SUSTAINABLE ACOUSTIC ABSORBERS FROM THE BIOMASS

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1 INTRODUCTION

Conventional porous sound absorbers are frequently manufactured from minerals using processes that require the consumption of significant amounts of energy. In addition, some materials are believed to pose serious health risks. For these reasons, in the field of thermal insulation, designers are currently exploring the use of biomass materials to replace conventional materials such as rock wool and glass fibre that are frequently also used as porous absorbers. In this paper we investigate the application of biomass materials as novel and sustainable sound absorbent treatments. Current models for the characterisation of porous absorbers are used to identify candidate materials. Impedance tube measurements are carried out for a number of these materials and the results are presented.

2 CANDIDATE MATERIALS FOR POROUS ABSORBERS

Conventional porous sound absorbers come in a variety of forms and their performance depends upon their pore structure[1]. The most common form of porous sound absorbers are fibrous materials and some foams. There are a number potential candidate materials in the form of organic fibres, many of which have a long history of cultivation for use in fabrics (cotton, wool, flax, silk), as floor coverings (wool, reeds), sacking (jute, hessian) and ropes (hemp).

A second form of porous sound absorbers includes those composed of loose or consolidated granular materials and/or fibres. Although these materials are almost homogeneous, their pore shape can be considerably different from the circular geometry normally assumed for fibrous materials. Also the pore length can have a considerable twist such that it is no longer considered to be straight. Commercial products are already available manufactured from biomass materials in the form of various board products consisting of shredded and compressed wood, straw or reed particles. Wassileiff[2] has shown how the performance of wood based materials can be predicted from application of the Attenborough [3] model and these will not be considered in this paper.

There are other granular based materials that have a highly heterogeneous structure such as those manufactured from crumbed rubber. In terms of pore distribution these have certain similarities to the pores occurring in layers of un-shredded straw or reeds. In the case of straw and reeds the pores arise from the non uniformity of the cross sections of individual lengths. This results in a large number of slit like pores, parallel to the straw or reed lengths, that communicate with large cavities between the individual straws or reeds.

In this paper we describe an investigation of the acoustical performance of a number of fibrous materials and a number of different orientations of reeds and relate these to established models for the prediction of their acoustical properties.

3 ABSORPTION COEFFICIENT

The normal incidence sound absorption coefficient of a wall is given by:

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

Where R is the sound pressure reflection coefficient and this in turn is given by:

$$R = \frac{z_s - \rho_0 c}{z_s + \rho_0 c} \tag{2}$$

Where Zs is the surface impedance of the wall

In the case of a single layer of porous material with a rigid backing the surface impedance, z_s , is given by:

$$z_s = -j z_c \cot(k_c d) \tag{3}$$

Where z_c is the characteristic impedance of the porous material, k_c is the complex wave number and d is the thickness of the layer. Thus in order to predict the performance of a porous material it is necessary to know both z_c and k_c.

4 CHARACTERISATION MODELS FOR POROUS ABSORBERS

4.1 Fibrous Materials

Fibrous materials and foams are highly porous and homogeneous. For these materials the most important parameter is the flow resistivity and this can be used to predict their characteristic impedance and propagation constant from a number of empirical formulae, most notably those given below which are based upon the work of Delany and Bazley[4].

$$z_c = \rho_o c\left(1 + 0.0571\left(\frac{\rho_o f}{\sigma}\right)^{-0.754} - j0.087\left(\frac{\rho_o f}{\sigma}\right)^{-0.732} \right) \tag{4}$$

$$k_c = \omega / c \left(1 + 0.0978\left(\frac{\rho_o f}{\sigma}\right)^{-0.7} - j0.189\left(\frac{\rho_o f}{\sigma}\right)^{-0.595} \right) \tag{5}$$

