitted energy to incident energy is defined as acoustic absorption. The ratio of transmitted energy to incident energy is defined as acoustic transmissibility (Lee *et al*. 2009). This paper focuses on the absorption and insulation phenomenon of bio-based materials.

The materials and structures using sound absorption and insulation materials to reduce ambient noise have received much attention. Noise-absorbing materials absorb unwanted sound by dissipating sound wave energy when it passes through and also by converting some of the energy into heat, making them very useful for the control of noise (Delany and Bazley 1970).

Although all materials absorb some incident sound, the term “acoustical material” has been primarily applied to those materials that have been produced for the specific purpose of providing high values of absorption. Stacy defined sound absorption as a measure of the propagation of sound energy that falls on a surface and is not reflected (Stacy 1959). Absorption coefficients range between 0 and 1 and are often evaluated at many frequencies in the audible range in order to create a performance curve for the material throughout the audio spectrum. The noise reduction coefficient (NRC) is the average of an acoustic material’s absorption coefficients at a specified set of frequencies, typically 250 Hz, 512Hz, 1024 Hz, and 2048 Hz in accordance with the type of tube and acoustic measuring instrument used for the tests. The sound insulation ability of a material is measured by sound transmission loss (TL), which can be defined as the difference between the sound power level of the incident wave and the transmitted sound power.

Most practical sound absorbing products used in the building industry consist of glass-fiber or mineral-fiber materials. In the 1970s, public health concerns helped change the main constituents of sound-absorbing materials from asbestos-based materials to synthetic fibers (Arenas and Crocker 2010). Because of the dominance of these materials in the commercial market, the study of sound propagation in alternative materials has been limited. However, these non-biodegradable materials not only cause pollution of the environment, but also contribute significantly in increasing the CO_2, contributing to global warming. Therefore researchers have now directed their attention to finding sustainable and eco-friendly materials to be alternative sound absorbers. In the current society, sustainable development becomes an increasingly significant goal in the evaluation of construction proposals.

A sustainable product is one that can be manufactured repeatedly over a long period of time without generating negative environmental effects, without causing waste products or pollution, and without compromising the wellbeing of workers or communities. At present, the bio-based materials, which are either completely natural or made of vegetable particles, also are renewable and store carbon dioxide over a long period (Asdrubali 2006). Bio-based products can be considered as the most ideal acoustical products because of their low cost, light weight, avoidance of pollution, and highly efficient sound absorption capability.

In the past few years many new sustainable bio-based materials for noise control have been studied as alternatives to the traditional ones. Their performance in sound absorption and sound insulation has been demonstrated. The objective of this review is to present an updated survey on the acoustical transmission properties of bio-based materials, including raw materials, structured composites, mechanism, and models, which have been described in a wide range of recent publications.

SOUND MEASUREMENT METHODS

Standing Wave Tubes

In most studies, the instrumental method for testing sound TL of bio-based materials is ASTM Work Item 5285. This method describes the use of an impedance tube, four microphones, and a digital frequency analyzer for measuring material TL. The Brüel and Kjær TL tube Type 4206T (Fig.1-a) is designed for the TL measurement. This tube set is actually an extension of the Type 4206, including an additional pair of microphones and two extended tubes, a large tube (diameter 100 mm) for measuring sound frequencies within the range 50 to 1600 Hz, and a small tube (diameter 29 mm) for measuring sound frequencies from 500 to 6400 Hz.

The TL test procedure is divided into two steps. In the first step, no sample is placed between the impedance tubes. In this case, the results should be 100% transmission and 0% reflection. In the second step, a material sample is placed between the source tube and receiving tube to provide a barrier to the incident plane waves. TL measurement is done with four microphones positioned at up- and down-stream positions relative to a test sample, as shown in Fig. 1 (b).

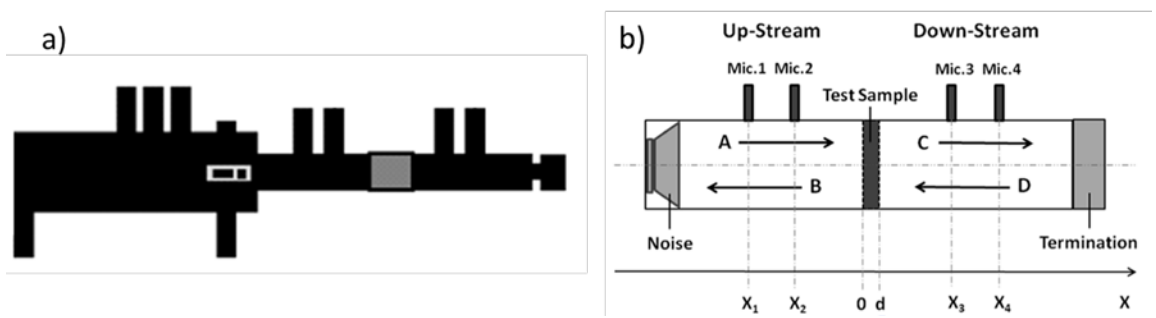

Fig. 1. The impedance tube system for sound transmission measurements. (a) Typical Transmission Loss Tube and (b) TL measurement with four microphones

In this system, sound pressures at the four measurement locations x_1 to x_4 can be expressed as super-positions of positive and negative directed plane waves ($\pm jkx$)(Jones 1979; Olivieri *et al.* 2006):

$$\begin{cases} P_1 = Ae^{-jkx_1} + Be^{jkx_1} \\ P_2 = Ae^{-jkx_2} + Be^{jkx_2} \\ P_3 = Ce^{-jkx_3} + De^{jkx_3} \\ P_4 = Ce^{-jkx_4} + De^{jkx_4} \end{cases} \quad (1)$$

where k is the wave number in ambient air. The letters *A, B, C,* and *D* are coefficients that represent complex amplitudes of the sound waves in the field of the normal incidence sound wave tube. This equation can be rearranged to solve for the respective coefficients in terms of the four sound pressures (P_1 to P_4) as (Song and Bolton 2000):

$$\begin{cases} A = \dfrac{j(P_1 e^{jkx_2} - P_2 e^{jkx_1})}{2\sin k(x_1 - x_2)} \\ B = \dfrac{j(P_2 e^{-jkx_1} - P_1 e^{-jkx_2})}{2\sin k(x_1 - x_2)} \\ C = \dfrac{j(P_3 e^{jkx_4} - P_4 e^{jkx_3})}{2\sin k(x_3 - x_4)} \\ D = \dfrac{j(P_4 e^{-jkx_3} - P_3 e^{-jkx_4})}{2\sin k(x_3 - x_4)} \end{cases} \quad (2)$$

The TL is defined as(Chen and Jiang 2009):

$$TL(dB) = 20\log_{10}\left|\frac{C}{A}\right| \quad (3)$$

Reverberation Room

The reverberation time, which characterizes the rate of sound decay, is considered to be the most important acoustic parameter for various kinds of rooms (Kanev 2012). Measured absorption coefficients in a reverberation room are estimated from the decay of sound under measurement conditions. The overall sound decay in a room consists of a number of normal modes of vibration, each having its own attenuation characteristic depending on its orientation with respect to the absorbing wall and the normal impedance of the absorbing material (Jeong 2010). Measurements of absorption coefficients in the reverberation room according to ISO 354 are performed by measurement of the reverberation time with (T_2) and without (T_1) the presence of the test sample. By using the Eq. (4), the random-incidence absorption coefficient α_s of the test sample can be obtained (Vorländer and Mommertz 2000),

$$\alpha_s = 55.3\frac{V}{cS}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (4)$$

where V is the room volume, c is the speed of sound, and S is the area of the test sample.

SOUND INSULATION MATERIAL

Natural Fibers as Efficient Sound Insulation Materials

Natural fibers are supposed to have the same mechanism for acoustic absorption as other conventional synthetic fibrous materials, such as glass fiber and mineral wool. These fibers are often light and they are not harmful for human health and can therefore be used as sound absorbers in room acoustical products and noise barriers. Furthermore, many of these materials are currently available on the market at competitive prices (Asdrubali *et al.* 2012). The sound absorption coefficient for bamboo fiber diameters of 90-125 µm, 125-210 µm, and 210-425 µm was tested. The sound absorption coefficient increases as the bamboo fiber diameter decreases. The energy loss increases as the surface friction increases, because the number of the bamboo fiber increases per the unit area when the bamboo fiber diameter decreases, the sound absorption coefficient becomes high (Koizumi *et al.* 2002). Meanwhile, tests of the sound absorption behavior of natural fibers have shown that their cell-lumens allow them to embrace more diversified modes to attenuate sound wave energy. Figure 2 (left) compares the cross-sections of natural fibers and synthetic fibers. It is found that a single sisal fiber is made up of a bundle of hollow subfibers that have lumen within them. However, glass fiber has the same regular and solid construction. Figure 2 (right) further indicates the unique structural characteristics of natural fibers. Therefore, natural fibers are porous fiber materials, which contain many connected air cavities, and those air cavities might be the major contributors of sound energy absorption (Yang and Li 2012).

