First International Conference on
Bio-based Building Materials

June 22nd - 24th 2015
Clermont-Ferrand, France

ACOUSTICAL CHARACTERIZATION AND MODELLING OF AGRICULTURAL BY-PRODUCTS FOR BUILDING INSULATION

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Abstract

In a general context of global warming, an increasing interest is observed on the use of bio-based insulating materials. Indeed, this kind of materials ensures good thermal characteristics while drastically reducing fossil energy consumption and greenhouse gas emissions associated with their manufacture. In addition, thanks to their permeancy (ability to allow diffusion of water vapor within their porous network), these materials present an alternative option to isolate and rehabilitate buildings made with non-industrial materials (rammed earth, cob, adobe,...) and whose stability requires to maintain a water exchange with the outside. Bio-based materials from plants have promising thermal and acoustical characteristics which are the subject of several studies now. In this work, the acoustical properties of hemp particles (shiv), flax (shiv), sunflower (pith and bark) and rape (straw) are measured and compared. These "green" materials are generally considered as harvesting “residues” and reuse is not always considered. These particles are all produced in most European countries and are the main available agricultural by-products which may be used for building insulation. It should be underlined that those products can be mixed with a binder to manufacture particular insulators (e.g. hemp concrete or sunflower pith/chitosan). The aim here is to deal with raw materials and not a particular mix of particle/binder. The sound absorption and transmission coefficients of those particles are characterized using laboratory experiments. Results show that they can all be used for acoustical absorption and insulation. We apply models to estimate not only the inter- and intra-particles porosities and thus the total porosity of the samples but also the particle and skeletal densities. Then, we show that equivalent fluid models can predict the sound absorption and transmission accurately. Thus inversion of these models enables to estimate micro-structural parameters such as the tortuosity, viscous and thermal characteristic lengths and resistivity.

Keywords:
Agricultural by-products, sound absorption and transmission coefficients.

1 INTRODUCTION

Bio-based materials from plants have several advantages compared to conventionally used materials for building insulation such as rock wool or fiberglass, large gray energy consumers. They are renewable, extracted from biomass and have thermal and acoustic characteristics that are the subject of several studies now [Asdrubali 2013, Glé 2011].

In this study, the acoustic properties of the main available agricultural by-products which may be used for building insulation are measured and compared. The acoustical behavior of hemp has already received some attention [Glé 2013a, Glé 2013b, Glé 2012]. Particles of bio-based materials from plants are mainly parallelepiped in shape and can be organized in a plurality of ways to create a considerable proportion of open pores with a complex connectivity pattern, the acoustical properties of which have rarely been examined systematically. Here, the sound absorption and transmission coefficients of various aggregates from agricultural by-products are characterized using laboratory experiments and theoretical models are used to simulate the acoustical behavior of such particles.

The acoustical properties of materials composed of parallelepiped shapes can be markedly different from those composed of spherical aggregates. Here, we show that it is possible to use equivalent fluid models that assume the rigid frame behavior in order to model the acoustical behavior of such materials with good accuracy. They are composed of a multi-scale porosity that is why the modeling must be adapted to take into account only one part of the porosity which participates to the acoustical dissipation into the material.

Moreover we show that we can use acoustical models to characterize the structure and microstructure of those materials. Indeed, we will show that it is possible to obtain the density of the skeleton of such products owing to the porosities obtained owing to an acoustical measurement.

2 MATERIALS

In this study, the acoustic properties of hemp particles (shiv), flax (shiv), sunflower (pith and bark) and rape (straw) are measured and compared (Fig. 1). These "green" materials are generally considered as harvesting “residues” and reuse is not always considered. These particles are all produced in France and are the main available agricultural by-products which may be used for building insulation.

