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MODELLING SOUND ABSORPTION OF VEGETAL WOOLS : CONSIDERATION OF FIBRE POLYDISPERSITY

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ABSTRACT

Vegetal wools are highly porous materials made of vegetal fibres and bicomponent polymer fibres. But despite their high-level multifunctional properties they suffer from poor low-frequency acoustic absorption for thin panels. A solution to this problem can be found in metamaterial methods and in particular double porosity. By using perforated multi-layered hemp wool panels, very good results have been obtained.

This promising use of double porosity has highlighted the necessity to accurately model the acoustic behaviour of vegetal wools in order to optimise their low-frequency sound absorption properties. However, unlike more conventional materials, vegetal wools don't have calibrated fibres, which poses a stalemate this work aims at answering.

Vegetal fibres exhibit high radius polydispersity. Most studies use a mean radius for simulations, and more recent works considered composite methods and used two mean radii (for vegetal and polymeric fibres). This work investigates weighted averaging methods with the aim of improving the estimation of the acoustic absorption for vegetal wools having large radius distribution.

Keywords: *acoustic, vegetal wools, polydispersity, optimisation*

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1. INTRODUCTION

From the growth of the plant from which the fibres come to the end of their life cycle, vegetal wools have many virtues that make them a very attractive insulation product for green buildings. These materials store atmospheric CO_2, have a low carbon footprint and reduced environmental impact [1–3]. They are hygroscopic, regulating humidity and temperature, contributing to the interior comfort of living spaces [4, 5], and offer good acoustic absorption thanks to their high porosity. Their main drawback is their low acoustic absorption at lower frequencies. To address this, it is first essential to accurately model their acoustic behaviour. Therefore, micro-macro modelling methods were investigated.

For this article, it seems relevant to use modelling methods to estimate static airflow resistivity (later referred as resistivity) from parameters such as porosity and fibre radii. Based on previous works [6, 7], which led to satisfactory results with monodisperse materials, the chosen formulas come from Tarnow's [8] and Umnova's [9] works.

However, vegetal wools are characterised by a large dimensional variability of their natural fibres [6]. Recent advances in the study of polydispersity in random fibrous materials demonstrated that optimised polydispersity can even lead to improved sound absorption at lower frequencies [10]. With this knowledge, this paper aims at investigating different analytical models for acoustic simulations taking these specificities into account.

To begin with, this paper introduce the materials involved in the study. Different vegetal wools, with different radius probability distributions, were experimented to investigate radius polydispersity as an optimisation method. To keep on, measurement protocols, methods, and analytical models used for this work are described. Eventually, measurement results on the radius probability distributions of the different wools are displayed. This is followed by analytical experiments to better understand how to implement materials with radius polydispersity in analytical models. As a conclusion, a promising path toward accurate estimation of airflow resistivity for these materials was found.

2. MATERIALS AND METHODS

2.1 Materials

For this work, the materials characterised are three vegetal wools : a wood wool (W), a hemp-flax wool (HF) and a wood-kenaf (WK) wool. The parameters used in the modelling of the resistivity, as well as the indirectly measured resistivity, are listed in Tab. 1.

Table 1: Characteristic parameters of the samples : mass proportion between vegetal and polymeric fibres, thickness (e), apparent density (ρ_a), porosity (ϕ) and resistivity (σ)

Material	W	HF	WK
Veg/pol	88/12	45/45/10	40/40/20
$\boldsymbol{e}$ (mm)	50	90	38
$\boldsymbol{\rho_a}$ $(kg \cdot m^{-3})$	60	35	58
$\boldsymbol{\phi}$	0.96	0.98	0.96
$\boldsymbol{\sigma}$ $(N \cdot m^{-4}s)$	35000	3000	5500

2.2 Methods

2.2.1 Measuring porosity and resistivity

Porosity was estimated by weighing the samples and using known mass densities of the fibres. The airflow resistivity is obtained indirectly from measurements of an impedance tube with the 3 microphones methods originally developed by Iwase et al. [11] and adapted by Salissou and Panneton [12]. The cylindrical impedance tube used is the type I Acoustitube from Akustik Forschung, with a diameter of $100mm$. The analysis is done between $100Hz$ and $2000Hz$. Based on the work by Olny and Panneton [13, 14], we were able to indirectly estimate the resistivity with measures made on an impedance tube with the 3 microphones method [11].

2.2.2 Radius distribution measurement

To measure the radii of the fibres studied for this work, a Scanning Electronic Microscope (SEM) Hitachi TM3000 was used. Prior to their visualisation, the samples were metallised with a thin gold layer deposited in a plasma.

The images obtained are analysed on the software ImageJ, and after manual treatment the transversal profiles are measured. Vegetal fibres are not perfectly cylindrical, therefore an equivalent diameter is calculated by averaging the longest and shortest Ferret's diameters measurable [15, 16].