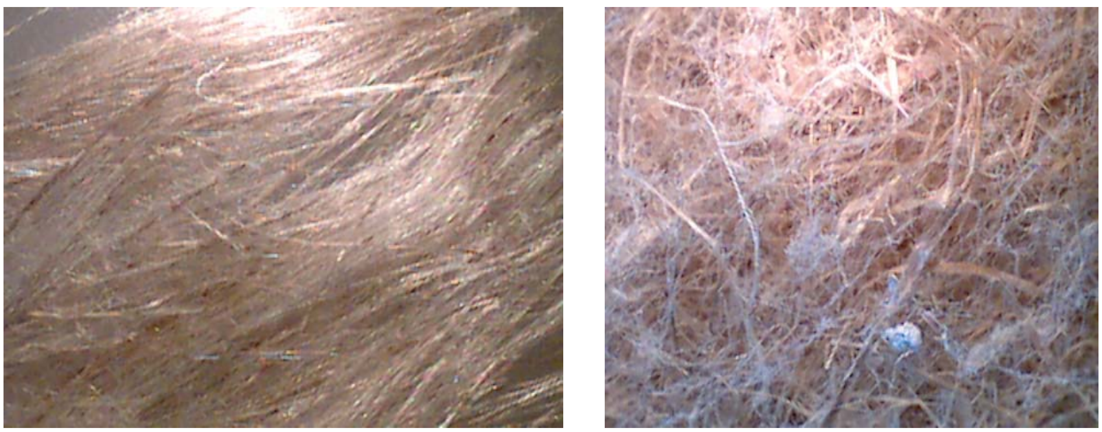
Where ρ_o is the density of air, σ is the flow resistivity and *f* is the frequency.

The flow resistivity is a property of the fibre diameter and porosity of the material. For a material having only a small amount of binder, the porosity, ε, is given by:

$$\varepsilon = 1 - \rho_B/\rho_m \quad (6)$$

Where ρ_B is the bulk density of the absorber and ρ_m is the density of the matrix material. For a material such as glass fibre where it is possible to obtain the matrix material, glass, in the form of a homogeneous solid, application of Equation (6) is straightforward. However, plant based fibrous materials are composed mainly of cellulose and the identification of an appropriate value for the density of the matrix material is more difficult. In this work the value employed was 700 kgm^{-3} which is typical of a dense hardwood i.e. wood containing few air filled voids.

The radii of natural fibres ranges typically from 10 to 50 microns. The fibres investigated in this work included flax and bamboo which have fibre diameters of approximately 25 microns and hemp which has coarser fibres of diameter typically 40 microns. The differing fibrous natures of flax and hemp can be seen in Figure 1.



Flax   Hemp

Figure 1. Flax and hemp fibres.

Several empirical relationships have been developed for the calculation of flow resistivity. In this work the formula employed was that reported by Mechel [5] for fibre radii ranging from 20 to 30 μm respectively in which the flow resistivity is given by:

$$\sigma = \frac{6.8\eta(1-\varepsilon)^{1.296}}{a^2\varepsilon^3} \quad (7)$$

where η is the viscosity of air (equal to 1.84 x 10^{-5} poiseuille) and *a* is the radius of the fibres.

4.2 Materials having highly heterogeneous pore structures

Characterisation models for materials having relatively complex pore structures have been developed using the micro structural approach which involves deriving the wave propagation inside individual pores and then generalizing the results to the macroscopic scale. This approach gives rise to expressions for the complex density, ρ_b, and complex compressibility, C_b, from which the characteristic impedance and complex wave number can be calculated as follows:

$$z_c = \left[\frac{\rho_b(\omega)}{C_b(\omega)}\right]^{\frac{1}{2}} \tag{8}$$

$$k_c = i\omega\left[\rho_b(\omega)C_b(\omega)\right]^{\frac{1}{2}} \tag{9}$$

The structure of highly heterogeneous materials is characterised by a wide variation in the pore size distribution which tends to have more effect on their performance than the shape and tortuosity of the pores. Thus the characterisation of materials with a highly heterogeneous pore structure requires the incorporation of a parameter to account for the pore size distribution in the material structure.