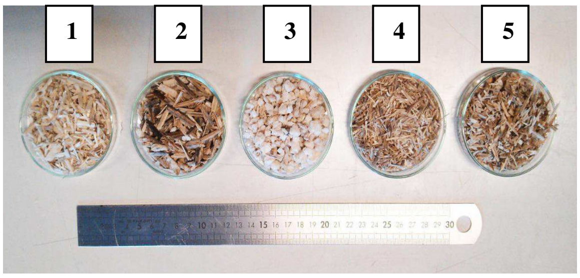

Fig. 1 : 1) Hemp shiv, 2) Sunflower bark, 3) Sunflower pith, 4) Flax shiv, 5) Rape straw

The pore structure of a sample made of vegetal particles can be described by different porosities (porosity is defined as the ratio of air volume over the total volume): the intra-particle porosity ϕ_{intra} which is the porosity inside the particle and the inter-particle porosity ϕ_{inter} which is found between the particles. This is a key parameter not only for acoustic insulation but also for thermal properties

The whole connected porosity, or total porosity ϕ_{tot}, is described from the inter-particle porosity and the intra-particle porosity according to:

$$\phi_{tot} = \phi_{inter} + (1 - \phi_{inter})\phi_{intra} \qquad (1)$$

ϕ_{tot} is measured with a classical air porosimeter : a sample of particles is introduced into a vessel equipped with a micrometric piston which allows changing the volume of the vessel (46 mm diameter). The total porosity measurements were all made with the same thickness of non-compressed particles in the vessel (46 mm diameter) which means a constant volume of 133 cm^3. The measurement results for ϕ_{tot} are given in Tab. 1.

Tab. 1: Measurement of porosities.

Particle type	ρ_v (g.cm^3)	ϕ_{tot} (%)
Hemp (shiv)	0.133	87
Sunflower (bark)	0.168	82.5
Sunflower (pith)	0.034	99
Flax (shiv)	0.115	90.5
Rape (straw)	0.115	90

A high porosity does not mean a high absorption coefficient. The most porous material is logically the sunflower pith (99%) which is also the lightest (sample density $\rho_v =$ 0.034 g.cm^3). It appears that the rape straw and flax shiv are also very porous (90 and 90.5% respectively). Hemp, which is commonly used for building insulation, is not the most porous of the studied material (87%) and sunflower bark, which is the heaviest particles of this study, is latest with a total porosity of 82.5%.

3 ACOUSTICAL PROPERTIES

3.1 Sound absorption coefficient

Measurements were performed using a Bruel & Kjaer® Kundt tube shown in Fig. 2 having a circular cross-section (100mm diameter). It should be noticed that two microphone positions (P1 and P2) are available on the top of the tube in front of the sample. A third one in the back (P3) is also used. This impedance tube is installed vertically so that the particles can remain in place (Fig. 2). In this way, sound absorption (measured with norm NF en ISO 10534-2, 2003), dynamic density $\rho(\omega)$ and bulk modulus $K(\omega)$ measurements are possible, in a typical frequency range of 20 to 2000Hz. These measurements were performed using a three-microphone method [Iwaze 1998].

$\rho(\omega)$ is the dynamic density of the material (kg.m^{-3}) which is also related to the visco-inertial dissipation of the porous sample and $K(\omega)$ is the dynamic modulus of the sample (Pa) which takes the thermal dissipation effects into account

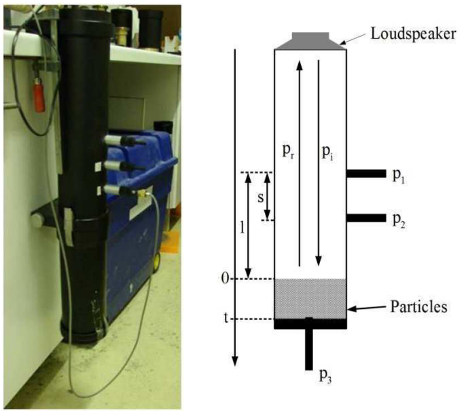

Fig. 2: Kundt tube measurement.

The Kundt tube measurements presented in this study are all made at with the same thickness (5.6 cm), which mean a constant volume (440 cm^3), for all tested particles. We chose the mass of the samples in order to have the same apparent density ρ_v into the Kundt and in the total porosity measurement apparatus. This means that the inter-particle porosity is the same for both experiments.