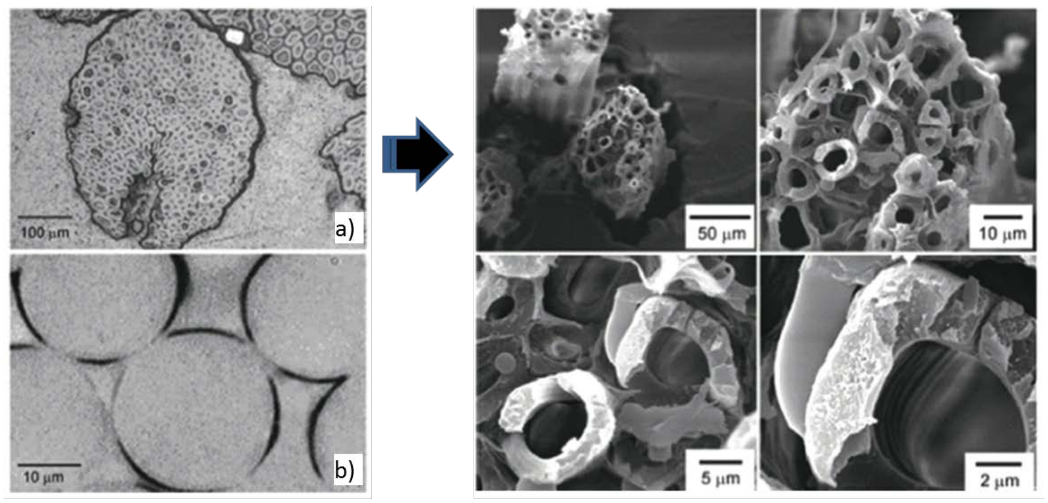

Fig. 2. Comparison of sisal fiber(a) with glass fiber(b) (Yang and Li 2012). Figure republished from Yang and Li (2012) with permission from Springer

The mechanism by which nature fiber materials absorb sound energy mainly involves three physical processes. First, when the sound wave is incident on the fibers, the viscous effect between fiber frame and numerous air cavities will attenuate part of sound energy and convert it into heat. Second, heat transfer will happen due to temperature distinction between different fibers caused by friction, which is an isothermal process (Sagartzazu *et al.* 2008). And this process will further dissipate sound energy. Third, the vibration of air in the bulk materials will also lead to the vibration of fibers (Allard and Daigle 1994; Voronina 1994). The sound wave could propagate by vibration through the air spaces and inside the lumen of natural fibers. Thus the unique lumen structure endows the natural fibers with superior sound absorption ability, compared to glass. Moreover, it can be realized that natural fiber possesses a multi-scale structure, as shown in Fig. 2 (right). A single sisal fiber is made up of a bundle of hollow subfibers. The cell wall of a subfiber is made up of millions of nanofibers (Li *et al.* 2010). In the presence of nanofibers, fine morphology involving more cells with smaller size can be achieved. Due to formation of this fine morphology, more paths for passing sound waves can be created, and also higher absorption of sound energy, because of higher created friction between sound waves and internal cell walls, can be dissipated (Bahrambeygi *et al.* 2013). On the other hand, the nano-sized fibers would also lead to the extra vibrations, which result in more dissipation of sound energy (Yang and Li 2012).

One-layer Structured Natural Fiber Composites for Sound Insulation

Despite their good acoustical absorption coefficients, natural fibers may not be used commercially in their natural form. Generally they need to be mixed with additives to keep them in shape and improve characteristics such as fire retardancy and stiffness. In the view of adding value to current natural fiber composites, considerable attention has been paid on the utilization of natural composite materials in sound absorption products. One-layer structured natural fiber composites are defined here as these made through one-step cold/hot compacting of natural fibers and/or natural fiber-bonding agent blends. These composites are divided into two general categories: low-density insulation panels and hot pressed medium to high-density composite panels.

Low-Density Insulation Panels

In the low-density insulation panels, natural fibers are compacted together to form highly porous structures. The sound insulation properties of low-density panels are controlled by inter-fiber voids and within-fiber voids (cell-lumen). Number, size, and type of pores are the important factors that one should consider while studying sound absorption mechanism in porous materials. To allow sound dissipation by friction, the sound wave has to enter the porous material. Thus, there should be enough pores in the material for the sound to pass through and to get dampened. The porosity of a porous material is defined as the ratio of the volume of the voids in the material to its total volume (Allard *et al.* 1989). Variable densities may result in different behavior of noise reduction since the density has great influence on the porosity of fibrous assemblies. The density is an important parameter that noise control engineers often are concerned about. Among many reported studies, the sound absorption coefficient for the bamboo fiber with apparent densities of 80 kg/m^3, 120 kg/m^3, and 160 kg/m^3 were measured. It was confirmed that the sound absorption coefficient was increased as the density of the sample was higher (Koizumi *et al.* 2002). The sound absorption coefficients of kapok fibrous assemblies were also measured. The results showed that the average noise absorption coefficient of kapok fibrous assemblies increased from 0.627 to 0.646 when the bulk density increased from 8.3 kg/m^3 to 25.0 kg/m^3 (Xiang *et al.* 2013). The maximum absorption coefficient increases monotonically with the fiber mass density for the cashmere and acrylic fibers, while for the kapok there is an optimal fiber mass density that maximizes the absorption coefficients (Yang *et al.* 2011). The number of the natural fibers increases per the unit area when the density is large. And compaction increases the chance of friction between sound waves and fibers. When the sound energy loss increases in passing the inter-fiber voids as the surface friction increases, the sound absorption coefficient becomes high. A summary of relevant published data for the acoustic properties of some traditional and natural fiber materials and their composites is given in Table 1.

Hot-pressed Medium to High Density Composite Panels

Hot-pressed natural fiber composites with medium or high density are made with resin coated fiber, particulate particle strands, and veneers of natural materials such as kenaf, flax, sisal, hemp, cork, sheep wool, bamboo, or coconut fibers, which have shown good absorbing performance, as given in Table 2.

Structural arrangement in these composites differs significantly. For example, fiber and particle-type composites are made to form a relatively homogeneous mat through thickness and hot pressing. Strand and veneer type composites are made by orienting face/core strands or veneers to take advantages of strength/expansion properties of wood along the longitudinal direction. The hot pressing process results in a distribution of density across the panel thickness with a highly compacted face layer and less-highly compacted core layers, as shown in Fig. 3. Compared to natural fibers, the sound absorption properties of hot-pressed composites generally are reduced. Natural fibers possess excellent sound absorption properties by themselves, whereas the free spaces within and between fibers can be significantly diminished in the case of hot-pressed composites. Meanwhile, the resin would occupy some effective volume of airflow, as well as cavities between fibers and inside lumens, which tend to become compressed by the pressure applied during the process of composite manufacturing. The sound absorption behavior of the resin system is very low. Additionally, the sound absorption properties largely depend on the frequencies of the sound waves (Yang and Li 2012). The higher the frequency, the shorter the sound wave length and the longer the propagation path of sound wave in the composites. Therefore, more dissipation of sound energy happens in the composites at high frequencies. This explains why natural fiber composites have the best sound absorption performance at high frequencies.