A model to describe heterogeneous material structures was presented by Horoshenkov, Attenborough and Chandler-Wilde [6]. Equations 10 and 11 show the expressions for calculating the complex density and complex compressibility using this model.

$$\rho_b(\omega) = \frac{q^2}{\varepsilon}\left(\rho_o - \frac{\varepsilon R_b}{i\omega q^2}F(\omega)\right) \tag{10}$$

$$C_b(\omega) = \frac{\varepsilon}{\gamma P_0}\left(\gamma - \frac{\lambda - 1}{1 - \dfrac{\varepsilon\sigma}{i\omega q_\infty N_{PR}}F(\omega N_{PR})}\right) \tag{11}$$

Where F is the viscosity correction factor which is a function of pore size distribution of the material, λ is a scaling factor to account for the different pore shapes, ρ_0 is the equilibrium density, q is the tortuosity, N_{PR} is the Prandtl number for air and *c* is the speed of sound.

5 EXPERIMENTAL RESULTS

The measurements reported in this paper were made on small samples using the Brüel & Kjær, Impedance Tube Kit Type 4206. Measurements were based on the two-microphone transfer-function method according to ISO 10534–2 [7].

5.1 Fibrous Materials

Measurements were made on three fibrous materials: flax, bamboo and hemp. The first two materials both consist of very fine strands and have a typical fibre diameter of 25 microns. The hemp fibres were much coarser, generally shorter and with a typical fibre diameter of 40 microns. The hemp also came in two forms, the first being a 70mm thick batt intended for use as a thermal insulator, and 8mm thick sheets intended for use as mats in animal enclosures. Applying these data plus an estimated matrix material density of 700 Kgm^{-3} to equations (6) and (7) yields the values of porosity and flow resistivity shown in Table 1.

Material	Porosity	Flow resistivity (rayl/m)
Flax	0.84	15,560
Bamboo	0.84	15,560
Hemp	0.92	3,350
Compressed hemp	0.84	7,930

Table 1: Fibre Data

Figure 3 shows the measured absorption coefficient as a function of frequency for different thicknesses of flax and bamboo fibres and Figure 4 shows the measured absorption coefficient as a function of frequency for different thicknesses and compressions of hemp fibres.

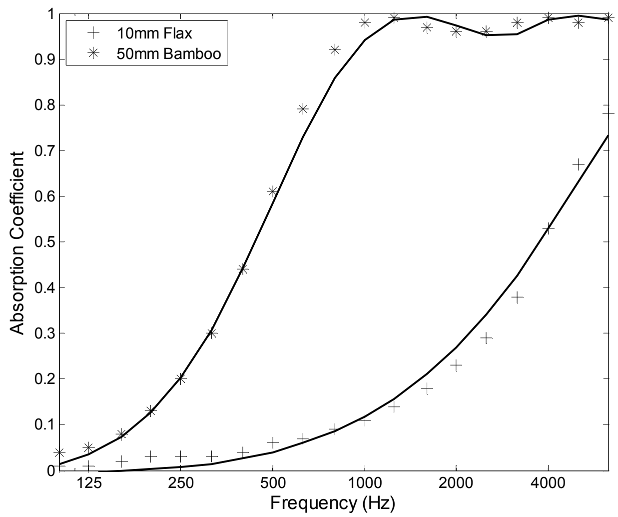


Figure 2 – Absorption coefficient of flax (10mm thickness) and bamboo samples 50mm thickness). Continuous line relates to predicted values and points relate to measured data.

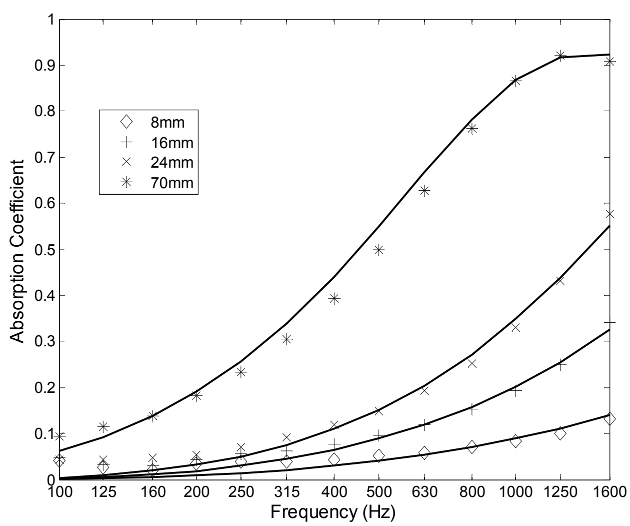


Figure 3 – Absorption coefficient of hemp fibre: thicknesses of 8mm, 16mm and 24mm (compressed) and 70mm