Results of the absorption measurements are shown on Fig. 3. The sound absorption coefficient curves are typical curves of granular materials with a peak around 800 Hz. The sound absorption coefficients are good compared to classical porous materials used as acoustic insulator. Flax shiv has the best absorption coefficient (α_{max} = 0.99 at 872 Hz) and sunflower pith the worst (α_{max} = 0.82 at 924 Hz). Rape straw and hemp shiv are good acoustical insulators with absorption coefficients α_{max} = 0.97 at 844 Hz for the worst one and α_{max} = 0.95 at 872 Hz for the second one. Sunflower bark seems to the worst for this purpose with α_{max} = 0.82 at 924 Hz.

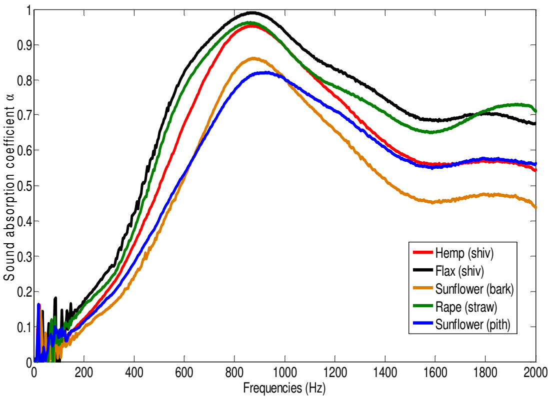

Fig. 3: Measured sound absorption coefficients.

3.2 Transmission coefficient

The third position of microphone (Fig. 2) allows to calculate the transmission coefficient τ of the samples.

The transmission curves of the studied particles are given on Fig. 4. Logically, flax shiv and rape straw have the lowest sound transmission coefficients and sunflower bark and pith the highest on the considered frequency range.

In both case, sunflower's bark and pith are aside because they are the lightest and the heaviest of the tested particles. Moreover, hemp, flax and rape are all produced using the same kind of cutting machine, so the form of the particles is quite identical contrary to sunflower bark and pith which are obtained using a crushing machine.

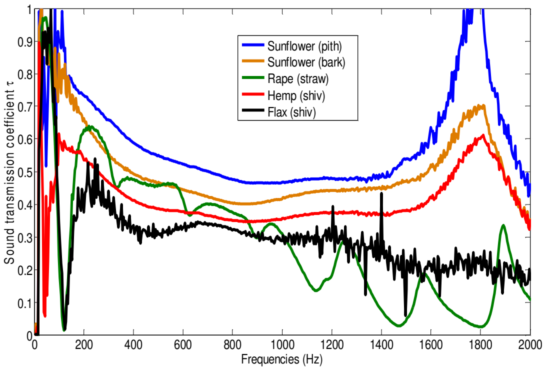

Fig. 4: Measured transmission coefficients.

4 OTHER PARAMETERS

4.1 Inter- and intra-particles porosities

Only a part of the porosity, the inter-particle one, participates to the dissipation of acoustic signal, other pores being too small or too large in the considered frequency range [Glé 2012]. ϕ_{inter} can then be estimated by the real part of $K(\omega)$. Indeed, $\mathcal{Re}(K(\omega)/P_0)$ ranges from P_0/ϕ_{inter} at low frequency – isotherm regime – to $\gamma P_0/\phi_{inter}$ at high frequency – adiabatic regime – [Zwikker 1949]. This means that ϕ_{inter} can be estimated according to:

$$\lim_{\omega\to 0}\mathcal{Re}\big(K(\omega)\big)=\frac{P_0}{\phi_{inter}} \tag{2}$$

As example $\mathcal{Re}(K(\omega)/P_0)$ is shown on Fig. 5 for hemp (shiv) at low frequencies. Then, with the values of ϕ_{inter} and ϕ_{tot} (measured previously), it is now possible to determine ϕ_{intra} for each sample according to Equation (1). Results are given in Tab. 2.

