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Agricultural by-products for building insulation: Acoustical characterization and modeling to predict micro-structural parameters

P.A. Chabriac [a,1], E. Gourdon [a,*], P. Gle [b], A. Fabbri [a], H. Lenormand [c]

[a] Laboratoire Génie Civil et Bâtiment (LGCB-LTDS UMR 5513), Ecole Nationale des Travaux Publics de l'Etat (ENTPE), 3 rue Maurice Audin, 69518 Vaulx-en-Velin, France
[b] Laboratoire Régional de Strasbourg, Cerema, 11, rue Jean Mentelin, 67035 Strasbourg, France
[c] Esitpa, Unité Agri'terr, 3 rue du tronquet, 76134 Mont Saint Aignan Cedex, France

HIGHLIGHTS

- Study of agricultural by-products available for acoustical applications.
- Characterization of five types of agricultural by-products acoustically and structurally.
- Measurements and modelings of sound absorption.
- Prediction of micro-structural parameters.

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ABSTRACT

The acoustical characteristics for building insulation of five largely available plant particles (hemp shiv, sunflower bark and pith, flax shiv and rape straw) without binder were investigated. Results show that they can all be used for acoustical absorption. Measurements were then analyzed to estimate not only the sound absorption coefficient, but also the particles intrinsic properties such as porosities (i.e. total, inter- and intra-particles porosities) and densities (i.e. bulk and skeletal). An equivalent fluid model is then used to predict the sound absorption. From acoustical measurements, simple analytical equations allow to estimate key micro-structural parameters such as tortuosity, viscous and thermal characteristic lengths and resistivity.

1. Introduction

Buildings now represent 23.5% of the greenhouse gas emissions in France [1]. Insulation is a key parameter in the energy performances of a building, and high-performance insulation can significantly reduce heating and cooling consumption. But building materials have not solely a thermal function, they also have an acoustical role and some materials can fulfill both. Green buildings design is focused on reducing energy use and improving use of sustainable materials. In particular, for *Green buildings* construction, builders tend to use natural materials instead of mineral ones (e.g. fiberglass or rock fibers). To encourage this effort, internationally recognized rating methods, such as LEED (Leadership in Energy and Environmental Design) assign positive points if natural materials are used in the construction of a building [2].

Bio-based materials derived from plants have several advantages compared to conventional materials for building insulation, which are often large grey energy consumers [3]. They are renewable, extracted from biomass and have promising thermal and acoustical characteristics which are the subject of several studies [4–6]. Most of them, such as rice straw [7], corn cob [8] or tannin-based foams [9] have interesting acoustical properties and are the subject of several ratings (e.g. Leadership in Energy and Environmental Design rating system).

In this study, 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" for which 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. The particles

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* Corresponding author.
E-mail address: emmanuel.gourdon@entpe.fr (E. Gourdon).

[1] Current address: Laboratoire TRANSFORMATIONS, Ecole Nationale Supérieure d'Architecture de St Etienne, 1 rue Buisson, 42000 St Etienne, France.

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investigated in this paper are produced in France. 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 [5,10]). In this paper, the aim is to deal with raw materials and not a particular mix of particle/binder. The acoustical behavior of hemp has already received some attention [11,12]. In the present paper, the sound absorption of the aggregates is evaluated using laboratory experiments and theoretical models are used to simulate the acoustical behavior of such particles.

The acoustical properties of this type of materials can be significantly different from those composed of spherical aggregates which can be predicted by several models [13,14]. In the case of agricultural by-products, the aggregate shapes have a strong impact on acoustical properties as well as the intra-particle porosity and there is still a lot of research to be carried out to completely understand the behavior of such materials.

One of the objectives of this paper is to show that it is possible to use equivalent fluid models – assuming a rigid frame behavior – in order to model the acoustical behavior of different plant particles with good accuracy. Indeed, equivalent fluid models – assuming some hypothesis on the micro-structure – may be applied for complex pores network [15]. Nevertheless, the studied materials are composed of a multi-scale porosity meaning that the modeling must be adapted to take into account the part of the porosity which participates in the acoustical dissipation into the material.