Table 1. Acoustic Properties of Some Traditional and Natural Fiber Materials

Fiber Material	Thickness (mm)	FD[a] (um)	BD[b] (g/cm^3)	NRCs (-)	AC[c] (-)	Acoustical property	Reference
Cotton	50	13.5	0.04	0.62	0.50	The most promising natural sound absorber fibers are those for which the average diameters are small and which are capable of being well compacted	(Oldham *et al.* 2011) (Yang and Li 2012)
Flax		21.8	0.08	0.55	0.40		
Ramie		24.4	0.10	0.55	0.40		
Wool		37.1	0.10	0.35	0.20		
Jute		81.2	0.07	0.35	0.20		
Sisal		213.0	0.04	0.16	0.10		
Bamboo	50	90-125	0.18	0.68	0.60	The NRC increases in the middle and high frequency range as the density becomes higher.	(Koizumi *et al.* 2002)
		125-210	0.12	0.58	0.40		
		210-425	0.06	0.48	0.30		
Kapok	60	-	0.01	0.63	0.57	Continuously increasing the bulk density leads to the decrease of NRC since every fibrous acoustic damping material has an optimal range of bulk density for obtaining best noise reduction behavior.	(Xiang *et al.* 2013)
		-	0.02	0.65	0.54		
		-	0.04	0.61	0.64		
		-	0.06	0.48	0.30		
Glass wool	40	-	0.03	0.56	0.40		(Asdrubali 2006)
Mineral wool		-	0.07	0.65	0.7		
Polystyrene		-	0.07	0.17	0.1		

[a] FD=Fiber Diameter; [b] BD=Bulk Density; [c] AC= Absorption coefficient at 500 Hz

Table 2. Chronological Events in the Exploration of Sound Transmission of Various Natural Fiber Composites

Year	Composite Types	SG[a]	Methods of fabrication	Acoustical property	Reference
1996	Wood-based material	0.65 0.80	Loose fibers or flakes, plus suitable resin binders, are compressed into a high-density panel.	It is viewed as inherently sound reflecting, rather than sound absorbing.	(Wassilieff 1996)
2003	Rice straw–wood particle composite	0.4 0.6 0.8	Mixing cut pieces of rice straw and wood particles, was slowly sprayed with UF resin adhesive.	It has higher AC than particleboard and plywood in the 500–8000 Hz frequency range.	(Yang *et al.* 2003)
2009	Tea-Leaf fiber composites	0.02	Composite samples are prepared by mixing tea-leaf fibers with a polyurethane formulation.	The 1 cm thick sample with backing, provides sound absorption which is almost equivalent to that provided by six layers of woven textile cloth.	(Ersoy and Küçük 2009) (Ekici *et al.* 2012)
2010	Coconut coir fiber composite	0.82	The industrial prepared coconut fibers were mixed with binder to keep it in shape	The fresh coir fiber has an AC of 0.8. But the samples, which mixed with binder had lower AC.	(Hosseini Fouladi *et al.* 2011) (Zulkarnain *et al.* 2011)
2011	Hemp concrete	0.40	It is the result of the mixing of hemp particles, binder and water.	It has high porosity that combines the microscopic pores of its binder and its vegetable particles.	(Glé *et al.* 2011).
2012	Kapok fiber composite	0.12	Kapok fibers were blended with polypropylene fiber	The special large lumen and thin cell walls structure would be beneficial for the sound absorption since it increases the chance of friction between sound waves and fibers.	(Veerakumar and Selvakumara 2012). (Xiang *et al.* 2013)
2012	Corn particleboard	0.33	Bind corn cob particles with wood glue according to the ratio of 1:4 (glue: corn cob particles).	A gain in terms of impact sound insulation capacity by applying it on the floor of the emitting room.	(Faustino *et al.* 2012)
2012	Ramie, Flax and Jute composites	1.09 1.12 1.04	Three kinds of natural fibers reinforced epoxy composites were made by hot press.	The multi-scale and hollow lumen structures contributed to the high sound absorption performance.	(Yang and Li 2012).
2002	Bamboo fiberboard	0.40 0.50 0.60	The bamboo fiberboard was formed using 10% binders of material weight by hot press molding.	The AC is higher in the high frequency than plywood, because it has both the characteristics of a board and cavities.	(Koizumi *et al.* 2002)

[a] SG=Specific Gravity

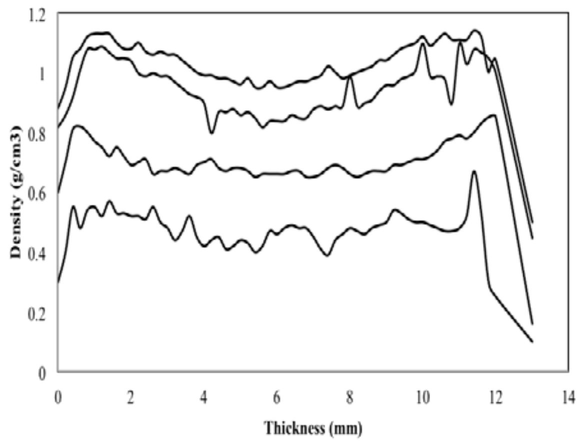

Fig. 3. Typical vertical density distribution of hot-pressed natural fiber composites with highly compacted fact and less-highly compacted core

Composites with Other Additives and/or Polymer Matrix Systems

Activated carbon fiber (ACF) composites have two levels of porous structures: macropores among fibers and yarns and micropores on the surface of activated carbon fiber. The diameter of an ACF cross-section is usually at a level of about 10 µm. After carbonization and activation, the unique slit-shaped micropores are produced on the surface of ACF with an average pore width of 2 to 3 nm. More porous area means a greater volume of air allowed to flow into the ACF non-woven structure (Amaral-Labat *et al.* 2013; Suzuki 1994).

When incident noise waves hit the non-woven composite, air vibration would happen in both the macroporous areas and the microporous areas. This unique fabric architecture renders a great potential for the ACF fabrics to be used as high-performance acoustical materials. The ACF composites exhibit an exceptional ability to absorb normal incidence sound waves in comparison to composites with either glass-fiber or cotton fiber or ramie fiber, as illustrated in Fig. 4 (Chen and Jiang 2007). Considering the light weight, biodegradability, and low cost of the raw material, activated carbon products have potential to be used as high-performance and cost-effective acoustical materials.

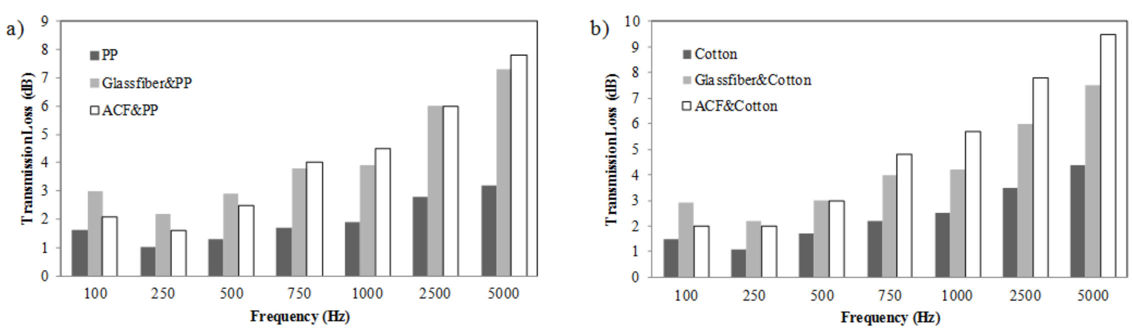

Fig. 4. TL of PP-based composite (a) and Cotton-based composite (b). Figure redrawn from the data of (Chen and Jiang 2007)

Recently, particulate-filled polymer composites having good sound absorption and insulation characteristics besides light quality and high specific strength have been received much attention as sound materials. Fillers occupying appropriate positions and with optimum size may achieve a better effect in soundproof performance (Ni *et al.*

2008). The presence of calcium carbonate can increase stiffness of the composite, providing better absorption of sound waves (Liang and Jiang 2012; Suhawati *et al.* 2013). The sound transmission loss of precipitated calcium carbonate (PCC)-filled wood plastic composite (WPC) was studied. The results showed that the TL of WPC increased with an increase in sound frequency and PCC weight ratio. The improvement of sound insulation was attributed to the mass increase, sound scattering enhancement by the fillers, and PCC weight ratio. Larger inorganic particle size led to higher TL, but its effect was not obvious at lower frequency ranges (Li *et al.* 2013). Rubber composites as sound insulators were prepared by incorporation of two types of fillers, namely kenaf and calcium carbonate. That combination exhibited excellent sound absorption properties with sound absorption coefficient values up to 0.87. The presence of kenaf in the composite was found to create void sections during the drying process, hence increasing the absorption coefficient value of the composite. The presence of calcium carbonate that was scattered on the walls of voids had increased stiffness of the composite, providing better absorption of sound waves (Liu *et al.* 2013; Suhawati *et al.* 2013).