It can be seen that the absorption coefficients are typical of porous materials with a homogeneous pore structure of these thicknesses against a solid backing surface. It can also be seen that the predicted values, obtained by using estimates of porosity and resistivity in the model of Delany and Bazley, are in good agreement with the measured data.

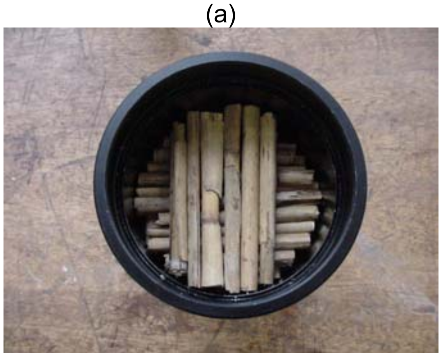
5.2 Heterogeneous pore structure

In this preliminary study three configurations of reed were investigated as can be seen in Figure 4.

The first consisted of 50 mm long reed lengths aligned such that the reed cross section was perpendicular to the direction of the incident sound wave. This configuration might not be suitable for use in outdoor applications as exposure of the cut ends to adverse climatic conditions would probably result in rapid deterioration. More suitable configurations would be similar to those employed for roof thatching with the more durable reed length exposed to the elements. Although the reeds on a thatched roof typically all lie in the same direction, in the context of reeds used as absorbers there might be benefits in arranging for reeds to lie with varying orientations. In this preliminary study, therefore, both orientation in a single direction and orthogonal orientations were investigated. Because of the irregular nature of the reed cylinder there are slit like gaps between reeds and these will link through to the large voids between reeds.


(a)


(b)


(c)

(a) End –on

(b) Orientation in single direction

(c) Orientation in alternating directions

Figure 4: Reed configurations

Figure 5 shows the measured absorption coefficient as a function of frequency for the "end on" configuration. The absorption characteristics are similar to those of a homogeneous porous material but exhibit a pronounced dip centred around 3.15kHz. This dip could be due to a resonance effect arising from the nature of the voids between reeds which tend to be largely open and extend the full 50mm of the sample depth. A distance of 50mm corresponds to the half wavelength of sound at a frequency of approximately 3.4 kHz which corresponds closely to the frequency where the dip in the value of the absorption coefficient is observed.

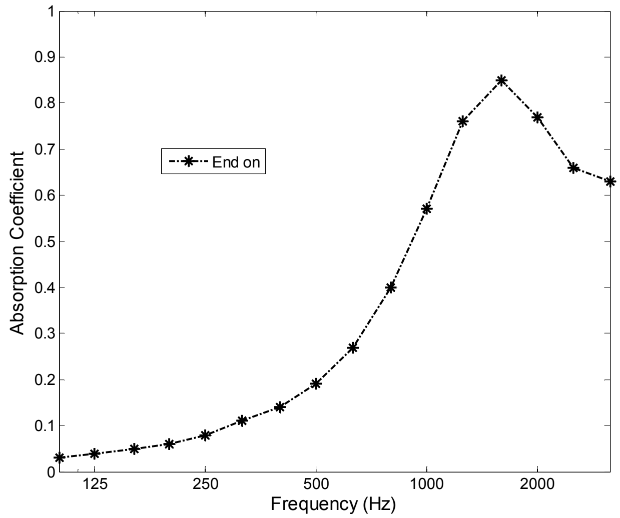


Figure 5: Absorption coefficient of reed samples: sound incident on to cut face.