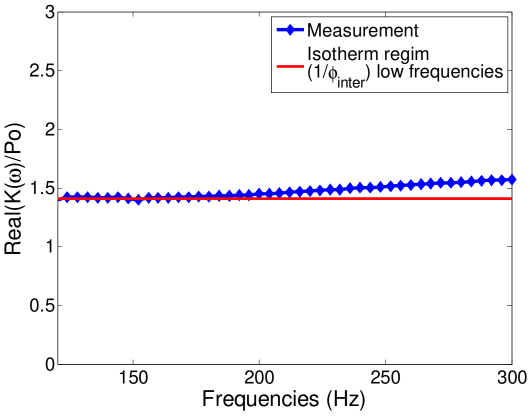

Fig. 5: Example of determination of ϕ_{inter} at low frequencies for hemp (shiv).

Tab. 2: Porosities.

Particle type	ρ_v (g.cm^{3})	ϕ_{inter} (%)	ϕ_{intra} (%)	ϕ_{tot} (%)
Hemp (shiv)	0.133	69	58	87
Sunflower (bark)	0.168	68	46	82.5
Sunflower (pith)	0.034	79	95	99
Flax (shiv)	0.115	78	56	90.5
Rape (straw)	0.115	77	57	90

The sunflower pith is logically the most porous particles with 95% of air in the particle and 79% between the particles in the sample. The heaviest, sunflower bark, is also logically the less porous of the studied materials in terms of inter-particle porosity (68%) and intra-particle porosity (46%). Hemp shiv particle is situated in an intermediate position. Indeed, the inter- and intra-particle porosities are respectively 69% and 58%. All particles appear to be good candidates for acoustic insulation.

4.2 Particles' density

It is now possible to determine other characteristics such as the particle density ρ_p (kg.m^{-3}) and the skeletal density ρ_s (kg.m^{-3}) according to the following relations [Glé 2013a]:

$$\phi_{inter}=1-\frac{\rho_v}{\rho_p} \tag{3}$$

$$\phi_{intra}=1-\frac{\rho_p}{\rho_s} \tag{4}$$

Results are given in Tab. 3.

Tab. 3: Densities.

Particle type	ρ_v (g.cm^{3})	ρ_p (g.m^{-3})	ρ_s (g.m^{-3})
Hemp (shiv)	0.133	0.423	1.02
Sunflower (bark)	0.168	0.518	0.96
Sunflower (pith)	0.034	0.165	3.4
Flax (shiv)	0.115	0.532	1.21
Rape (straw)	0.115	0.491	1.15

Hemp shiv, flax shiv, rape straw and sunflower bark are woody materials essentially composed of cellulose. This is why there particle and skeletal densities are in the same range ($\rho_p \approx$ 0.5 g.m^{-3} and $\rho_s \approx$ 1 g.cm^{-3}). The sunflower pith is different because it is not a woody material. It is composed of 95% of air, this is why it appears light but the skeleton can be heavy.

5 MODELLING

Prediction of the particles physical characteristics using acoustic methods is of great interest. There are many models – more or less accurate and more or less complex – to describe the acoustic characteristics of a porous material (e.g; [Allard 2009]). In this study, it is assumed that the skeleton is motionless. To justify this assumption, the studied materials have a stiffness and a mass higher than that of air, then, when excited by an acoustic wave at a frequency higher than the phase decoupling frequency, the skeleton can be considered as rigid and motionless.

The chosen model is the so called Johnson-Champoux-Allard model (JCA) [Champoux 1991, Johnson 1987]. In this semi-phenomenological model, $\rho(\omega)$ and $K(\omega)$ are defined in function of geometrical parameters: α_∞ the tortuosity (-), σ the air resistivity (N.s.m^{-4}), Λ the viscous characteristic length (m) and Λ' the thermal characteristic length (m).

Results of sound absorption and transmission coefficients modelling are given on Fig. 6 and Fig. 7.