Multilayer Structured Composites for Sound Insulation

The development of materials both rigid and light with high damping effect and acoustic insulation is possible by using a multilayer panel with viscoelastic material. The layered absorbing structure is composed of different sound absorption materials according to certain parameters, making the acoustic attenuation in the absorbing layer structure achieve good sound absorption. The object vibrates according to the change of the atmospheric pressure when sound impacts it. This vibration energy dissipates during the transmissible process from inside to outside of the object and increases according to the increase of the weight of the object. This relation is called the Mass Law of Sound Insulation (Heckl 1981). Over the years, a great deal of research has been carried out in identifying the TL characteristics of different panel constructions. Unique approaches to achieving high TL within mass limitations include the "shear wall" developed by Kurtze and Watters (1959), and the "coincidence wall" developed by Holmer (1969). These designs are based on an understanding of coincidence effects in the interaction of the incident sound field with the vibration response of the panel. Coincidence involves a matching of wave speeds between the incident sound fields as it propagates across the surface of the panel and the wave speed of vibratory motion within the panel. It results in a reduction in acoustic TL performance of the panel.

Sandwich Structure

Due to the high stiffness-to-weight and strength-to-weight ratios, sandwich composite materials consisting of two thin and stiff skin sheets and a lightweight core without adding an excessive mass are widely employed for sound absorption and vibration damping in various structural applications including aircraft, spacecraft, automotive, wind-turbine blades, and so on. Kurtze and Watters (1959) suggested that a sandwich panel might be a useful way to increase the sound insulation between adjoining spaces over that which could be obtained using a homogeneous plate. The results are based on an elementary model of sandwich behavior, wherein the core acts as a spacer that has mass and that does transmit shear, while the skins respond as elementary bent plates (Moore and Lyon 1991).

Natural cork agglomerate can serve as a core material, coupled with carbon fiber face sheets, in sandwich structures. Results showed vastly improved sound and vibration performance over traditional synthetic sandwich structures. More combinations of other types of natural materials have been explored in a sandwich structure configuration. Cotton, bamboo, and carbon fiber based composites are chosen as face sheets, while balsa wood, pine wood and synthetic foam are used as core materials in sandwich composite materials. These results suggest that, if optimized, natural material based sandwich composites could be an environmentally friendly solution to the sandwich structure-noise radiation problem (Sargianis *et al.* 2013). The structural–vibrational performance of carbon-fiber face sheet sandwich composite beams with varying core materials and properties were investigated. It was determined that low shear modulus cores have similar material damping values to structural damping values. However as the core's shear modulus increases, the percent difference between these values was found to increase linearly. It was also observed that high structural damping values correlated to low wave number amplitudes, which correspond to reductions in the level of noise radiation from the structure (Sargianis and Suhr 2012).

Honeycomb Structure

A honeycomb panel is a thin lightweight plate with a honeycomb core with hexagonal cells. Layered laminates are bonded to both sides of the core. Each component is by itself relatively weak and flexible. When combined into a sandwich panel the elements form a stiff, strong and lightweight structure. The facings carry the bending loads and the core carries the shear loads. In general, the honeycomb core is strongly orthotropic. The laminates are not necessarily symmetric and are usually orthotropic. The core acts as a spacer between the two laminates to give the required bending stiffness for the entire beam. The bending stiffness of the core itself is in general very low. The cells in the core give an orthotropic structure. The dynamic characteristics should be expected to vary in all directions.

A new honeycomb core design has been used to improve the noise transmission loss. In comparison to a cement panel of the same mass, the honeycomb panels have higher TL at low frequencies between 100 and 200 Hz due to higher stiffness and damping. The honeycomb panels have more significant vibration responses above 500 Hz but these are limited by damping (Ng and Hui 2008). Thin continuous rolls were produced in conical twin-screw extruders that were then thermoformed into half hexagonal or sinusoidal profiles. The corrugated profiles were stacked and then bonded using ultrasonic methods to form cores for sandwich panels. The characteristic sound absorption of these panels at particular frequencies, coupled with good mechanical properties, make them eco-friendly and suitable in automobile, aerospace, packaging and building/construction industries (Rao *et al.* 2011)

APPLICATIONS OF THE MODELING METHODS

To predict the acoustic behavior of bio-based materials and structures, models with the power of predicting the noise absorption coefficient have been investigated (Shoshani and Yakubov 1999). One of the first fundamental works on the bending of sandwich plates was published by Hoff (1950). Hamilton's principle was used to derive the differential equations governing the bending of rectangular sandwich panels. Another classic paper develop a simple model to predict the sound transmission through sandwich panels (Kurtze and Watters 1959). The laminates are described as thin plates. The thick core is isotropic, and only shear effects are included. A more general description of the bending of sandwich beams is given by Nilsson (1990). The general wave equation is used to describe the displacement in the core. Most of the models that have been found to be useful for predicting acoustical properties fall in one of two categories: theoretical micro-structural and empirical phenomenological models (Cox *et al.* 2004). These modeling categories are explained in the following sections.

Transfer Matrix Method

The matrix method is used to systematize the analysis and to present the equations in a form suitable to compute the transmission of a plane elastic wave at oblique incidence through a stratified solid medium (Thomson 1950). It is a very powerful technique that can be applied to single or multiple layer absorbers (Cox *et al.* 2004). This approach is especially useful for determining surface impedance values of layered porous materials with impervious screens. The screens can be located inside the material or at the surface (Lauriks *et al.* 1990). It is also shown that the present transfer matrix obeys the necessary checks to categorize the physically symmetric multi-layer plate as dynamically symmetric. Expressions are derived to obtain the wave propagation parameters, such as the transmission, absorption and reflection coefficients, in terms of the elements of the transfer matrix presented. The transfer matrix, relating with sound pressures (*P*) and particle velocities (*V*) at the two surfaces (front and rear) of the test sample, extending from x=*0* (front) to x=*d* (rear) as shown in Fig. 1 (b), has the following form (Olivieri *et al.* 2006),

$$\begin{bmatrix} P \\ V \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix}_{x=d} \quad (5)$$

where, T_{ij} are frequency-dependent quantities, related to the acoustical properties of the test sample. Thus, the *P* and *V* at the two surfaces of the test sample can be effectively expressed by the positive and negative plane wave components ($\pm jkx$ and complex coefficients),

$$P\big|_{x=0} = A + B \quad (6a)$$

$$V\big|_{x=0} = \frac{A - B}{\rho_0 c} \quad (6b)$$

$$P\big|_{x=d} = Ce^{-jkd} + De^{jkd} \quad (6c)$$

$$V\big|_{x=d} = \frac{Ce^{-jkd} - De^{jkd}}{\rho_0 c} \quad (6d)$$

where, ρ_0 is ambient air density and c is the speed of sound in air. When the plane wave components are known, based on the measurements of complex pressures at the four locations, the *P* and *V* values at the two surfaces of the test sample can be determined. Consequently, when a two-load method with a perfectly anechoic termination (*i.e.*, *D*=0) is used, TL can be calculated as (Jones 1979; Olivieri *et al.* 2006):

$$TL_{normal}(dB) = 10\log_{10}\left(\frac{1}{4}\left|T_{11} + \frac{T_{12}}{\rho_0 c} + \rho_0 c T_{21} + T_{22}\right|^2\right) \tag{7}$$

A modified transfer matrix method, for evaluating normal incidence sound transmission loss of multilayer solid materials, is presented by Lee and Xu (Lee and Xu 2009). The original transfer matrix was measured directly via a standing wave tube method, but modified for solid layers, in accord with data from the vibration of thin plates and the mass law effect. The feasibility of this method was validated through experiments on several different kinds of materials.

Finite Element Method

However, the transfer matrix methods are not adapted to predict the vibro-acoustic behavior of finite skew plates. On the contrary, the finite element method (FEM) used by Panneton and Atalla (1996) to predict the sound transmission through finite multilayer systems with poroelastic materials is well adapted to model complex finite geometries. These models, while accurate, lead to large frequency-dependent matrices for three-dimensional problems, necessitating important setup time, computer storage, and solution time. Various finite element methods are often proposed for describing the vibration of sandwich panels. For example, Liew *et al.* (1995) used a finite element model for the numerical evaluation of frequency response functions of honeycomb panels. Structures with and without delamination were considered. A finite element vibration analysis of composite beams based on Hamilton's principle is presented by Shi and Lam (1999). A standard finite element method code is used by Cummingham *et al.* (2000) to determine the eigenfrequencies of curved sandwich panels. The agreement between predicted and measured eigenfrequencies is found to be very good.