Three objectives are achieved in this work: the first one is to acoustically characterize plant particles for building application; the second one is to show that modeling can be used to predict accurately the acoustical properties of agricultural by-products with relatively complex shapes; and the third one is to use acoustical measurements to characterize the structure and microstructure of those materials.

Theory, materials and methods to measure sound absorption and acoustical parameters are presented in Section 2. Experimental results as well as modeling to predict micro-structural parameters are presented and discussed in Section 3. Details about the theory behind the models are then given in Appendix.

2. Theory, materials and methods

The pictures of the five studied agricultural by-products are reported on Fig. 1. All materials are produced in France and manufactured in cooperatives farms.

2.1. Theory

2.1.1. Propagation equation

The acoustic propagation is described using harmonic waves in which the temporal dependency is written $e^{j\omega\tau}$ (τ being the time), where $\omega = 2\pi f$, with f the frequency of the wave (Hz) and j is the imaginary unit ($j^2 = -1$). In this case, waves are propagating under normal incidence. The state of the air in the pores is defined with the complex variables:

- $\vec{v}_a$ the velocity of the air in the pores: $\vec{v}_a = \vec{v}e^{j\omega\tau}$.
- p the pressure of the air in the pores: $p_a = pe^{j\omega\tau}$.

It is assumed that the material skeleton is rigid, motionless (i.e. above the phase decoupling frequency given by Zwikker et Kosten [16]), at constant temperature and the pore network is saturated with air. 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 expression of the phase decoupling frequency f_d given by [16]:

$$f_d = \frac{\sigma\phi^2}{2\pi\rho} \tag{1}$$

where σ is the static air flow resistivity of the material (N m^{-4} s), ϕ its open porosity (–) and ρ its mass density (kg m^{-3}). For these types of materials, the decoupling frequency is about 1 Hz [11]. For example, hereafter the decoupling frequency of hemp shiv is evaluated, according to Eq. (1), at 2.62 Hz. The velocity of air is considered to be zero on the edges of the skeleton. Then the dissipation of the acoustic wave depends both on the visco-inertial and thermal phenomena. Indeed, it appears that visco-inertial and thermal effects can be treated separately using a complex mass density and a complex bulk modulus functions.

The model which is used to predict the acoustical properties of porous media such as agricultural by-products is now introduced. The full derivation of the equation is not detailed in this paper since it has already been done many times and authors believe it makes sense to only present the actual model. Nevertheless, the visco-inertial and thermal effects at microscopic scale are detailed in Appendix. Applying homogenization theory [15] (considering the existence of a Representative Elementary Volume and scale separation) enables the transcription of the equations from microscopic to macroscopic scale as described in Appendix.

Combining Eqs. (24) and (26) with the mass conservation principle and considering air as a perfect gas leads to the well-known propagation equation (analogous to the Helmholtz equation used to describe the sound propagation in free air with no dissipation):

$$\nabla^2 p + \omega^2 \frac{\rho_{eq}(\omega)}{K_{eq}(\omega)} p = 0 \tag{2}$$

where $\rho_{eq}(\omega)$ is the dynamic density of the material (kg m^{-3}) – which is also related to the visco-inertial dissipation of the material – and $K_{eq}(\omega)$ is the dynamic bulk modulus of the equivalent fluid in the pores sample (Pa) which takes the thermal dissipation effects into account. For porous media, the dynamic density $\rho_{eq}(\omega)$ and the dynamic bulk modulus $K_{eq}(\omega)$ are complex functions of the frequency and the pores size and shape. Motionless skeleton models aim at providing expressions of these two values for the acoustics frequency spectrum and for given pore shapes.