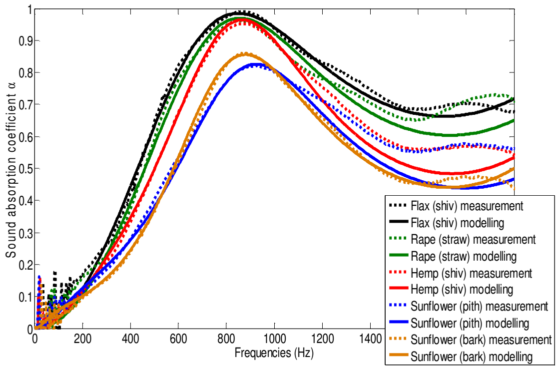

Fig. 6: Modelling of sound absorption coefficients.

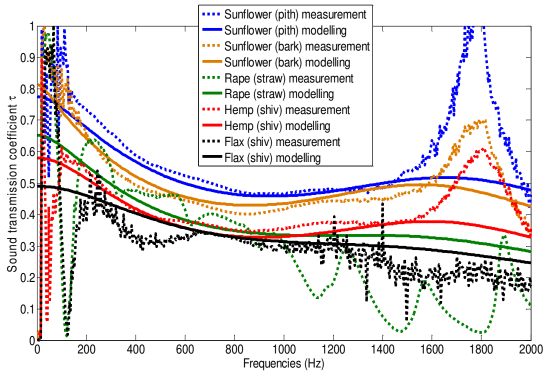

Fig. 7: Modelling of transmission coefficients.

The calculated parameters are given in Tab. 4. Agreements between model and measurement can be considered as quite good and parameters values seem relevant for this type of materials. So model inversion can be considered to predict micro-structural parameters which are of interest for thermal characterization. For example a link can be done between air resistivity, air flow resistance R_f (N.s.m^{-3}) and static permeability $\Pi(0)$ (m^2) of the material with:

$$\sigma = \frac{R_f}{t} \tag{5}$$

$$\Pi(0) = \frac{\eta}{\sigma} \tag{6}$$

where t (m) is the thickness of the sample and $\eta = 1.84\ 10^{-5}$ Pa the dynamic viscosity of air at room temperature.

Tab. 4: Parameters.

Particle type	**α_∞ (-)**	**σ (N.s.m^{-4})**	**Λ (m)**	**Λ' (m)**
Hemp (shiv)	2.4	4600	$2.6\ 10^{-4}$	$2.6\ 10^{-4}$
Sunflower (bark)	2.6	1600	$2.9\ 10^{-4}$	$5.5\ 10^{-4}$
Sunflower (pith)	2.4	2000	$3.6\ 10^{-4}$	$3.6\ 10^{-4}$
Flax (shiv)	2.25	6300	$1.8\ 10^{-4}$	$1.8\ 10^{-4}$
Rape (straw)	2.2	3500	$1.95\ 10^{-4}$	$1.95\ 10^{-4}$

6 SUMMARY

Several types of agricultural by-products have been acoustically characterized for building insulation. It appears that hemp shiv, sunflower bark and pith, flax shiv and rape straw have good sound absorption coefficients and low transmission coefficients, and thus could be considered for building insulation.

Using acoustical mesaurements enables to determine other structural parameters such as intra-particle porosity, skeletal and particle densities. It is well-known that the skeletal density is difficult to obtain with other methods.

We have shown that it is possible to predict sound absorption and transmission coefficients by using JCA model and obtain microstructural parameters such as viscous and thermal characteristic lengths.

Further researches will focus on characterizing those materials mixed with a binder for applications in more complex building structures. Moreover, their hygrothermal behavior should be investigated in order to test their abilities to insulate buildings made with materials that must not be covered hermetically (rammed earth for example).

7 ACKNOWLEDGMENTS

The present work is supported by the French Agency for Environment and Energy Management (ADEME) through Project IBIS. This work was performed within the framework of the LABEX CeLyA (ANR-10-LABX-0060) of Université de Lyon.

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