Patch-mobility Approach

Nevertheless, the main drawback of finite element models comes from the significant computational time required. The patch-mobility method (PMM), which is used to couple acoustic linear problems, is presented by Ouisse *et al.* (2005). It allows one to consider several acoustic subsystems, coupled through surfaces divided into elementary areas called patches. These subsystems have to be studied independently with any available method, in order to build a database of transfer functions called patch transfer functions, which are defined using mean values on patches, and rigid boundary conditions on the coupling area. Indeed, the use of a mobility technique makes it possible to characterize each component of the vibro-acoustic problem separately, either analytically or numerically, and then to calculate the global response, solving the interaction equation. If one element is modified, then only its own characterization has to be calculated before solving interaction equations (Chazot and Guyader 2007).

Capillary Pore Model

The most often applied microstructure model for porous materials is a rigid solid matrix through which cylindrical, capillary pores with a constant radius run normal to its surface, as illustrated in Fig. 5(a).

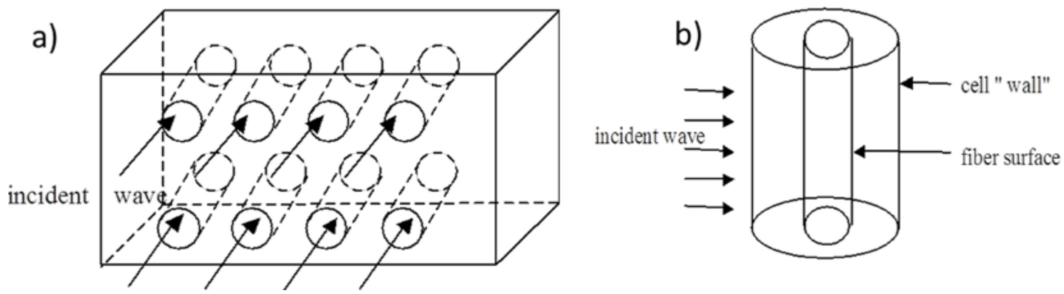

Fig. 5. Illustration of capillary pore (a) and parallel cylinder model (b). Figure redrawn from (Mechel 1988)

Strutt and Rayleigh (1877) were the first to use the capillary pore approach. Since then, there have been many later theories, which generalized this approach and introduced phenomenological parameters. Some of the most important contributions carried out on the capillary pore model are listed in Table 3.

Table 3. Important Event of the Capillary-Pore Model

Year	Event	Reference
1877	Introduced capillary pore model	(Strutt and Rayleigh 1877)
1941	Presents a theoretical description of porous materials saturated with a viscous fluid.	(Biot 1941)
1943	The first work regarded a porous medium as a mixture of two phases.	(Zwikker *et al.* 1943)
1944	Introduced effective mass and flow resistance.	(Morse and Bolt 1944)
1956	Identified of three types of waves for continuous material in 3D: two compression waves and one shear wave.	(Biot 1956)
1985	Established a matrix formulation for pulse propagation through a fluid-saturated porous media by using Biot's theory.	(Chin *et al.* 1985)
1989	A simpler model was derived with transfer matrices which described the sinusoidal wave propagation in a layered porous material.	(Allard *et al.* 1989)
1993	A five parameters model, which yields the noise absorption coefficients of fiber webs as a function of their thickness and porosity.	(Allard, Herzog *et al.* 1993)
1993	Studied the wave propagation in an anisotropic layered fluid saturated porous medium backed by an impervious surface at oblique incidence	(Sun *et al.* 1993).
1998	A novel exact mixed displacement pressure formulation. It has the form of a classical coupled fluid-structure problem.	(Atalla *et al.* 1998)
1999	The model yields the noise absorption coefficient of nonwovens as a function of thickness and porosity.	(Shoshani and Yakubov 1999)
2008	Two simplified models make it possible to evaluate the contributions of the compressional and shear waves in the solid phase.	(Nennig *et al.* 2008)
2008	The solid/fluid model of Biot's theory is transformed to an equivalent fluid/fluid model.	(Chazot and Guyader 2008)
2009	Study on the sensitivity analysis of porous materials models.	(Bolton and Hong 2009)
2010	A suitable theoretical model for calculating the sound absorption coefficient of weft knitted fabrics with complex structures	(Honarvar and Jeddi 2010).
2012	A more general model for calculating the absorption coefficients of double layered nonwovens	(Su 2012).

Solid Cylinders Models

As the capillary pore model does not provide an accurate representation of fibrous absorbers, models consisting of solid cylinders in a fluid medium have been developed. These models include either arrays of parallel cylinders or stacks of cylinders. Another classification of the "solid cylinders in fluid medium" models may be made as discrete and continuous models. In discrete models, the porous material is divided into "finite elements" which contain both the fluid and the solid phases, whereas in continuous models, the material is considered as a suspension of cylinders in a fluid medium. Beranek (1947) was the first to assume a model of rectangular cells as finite elements. The rectangular cells are divided into rigid solid and fluid parts in conformity the porosity. Attenborough and Walker (1971) suggested a multiple-scattering model. The model includes an array of parallel, elastic cylindrical fibers in air. The mechanism of sound dissipation was explained as that the incident waves being converted to viscous and thermal waves during scattering at the fiber periphery. The multiple-scattering model can benefit from the open-cell model for the evaluation of the scattered wave field. Mechel (1988) investigated parallel cylinder models as the sound waves propagating parallel versus perpendicular to fiber axis. He examined the transversal sound wave approach in three different modes: closed-cell, open-cell, and multiple-scattering modes. In closed-cell mode, the cell walls, as illustrated in Fig. 5(b), are transparent to the incident wave but impermeable for the scattered waves. In the open-cell model, the cell wall is transparent to both incident and scattered waves.

Empirical Models

Due to structural and geometrical complexities, it is extremely hard to define the acoustical behavior of most sound absorbers based on theoretical models (Fahy 2003). Thus, a number of empirical models have been developed for sound absorption behavior (Cox *et al.* 2004; Oldham *et al.* 2011). One of the most used empirical models for absorbent materials has been proposed by Delany and Bazley (1970). They obtained simple power-law relations by best fitting a large amount of experimental data for a range of fibrous porous absorbers. The empirical model is a good and fast approximation to the theoretical calculations because the model needs only one input parameter, the airflow resistivity. Bies and Hansen (1980) extended the lower and upper frequency ranges of validity of this model. Further updates and improvements were recommended by Miki (1990a, b). The model of Allard and Champoux (1992) is derived purely from a more rigorous theoretical basis. The range of validity extends further than that of Delany and Bazley, but it is also limited to fibrous materials. The main reason for these models being restricted to fibrous material only is due to the two other important material parameters, porosity and tortuosity, being significantly different from unity.

Unlike upon models developed for particular absorbing materials and frequency ranges, the Johnson-Champoux-Allard model is a generalized model for sound propagation over a wide range of frequencies. The model of Johnson-Champoux-Allard is based on five intrinsic properties of the porous medium: the flow resistivity, the porosity, the tortuosity, the viscous characteristic length, and the thermal characteristic length. While the open porosity and airflow resistivity can be directly measured, the measurements of the three remaining properties are usually complex. To solve the problem, an inverse characterization method based on impedance tube measurements is proposed. It is shown that this method can yield reliable evaluations of the tortuosity, the viscous and thermal characteristic lengths (Atalla and Panneton 2005).

In addition, Garai and Pompoli (2005) developed an empirical model based on a number of measurements upon polyester fibers. Due to the differences of fiber diameters and the densities of the matrix materials, they corrected some parameters in order to apply the calculations of polyester fibers effectively. The model due to Delany and Bazely was found to predict values of absorption coefficients for fibers with a large range of diameters that were in better agreement with measured values than predicted by the model of Garai and Pompoli. However, the latter model gave more accurate predictions for the case of wool, for which the fiber diameters were similar to those of the polymer fibers on which the Garai–Pompoli model was based. Both models were not effective when dealing with large diameter fibers. This failure may be due to the differences in the diameters of the fibers involved in their derivation from those of the coarser natural fibers. This could be resolved by a systematic study similar to that carried out by Delany and Bazely and Garai and Pompoli (Oldham *et al.* 2011). It should be pointed out that the diameter and density of polyester are similar to natural fiber. Thus, using the Garai and Pompoli model to predict the sound absorption parameter of natural fiber might give an accurate result (Yang and Li 2012).