The “end-on” structure consists of reed tubes with significant voids between them. The reeds are hollow but contain pith which might be expected to act as a homogeneous porous material. Because of the lined tube structure, reeds arranged in this orientation do not conform well to the heterogeneous model and might be expected to act more like a homogeneous material. However, the holes in the reed are blind and although they might be expected to make a significant contribution to the sound absorption, it is not clear how they might affect the effective bulk flow resistivity. It was not possible, therefore, to apply the Delany-Bazley model to this case.

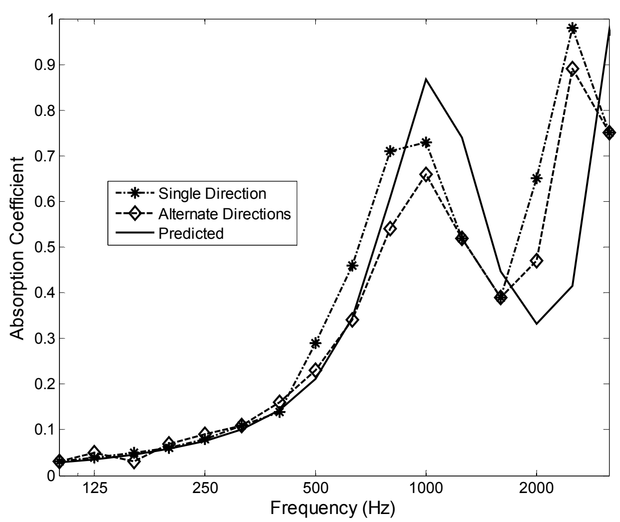


Figure 6: Absorption coefficient of reed samples: orientated in single and alternate directions.

The measured values of the absorption coefficient as a function of frequency for reeds arranged in a single direction and in alternate directions are shown in Figure (6). it can be seen that the results for configurations show a pronounced dip in the characteristics at 1.6 kHz and are then virtually identical above this frequency. Below 1.6 kHz the shape of the characteristics are similar but the single direction orientation configuration has higher values of absorption coefficient.

The values of absorption coefficient are small at low frequencies and although they rise with increasing frequency, they exhibit a number of peaks and troughs. The characteristics are typical of a material having a heterogeneous pore structure. An attempt was made to apply the model of Horoshenkov, Attenborough and Chandler-Wilde [6]. In the absence of any measured data relating to flow resistivity, porosity, tortuosity and pore size distribution these were estimated by a combination of visual inspection (porosity, tortuosity and pore size distribution) and previous experience (flow resistivity). It should be noted that because of the large pore size the use of visual inspection is more practicable than it would be with most absorbers. The predicted absorption characteristics for a flow resistivity of 1,500 rayl/m, porosity of 0.6, tortuosity of 1.5 and standard deviation of pore size of 0.7 are show in Figure (6). It can be seen that the predicted values have similar trends to the measured data. However, given the use of estimated parameters in the prediction model the only conclusion that can be drawn is that the Horoshenkov, Attenborough and Chandler-Wilde possibly offers a route to the understanding of the performance of these structures.

6 CONCLUDING REMARKS

The application of biomass materials as novel and sustainable sound absorbent treatments has been investigated. Current models for the characterization of porous absorbers have been used to identify candidate materials and impedance tube measurements are carried out for a number of these materials and the results are presented. Examination of the acoustical characteristics of natural fibres has confirmed their effectiveness as porous sound absorbers with properties similar to those of conventional absorbers made from rock wool or fiberglass. Examination of the acoustical performance of different configurations of whole reeds has revealed that these also possess considerable potential for application of sound absorbers.

In practical applications, however, other performance criteria have to be achieved. Of particular importance in situations in which porous absorbers might be employed are durability and fire resistance. The biomass materials examined in this work have been largely composed of cellulose and are not generally attractive as food to insects. However, if exposed to water they can be subject to fungal attack. In a dry building this will present no problem but might preclude their application in some environments. With regard to fire risk, cellulose based materials such as hemp thermal insulation and re-cycled newspapers used as thermal insulation, are routinely treated with fire retardant chemicals to make them safe.

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