2.2.3 Evaluation of the average radii

Different ways of calculating an average fibre radius can be found in the literature. For this paper, four of them were selected.

- Piégay et al. [17] used a non weighted arithmetic average (NWA),
- Xue et al. [18] a non weighted quadratic average (NWQ).
- To predict the static viscous permeability of heterogeneous fibrous materials, Peyrega and Jeulin [19] preferred a volume weighted average (VW).
- For characteristic lengths, Tran et al. [10] chose an inverse volume weighted average (IVW).

The equations for these calculations are expressed in Eqn. (1) to (4). It is assumed in these calculations that the fibres all have an equal length L_f and are cylindrical. Therefore the volume and inverse volume weightings are simplified as square radius and square inverse radius weightings ($V_i \propto R^2_{f,i}$).

$$R_{f,NWQ} = \sqrt{\frac{1}{N_f}\sum_j R^2_{fj}} \qquad (1)$$

$$R_{f,NWA} = \frac{1}{N_f}\sum_j R_{fj} \qquad (2)$$

$$R_{f,VW} = \frac{\sum_j V_j R_{fj}}{\sum_j V_j} \approx \frac{\sum_j R^3_{fj}}{\sum_j R^2_{fj}} \qquad (3)$$

$$R_{f,IVW} = \frac{\sum_j \frac{1}{V_j} R_{fj}}{\sum_j \frac{1}{V_j}} \approx \frac{\sum_j R^{-1}_{fj}}{\sum_j R^{-2}_{fj}} \qquad (4)$$

2.2.4 *Estimation of airflow resistivity*

In order to evaluate the relationships presented in Eqn. (1) to (4), it was first decided to use the values obtained to determine the airflow resistivity of the materials, a key parameter in acoustic absorption modelling methods.

Two micro-macro modelling methods, proposing analytical relationships between a fibre radius value and characteristic pore network parameters, were selected for this work. These are the modelling approaches of Tarnow (Eqn. (5) for perpendicular incidence with random fibre arrangement) [8] and Umnova (Eqn. (6) for perpendicular incidence) [9] :

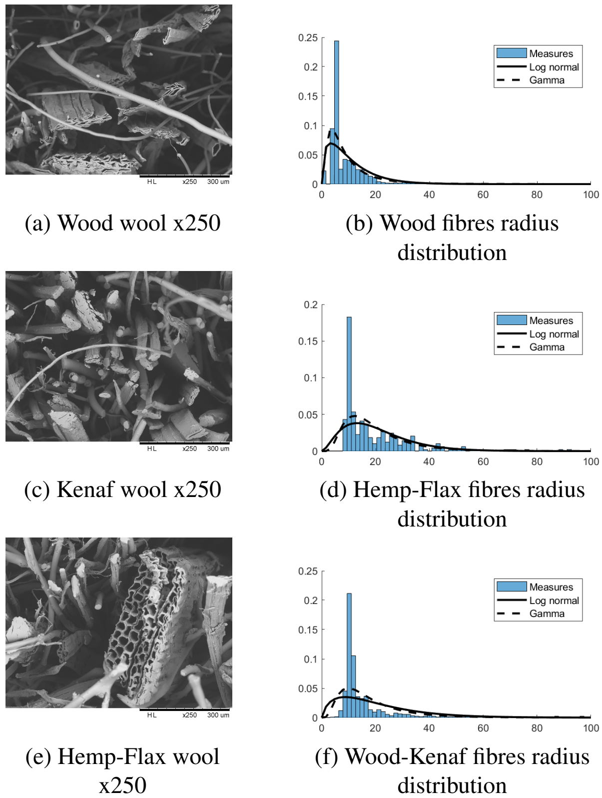
$$\sigma_{\perp} = 4\eta \frac{1-\phi}{R_f^2\left[0.64ln(1/(1-\phi)) - 0.737 + (1-\phi)\right]} \tag{5}$$

$$\sigma_{\perp} = \frac{16\eta}{R_f^2} \frac{(1-\phi)}{-2ln(1-\phi) - 2\phi - \phi^2} \tag{6}$$

3. RESULTS

3.1 Measurements of fibre radius distributions

The images obtained with the SEM are displayed in Fig 1(a),(c) and (e). In Fig 1(b),(d) and (f) the resulting radius probability distributions calculated with the software ImageJ are presented.



(a) Wood wool x250 (b) Wood fibres radius distribution

(c) Kenaf wool x250 (d) Hemp-Flax fibres radius distribution

(e) Hemp-Flax wool x250 (f) Wood-Kenaf fibres radius distribution

Figure 1: Photos of wood, wood-kenaf and hemp-flax wools with the SEM, with measured radius probability distributions.

3.2 Average radii

These distributions allowed the calculation of average radii following the methods in Eqn. (1) to (4). They are presented in Tab. 2.