STRUCTURE OPTIMIZATION AND FUTURE WORK

The sound transmission performance of the materials is of the utmost importance for noise control in automobiles, aircrafts, buildings, highway infrastructures, and several other engineering applications. There is a growing interest in optimizing and developing layered absorbing composite, which will meet the high stiffness-to-weight ratio and offer improved acoustic performance.

In order to design noise absorbers including several layers with different properties, a theoretical generalization of the Zwikker and Kosten model was suggested (Shoshani and Yakubov 2000, 2001). The material and geometric properties of the structure are treated as the design variables with the objective to maximize the sound transmission loss across the beam. Appropriate constraints are imposed to maintain material and structural integrity (Thamburaj and Sun 2002). An optimization study of cylindrical sandwich shells to minimize the transmitted sound into the interior is presented. From the promising optimization results it is seen that the reinforcement angles in the composite sandwich layers are effective structural design parameters to minimize the sound transmission into the interior without giving up the structural rigidity, particularly at low frequencies where the structural damping is not effective (Denli and Sun 2008). The novel Discrete Material Optimization (DMO) formulation has been applied to achieve the design optimization of fiber angles, stacking sequence and selection of material for laminated composite plates. Several numerical examples are presented in order to illustrate this approach (Niu *et al.* 2010).

The influence of morphologically altered cellulose fibers on the acoustic and mechanical properties was described (Neithalath *et al.* 2004). Three fiber morphologies for macro-nodules, discrete fibers, and petite nodules were considered. The acoustic absorption coefficient was found to increase with an increase in fiber volume for three fiber types investigated, though “macro-nodule” fibers were found to be the most effective. This suggests that there is an optimum fiber volume, which maximizes the loss modulus for saturated composites while the loss modulus is practically independent of fiber volume for dry composites (Neithalath *et al.* 2004). The acoustic absorption properties of four common fiber assemblies, including cashmere, goose down, and kapok fiber materials, were studied (Yang *et al.* 2011). There generally exists a sound frequency maximizing the absorption capability of fiber assembly at a given fiber mass. In addition, the characteristic diameter of effective pores, instead of the porosity or the fiber volume fraction, is the dominant factor on the sound absorption of the fiber assemblies. The results suggest that a fiber assembly with a lower fiber density and a smaller fiber average diameter leads to a better sound absorption performance (Yang *et al.* 2011).

Recent development in wood/natural fiber filled plastic composite coextrusion technology allows creating multi-layer composites with different complementary layer characteristics, and in making properties of final products highly "tunable". For example, target composite properties such as oxygen, sound and moisture barrier, shading and insulation, and mechanical properties can be achieved by incorporating one or more layers with target properties. In addition, coextrusion can significantly reduce material and production costs, and help recycle used material (Kim *et al.* 2012; Kim 2012; Yao and Wu 2010). Sound insulation application of co-extruded wood/natural fiber plastic composites can help develop new market opportunities for the materials in both exterior and interior uses. Future development in the field will include controlling composite morphology, density, and strength through layering, core foaming, and shell hardening, and developing/using sound absorbing and deadening materials such as nano fillers in the composite formulations (Fig. 6).

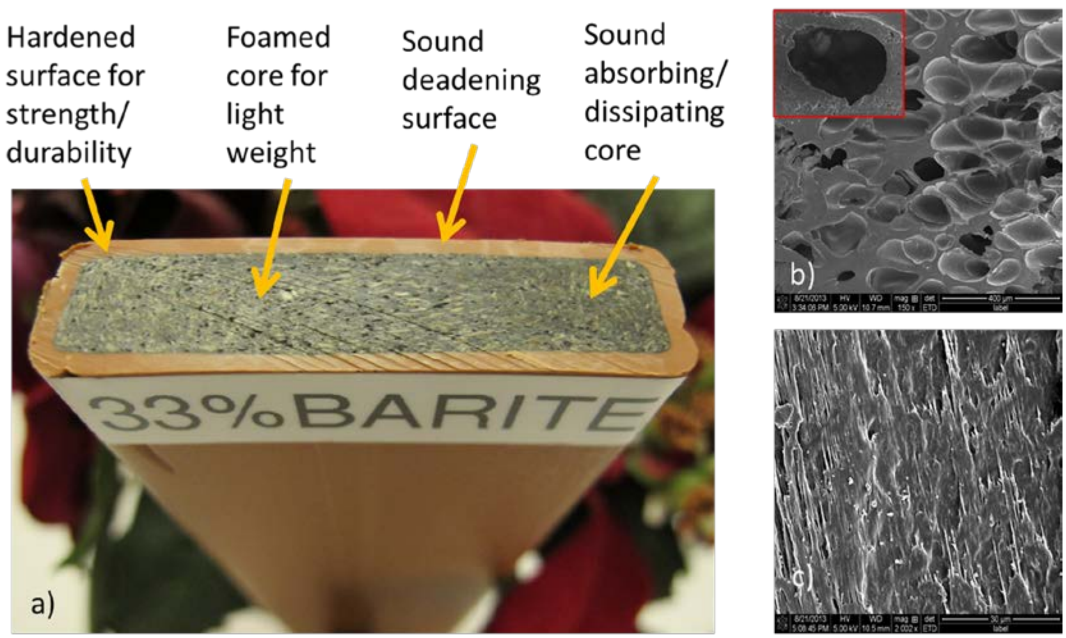

Fig. 6. Co-extruded wood plastic composites (WPCs). a) Core-shell structured WPC for sound insulation applications; b) microstructure of foamed WPC core (density=0.55 g/cm^3), and c) microstructure of unfoamed WPC core (density=1.05 g/cm^3). Photographs taken by Q. Wu.

SUMMARY STATEMENTS

1. Examination of the acoustical characteristics of a range of natural fibers has confirmed their effectiveness as porous sound absorbers. The most promising natural fibers for use are those for which the average diameters are small and which are capable

of being well compacted, since compaction increases the chance of friction between sound waves and fibers.

2. The sound insulation properties of natural fiber based composites are controlled by inter-fiber voids and within-fiber voids. Variable densities may result in different behavior of noise reduction since the density has great influence on the porosity of fibrous assemblies.

3. Activated carbon materials and nano-composites are ideal for use as high-performance adsorbents, because of their very high specific surface area and a high micropore volume.

4. The sandwich panel is a useful way to increase the sound insulation, wherein the core acts as a spacer construction that has mass and that does transmit shear, while the skins respond as elementary bent plates.

5. The available theoretical and empirical models were not effective when dealing with large diameter fibers. This failure may be due to the differences in the diameters of the fibers. This could be resolved by a systematic study similar to that carried out by Garai and Pompol, which is suitable to predict the sound absorption parameter of natural fiber.

6. There is a growing interest in optimizing and developing a new sandwich composite, which will meet the high stiffness-to-weight ratio and offer improved acoustic performance. The layered absorbing structure can produce a sufficiently satisfying sound absorption level in a cared frequency range.

7. There are still technical challenges for the best combination of cellulose-based materials and structures of different densities to deal with the low frequency noise effectively.

ACKNOWLEDGMENTS

We acknowledge the support from the Fundamental Research Funds for the Central Universities of China (DL12EB02-03), from the National Natural Science Foundation of China (Grant No.31010103905), and from the LSU Agricultural Center.

REFERENCES CITED

Allard, J. F., and Champoux, Y. (1992). "New empirical equations for sound propagation in rigid frame fibrous materials," *The Journal of the Acoustical Society of America* 91, 3346-3353.

Allard, J. F., and Daigle, G. (1994). "Propagation of sound in porous media: Modeling sound absorbing materials," *The Journal of the Acoustical Society of America* 95(5), 2785-2785.

Allard, J. F., Depollier, C., Rebillard, P., Lauriks, W., and Cops, A. (1989). "Inhomogeneous Biot waves in layered media," *Journal of Applied Physics* 66(6), 2278-2284.

Amaral-Labat, G., Gourdon, E., Fierro, V., Pizzi, A., and Celzard, A. (2013). "Acoustic properties of cellular vitreous carbon foams," *Carbon* 58(0), 76-86.