In Eq. (2), the two parameters $\rho_{eq}(\omega)$ and $K_{eq}(\omega)$ are defined as:

$$\begin{cases} \rho_{eq}(\omega) = \frac{\mu}{j\omega\Pi_{eq}(\omega)} & (3) \\ K_{eq}(\omega) = \frac{\gamma\frac{P_0}{\phi}}{\gamma - j(\gamma-1)\frac{\Theta_{eq}(\omega)}{\delta_t^2}} & (4) \end{cases}$$

where $\gamma = C_p/C_v$ with C_p and C_v the specific heats of air at constant pressure and constant volume respectively (J kg^{-1} K^{-1}) and δ_t the thickness of the thermal boundary layer (m). μ is the shear dynamic viscosity of air (Pa s) and P_0 is the atmospheric pressure of air at equilibrium (Pa).

In Eqs. (3) and (4), $\Pi_{eq}(\omega)$ and $\Theta_{eq}(\omega)$, and thus $\rho_{eq}(\omega)$ and $K_{eq}(\omega)$, can be expressed from micro-structural characteristics of the material. Indeed, porous material behaves as fictional homogeneous material with a density $\rho_{eq}(\omega)$ and a dynamic modulus $K_{eq}(\omega)$ evaluated from the geometrical characteristics of the porous material and the ones of air.

There are many models – more or less accurate and complex – to describe the acoustic characteristics $\rho_{eq}(\omega)$ and $K_{eq}(\omega)$ of a porous material (see [15]). Three classes of models (i.e. expressions of characteristics ρ_{eq} and K_{eq} as functions of the frequency and the pore shape) can be listed. First, "empirical models" may be used: they usually require to know a limited number of parameters (or information). They are very popular and still very used in spite of their restrictive limits. Then "analytical models" are valid for porous materials with simple pore morphologies e.g. slit-like pores or parallel cylindrical pores with a singular cross-section (circular, square, triangular). These models assume a specific pore geometry but are effective for more complex geometries because the choice of pore geometry is not crucial for the acoustical properties providing that the wavelength is much greater than the characteristic lengths. The effect of pore geometry is captured in this case in the values of the acoustical parameters. Finally, "semi-phenomenological models" have been also developed for more complicated pore morphologies (e.g. [17]). These latter models are based on physical asymptotic behaviors at low and high frequencies. A behavior between these asymptotes is then assumed.

A semi-phenomenological model is used here. The chosen model is the so called Johnson-Champoux-Allard model (referred here as JCA) [17,18] because it is often used to acoustically characterize porous materials having geometrical parameters related to the microstructure. JCA model is robust and has made its proofs [15]. Another semi-phenomenological model could also be used but this would not change the principle of the present paper.

In the JCA model, the dynamic density, $\rho_{JCA}(\omega)$, is defined using Biot's theory [19,20] and calculated according to Eq. (5) while the dynamic modulus, $K_{JCA}(\omega)$, is calculated according to Eq. (6):

$$\rho_{JCA}(\omega) = \frac{\rho_0\alpha_\infty}{\phi_{inter}}\left[1 - j\frac{\sigma\phi_{inter}}{\rho_0\alpha_\infty\omega}\sqrt{1 + j\frac{4\mu\alpha_\infty^2\rho_0\omega}{\Lambda^2\sigma^2\phi_{inter}^2}}\right] \tag{5}$$

$$K_{JCA}(\omega) = \frac{\gamma P_0}{\phi_{inter}}\left[\gamma - (\gamma-1)\left(1 - j\frac{8\kappa}{\Lambda'^2 C_p\rho_0\omega}\sqrt{1 + j\frac{\Lambda'^2 C_p\rho_0\omega}{16\kappa}}\right)^{-1}\right]^{-1} \tag{6}$$

where ρ_0 is the density of air at equilibrium (kg m^{-3}), ϕ_{inter} is the inter-particle porosity (–), Λ is the viscous characteristic length (–), Λ' is the thermal characteristic length (m), α_∞ is the tortuosity (–) and κ is the heat conductivity of air (W m^{-1} K^{-1}).