3.3 Using the radii in the calculations

Using the average radii found for the global distribution and this formula, we can compare the predicted resistivity with the values obtained via indirect (Kundt tube) measurements.

The four averaging methods of the global distributions were considered. The results are displayed with the experimental values in Fig 2. To estimate the accuracy of our new analytical results, the ratios for every method was calculated relatively to these characterisation values, as presented in Tab. 3.

4. CONCLUSION AND PERSPECTIVES

All three of the material's radius distributions showcase a peak between $5\mu m$ and $10\mu m$. This is due to the presence of the polymeric fibres. Although they represent a low mass proportion of the fibres used, between 10% and 20%, thanks to their lower mean radius, they can represent between 34% and 77% of the total measured fibres.

When calculating the different average radii, what can be observed is that these calculations show very contrasted results. This is easily explainable due to the quadratic and cubic exponents augmenting the part played by the highest radii in the results. In ascending order, we have radii obtained with Inverse Volume Weight IVW, for which the lowest radii are more impactful, then arithmetic average NWA which is linear, quadratic average NWQ, and volume weight average VW, with quadratic and cubic exponents. The contrast can vary from almost equal for poly-

Table 2: R_f calculated with different averaging methods : Non Weighted Quadratic (NWQ), Non Weighted arithmetic (NWA), Volume Weighted (VW), Inverse Volume Weighted (IVW)

$R_f(\mu m)$		W	HF	WK
Global	NWA	10.8	20.7	20.7
	NWQ	21.0	26.3	34.0
	VW	210.9	54.7	139.3
	IVW	5.7	12.3	10.1
Vegetal	NWA	25.1	26.1	41.0
	NWQ	41.5	31.5	58.9
	VW	228.8	57.3	152.5
	IVW	13.6	15.7	13.3
Polymer	NWA	6.4	10.4	12.0
	NWQ	6.9	10.5	13.2
	VW	8.6	11.2	26.7
	IVW	5.4	10.1	10.8

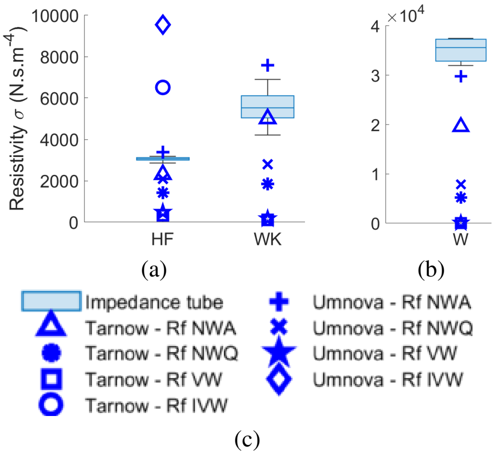


Figure 2: Predicted resistivity versus indirect measurements for the hemp-flax wool (HF), wood-kenaf wool (WK), and wood wool (W)

meric fibres, that have narrow distributions, to thirty-six times between the VW and IVW average radii of the wood wool.

We note that the two averaging methods producing the highest mean radii, NWQ and VW, systematically lead to a underestimation of the resistivity, whereas IVW, which gives the lowest mean radii, always leads to a great overestimation. In our case of our three materials made of mixed vegetal and polymeric fibres, the averaging method giving

Table 3: Resistivity relative error between measures and analytical estimations for the different averaging methods : Non Weighted Arithmetic (NWA), Non Weighted Quadratic (NWQ), Volume Weighted (VW), Inverse Volume Weighted (IVW)

		Resistivity relative error (%)			
		W	HF	WK	Mean
Tarnow	NWA	-44	-23	-9	-25
	NWQ	-85	-52	-66	-68
	VW	-99.9	-89	-98	-95
	IVW	+102	+117	+277	+166
Umnova	NWA	-15	+12	+38	+11
	NWQ	-77	-30	-49	-52
	VW	-99.8	-84	-97	-94
	IVW	+208	+219	+472	+300

the least error for the calculation of resistivity therefore seems to be a non weighted arithmetic average NWA. The mean error also seems to favour Umnova's formula for the calculation of resistivity. Further investigations will be lead in order to verify the current conclusion. Other vegetal wools will be studied to widen the database and have more statistically relevant results. Also, the biggest fibres measured may be wrongfully counted the same way as the others, because of the equal fibre length hypothesis used for this work. The widest fibres are, in fact, usually not as long as the others, and may need to be removed from the calculations. This would lead to a more precise use of the volume weighting in the calculation of resistivity, even though this method is not recommended. Another improvement could be brought with the use of a composite method [6], considering two or three parallel materials made of the types of fibres found in the wools, and in fine combining the results of the calculations.

The next step will then be to replicate this work for the modelling of sound absorption. Eventually, with knowledge on the fibre radius distributions for different vegetal fibres and having suitable analytical modelling methods, it will be possible to optimise the performances of a vegetal wool panel through its fibre radius distribution.

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