Arenas, J. P., and Crocker, M. J. (2010). "Recent trends in porous sound-absorbing materials," *Sound & Vibration* 44(7), 12-18.

Asdrubali, F. (2006). "Survey on the acoustical properties of new sustainable materials for noise control," *Euronoise 2006*, 30.

Asdrubali, F., Schiavoni, S., and Horoshenkov, K. (2012). "A review of sustainable materials for acoustic applications," *Building Acoustics* 19(4), 283-312.

Atalla, N., Panneton, R., and Debergue, P. (1998). "A mixed displacement-pressure formulation for poroelastic materials," *The Journal of the Acoustical Society of America* 104, 1444.

Bahrambeygi, H., Sabetzadeh, N., Rabbi, A., Nasouri, K., Shoushtari, A. M., and Babaei, M. R. (2013). "Nanofibers (PU and PAN) and nanoparticles (Nanoclay and MWNTs) simultaneous effects on polyurethane foam sound absorption," *Journal of Polymer Research* 20(2), 1-10.

Beranek, L. L. (1947). "Acoustical properties of homogeneous, isotropic rigid tiles and flexible blankets," *The Journal of the Acoustical Society of America* 19, 556-568.

Bies, D., and Hansen, C. (1980). "Flow resistance information for acoustical design," *Applied Acoustics* 13(5), 357-391.

Biot, M. (1956). "Theory of deformation of a porous viscoelastic anisotropic solid," *Journal of Applied Physics* 27(5), 459-467.

Biot, M. A. (1941). "General theory of three ‐ dimensional consolidation." *Journal of applied physics*, 12(2), 155-164.

Bolton, J. S., and Hong, K. (2009). "Inverse characterization of poro-elastic materials based on acoustical input data," *The Journal of the Acoustical Society of America* 126, 2297-2297.

Chazot, J.-D., and Guyader, J.-L. (2007). "Prediction of transmission loss of double panels with a patch-mobility method," *The Journal of the Acoustical Society of America* 121, 267-278.

Chazot, J.-D., and Guyader, J.-L. (2008). "Acoustic modeling of light and non-cohesive poro-granular materials with a fluid/fluid model," *Acta Mechanica* 195(1-4), 227-247.

Chen, Y., and Jiang, N. (2007). "Carbonized and activated non-wovens as high-performance acoustic materials: Part I - Noise absorption," *Textile Research Journal* 77(10), 785-791.

Chen, Y., and Jiang, N. (2009). "Carbonized and activated non-woven as high performance acoustic materials: Part II. Noise insulation," *Textile Research Journal* 79(3), 213-218.

Chin, R., Berryman, J., and Hedstrom, G. (1985). "Generalized ray expansion for pulse propagation and attenuation in fluid-saturated porous media," *Wave Motion* 7(1), 43-65.

Cox, T. J., D'Antonio, P., and Avis, M. R. (2004). "Room sizing and optimization at low frequencies," *Journal of the Audio Engineering Society* 52(6), 640-651.

Cunningham, P. R., White, R. G., and Aglietti, G. S. (2000). "The effects of various design parameters on the free vibration of doubly curved composite sandwich panels," *Journal of Sound and Vibration* 230(3), 617-648.

Delany, M. E., and Bazley, E. N. (1970). "Acoustical properties of fibrous absorbent materials," *Applied Acoustics* 3(2), 105-116.

Denli, H., and Sun, J. Q. (2008). "Structural–acoustic optimization of sandwich cylindrical shells for minimum interior sound transmission," *Journal of Sound and Vibration* 316(1-5), 32-49.

Ekici, B., Kentli, A., and Küçük, H. (2012). "Improving sound absorption property of polyurethane foams by adding tea-leaf fibers," *Archives of Acoustics* 37(4), 515-520.

Ersoy, S., and Küçük, H. (2009). "Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties," *Applied Acoustics* 70(1), 215-220.

Fahy, F. (2003). "Some applications of the reciprocity principle in experimental vibroacoustics," *Acoustical Physics* 49(2), 217-229.

Faustino, J., Pereira, L., Soares, S., Cruz, D., Paiva, A., Varum, H., Ferreira, J., and Pinto, J. (2012). "Impact sound insulation technique using corn cob particleboard," *Construction and Building Materials* 37, 153-159.

Garai, M., and Pompoli, F. (2005). "A simple empirical model of polyester fibre materials for acoustical applications," *Applied Acoustics* 66(12), 1383-1398.

Glé, P., Gourdon, E., and Arnaud, L. (2011). "Acoustical properties of materials made of vegetable particles with several scales of porosity," *Applied Acoustics* 72(5), 249-259.

Heckl, M. (1981). "The tenth Sir Richard Fairey memorial lecture: Sound transmission in buildings," *Journal of Sound and Vibration* 77(2), 165-189.

Hoff, N. J. (1950). *Bending and Buckling of Rectangular Sandwich Plates*, National Advisory Committee for Aeronautics.

Holmer, C. I. (1969). "The coincidence wall: A new design for high transmission loss or high structural damping." *The Journal of the Acoustical Society of America* 46, 91-91.

Honarvar, M. G., and Jeddi, A. A. A. (2010). "Noise absorption modeling of rib knitted fabrics," *Textile Research Journal* 80(14), 1392-1404.

Hosseini Fouladi, M., Ayub, M., and Jailani Mohd Nor, M. (2011). "Analysis of coir fiber acoustical characteristics," *Applied Acoustics* 72(1), 35-42.

Jeong, C.-H. (2010). "Non-uniform sound intensity distributions when measuring absorption coefficients in reverberation chambers using a phased beam tracing," *The Journal of the Acoustical Society of America* 127, 3560-3560.

Jones, R. E. (1979). "Intercomparisons of laboratory determinations of airborne sound transmission loss," *The Journal of the Acoustical Society of America* 66, 148-164.

Kanev, N. (2012). "Sound decay in a rectangular room with impedance walls," *Acoustical Physics* 58(5), 603-609.

Kim, B.-J., Yao, F., Han, G., Wang, Q., and Wu, Q. (2012). "Mechanical and physical properties of core-shell structured wood plastic composites: Effect of shells with hybrid mineral and wood fillers," *Composites Part B: Engineering* 45, 1040-1048.

Kim, B. J. (2012). "The effect of inorganic fillers on the properties of wood plastic composites," Louisiana State University.

Koizumi, T., Tsujiuchi, N., and Adachi, A. (2002). "The development of sound absorbing materials using natural bamboo fibers." *High performance structures and composites*, 4, 157-166.

Kurtze, G., and Watters, B. (1959). "New wall design for high transmission loss or high damping," *The Journal of the Acoustical Society of America* 31, 739-748.

Kuttruff, H. (1995). "A simple iteration scheme for the computation of decay constants in enclosures with diffusely reflecting boundaries," *The Journal of the Acoustical Society of America* 98, 288-293.

Lauriks, W., Cops, A., Allard, J. F., Depollier, C., and Rebillard, P. (1990). "Modelization at oblique incidence of layered porous materials with impervious screens," *The Journal of the Acoustical Society of America* 87, 1200-1205.

Lee, C. M., and Xu, Y. (2009). "A modified transfer matrix method for prediction of transmission loss of multilayer acoustic materials," *Journal of Sound and Vibration* 326(1-2), 290-301.

Lee, J.-C., Hong, Y.-S., Nan, R.-G., Jang, M.-K., Lee, C. S., Ahn, S.-H., and Kang, Y.-J. (2009). "Soundproofing effect of nano particle reinforced polymer composites,"

Journal of Mechanical Science and Technology 22(8), 1468-1474.
Li, P., Kim, B.-J., Wang, Q., and Wu, Q. (2013). "Experimental and numerical analysis of the sound insulation property of wood plastic composites (WPCs) filled with precipitated $CaCO_3$," *Holzforschung* 67(3), 301-306.
Li, Y., Luo, Y., and Han, S. (2010). "Multi-scale structures of natural fibres and their applications in making automobile parts," *Journal of Biobased Materials and Bioenergy* 4(2), 164-171.
Liang, J. Z., and Jiang, X. H. (2012). "Soundproofing effect of polypropylene/inorganic particle composites," *Composites Part B-Engineering* 43(4), 1995-1998.
Liew, K., Jiang, L., Lim, M., and Low, S. (1995). "Numerical evaluation of frequency responses for delaminated honeycomb structures," *Computers & Structures* 55(2), 191-203.
Liu, D., Ruan, M., Xia, K., Yang, R., Zeng, J., and Yang, F. (2013). "Manufacturing gradient acoustic pulp/granular particle biocomposites," *Journal of Biobased Materials and Bioenergy* 7(1), 122-126.
Mechel, F. (1988). "Design charts for sound absorber layers," *The Journal of the Acoustical Society of America* 83, 1002-1013.
Miki, Y. (1990a). "Acoustical properties of porous materials - Modifications of Delany-Bazley models," *J. Acoust. Soc. Jpn. (E)* 11(1), 19-24.
Miki, Y. (1990b). "Acoustical properties of porous materials: Generalizations of empirical models," *Journal of the Acoustical Society of Japan (E)* 11(1), 25-28.
Moore, J., and Lyon, R. (1991). "Sound transmission loss characteristics of sandwich panel constructions," *The Journal of the Acoustical Society of America* 89, 777-790.
Morse, P. M., and Bolt, R. H. (1944). "Sound waves in rooms," *Reviews of Modern Physics* 16(2), 69-100.
Neithalath, N., Weiss, J., and Olek, J. (2004). "Acoustic performance and damping behavior of cellulose–cement composites," *Cement and Concrete Composites* 26(4), 359-370.
Nennig, B., Chazot, J.-D., Perrey-Debain, E., and Ben Tahar, M. (2008). "Influence of solid phase elasticity in poroelastic liners submitted to grazing flows," *Journal of the Acoustical Society of America* 123(5), 3571-3571.
Ng, C. F., and Hui, C. K. (2008). "Low frequency sound insulation using stiffness control with honeycomb panels," *Applied Acoustics* 69(4), 293-301.
Ni, Q.-Q., Lu, E., Kurahashi, N., Kurashiki, K., and Kimura, T. (2008). "Development of insulation sheet materials and their sound characterization," *Advanced Composite Materials* 17(1), 25-40.
Nilsson, A. (1990). "Wave propagation in and sound transmission through sandwich plates," *Journal of Sound and Vibration* 138(1), 73-94.
Niu, B., Olhoff, N., Lund, E., and Cheng, G. (2010). "Discrete material optimization of vibrating laminated composite plates for minimum sound radiation," *International Journal of Solids and Structures* 47(16), 2097-2114.
Oldham, D. J., Egan, C. A., and Cookson, R. D. (2011). "Sustainable acoustic absorbers from the biomass," *Applied Acoustics* 72(6), 350-363.
Olivieri, O., Bolton, J. S., and Yoo, T. (2006). "Measurement of transmission loss of materials using a standing wave tube," *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 3515-3522.
Ouisse, M., Maxit, L., Cacciolati, C., and Guyader, J.-L. (2005). "Patch transfer functions as a tool to couple linear acoustic problems," *Journal of Vibration and Acoustics* 127(5), 458-466.

Panneton, R., and Atalla, N. (1996). "Numerical prediction of sound transmission through finite multilayer systems with poroelastic materials," *The Journal of the Acoustical Society of America* 100, 346-353.

Rao, S., Jayaraman, K., and Bhattacharyya, D. (2011). "Short fibre reinforced cores and their sandwich panels: Processing and evaluation," *Composites Part A: Applied Science and Manufacturing* 42(9), 1236-1246.

Sagartzazu, X., Hervella-Nieto, L., and Pagalday, J. (2008). "Review in sound absorbing materials," *Archives of Computational Methods in Engineering* 15(3), 311-342.

Sargianis, J., and Suhr, J. (2012). "Core material effect on wave number and vibrational damping characteristics in carbon fiber sandwich composites," *Composites Science and Technology* 72(13), 1493-1499.

Sargianis, J. J., Kim, H. I., Andres, E., and Suhr, J. (2013). "Sound and vibration damping characteristics in natural material based sandwich composites," *Composite Structures* 96, 538-544.

Shi, G., and Lam, K. (1999). "Finite element vibration analysis of composite beams based on higher-order beam theory," *Journal of Sound and Vibration* 219(4), 707-721.

Shoshani, Y., and Yakubov, Y. (1999). "A model for calculating the noise absorption capacity of nonwoven fiber webs," *Textile Research Journal* 69(7), 519-526.

Shoshani, Y., and Yakubov, Y. (2000). "Generalization of Zwikker and Kosten theory for sound absorption in flexible porous media to the case of variable parameters," *Journal of Computational Acoustics* 8(3), 415-441.

Shoshani, Y., and Yakubov, Y. (2001). "Use of nonwovens of variable porosity as noise control elements," *Int Nonwovens J*. 10, 23-28.

Song, B. H., and Bolton, J. S. (2000). "A transfer-matrix approach for estimating the characteristic impedance and wave numbers of limp and rigid porous materials," *The Journal of the Acoustical Society of America* 107, 1131-1151.

Stacy, E. (1959). "Sound insulation in buildings," *The Journal of the Royal Society for the Promotion of Health* 79(6), 789-797.

Strutt, J. W., and Rayleigh, B. (1877). *The Theory of Sound*, Vol. 1, Dover Publications, New York.

Su, X. (2012). "Simulation model for the absorption coefficients of double layered nonwovens," *Fibres & Textiles in Eastern Europe* 20(4), 102-107.

Suhawati, I., Shamsul, K., Ismaliza, I., and Kamarudin, A. M. (2013). "Sound absorption analysis of foamed rubber composites from kenaf and calcium carbonate," *Journal of Rubber Research* 16(1), 36-44.

Sun, F., Banks-Lee, P., and Peng, H. (1993). "Sound absorption in an anisotropic periodically layered fluid-saturated porous medium," *Applied Acoustics* 39(1), 65-76.

Suzuki, M. (1994). "Activated carbon fiber: Fundamentals and applications," *Carbon* 32(4), 577-586.

Thamburaj, P., and Sun, J. Q. (2002). "Optimization of anisotropic sandwich beams for higher sound transmission loss," *Journal of Sound and Vibration* 254(1), 23-36.

Thomson, W. T. (1950). "Transmission of elastic waves through a stratified solid medium," *Journal of Applied Physics* 21, 89-93.

Veerakumar, A., and Selvakumara, N. (2012). "A preliminary investigation on kapok/polypropylene nonwoven composite for sound absorption," *Indian Journal of Fibre & Textile Research* 37, 385-388.

Vorländer, M., and Mommertz, E. (2000). "Definition and measurement of random-incidence scattering coefficients," *Applied Acoustics*, 60(2), 187-199.

Voronina, N. (1994). "Acoustic properties of fibrous materials," *Applied Acoustics* 42(2),

165-174.
Wassilieff, C. (1996). "Sound absorption of wood-based materials," *Applied Acoustics* 48(4), 339-356.
Xiang, H. F., Wang, D., Liu, H. C., Zhao, N., and Xu, J. (2013). "Investigation on sound absorption properties of kapok fibers," *Chinese Journal of Polymer Science* 31(3), 521-529.
Yang, H.-S., Kim, D.-J., and Kim, H.-J. (2003). "Rice straw–wood particle composite for sound absorbing wooden construction materials," *Bioresource Technology* 86(2), 117-121.
Yang, S., Yu, W., and Pan, N. (2011). "Investigation of the sound-absorbing behavior of fiber assemblies," *Textile Research Journal* 81(7), 673-682.
Yang, W. D., and Li, Y. (2012). "Sound absorption performance of natural fibers and their composites," *Science China-Technological Sciences* 55(8), 2278-2283.
Yao, F., and Wu, Q. (2010). "Coextruded polyethylene and wood-flour composite: Effect of shell thickness, wood loading, and core quality," *Journal of Applied Polymer Science* 118(6), 3594-3601.
Zulkarnain, Zulkifli, R., and Nor, M. J. M. (2011). "Effect of porous layer backing and perforation ratio of perforated plate on acoustic characteristics of coconut fibre as a sound absorbent," *Sains Malaysiana* 40(6), 623-629.
Zwikker, C., Van den Eijk, J., and Kosten, C. W. (1943). "Absorption of sound by porous material, V," *Physica* 10, 239-247.

Article submitted: October 1, 2013; Peer review completed: October 25, 2013; Revised version received: December 10, 2013; Accepted: December 15, 2013; Published: December 17, 2013.