On the modelling of the acoustical properties of hemp concrete

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Abstract

Hemp concrete is an attractive alternative to traditional materials used in building construction. It has a very low environmental impact and it is characterized by high thermal insulation and sound absorption properties. The shape of hemp aggregates is parallelepiped and individual particles in a hemp mix can be organized in a plurality of ways. As a result, modeling of such material is quite complicated.

This paper is focused on the fundamental understanding of the relations between the particle shape and size distribution and the acoustical properties of the resultant material mix. The sound absorption and the transmission loss of various hemp aggregates is characterized using laboratory experiments and three theoretical models. These models are used to relate the particle size distribution to the pore size distribution. It is shown that the pore size distribution is one of the main characteristic which controls the observed acoustical behavior.

1 Introduction

There is an increasing interest today for alternative materials in buildings, in order to meet the expectations of low environmental impact and multifunctionnal properties. Hemp concrete is a mix of plant particles (hemp particles) with a binder (lime or cement), and is one of these key materials. Its life cycle analysis [1] shows that 1 m^2 of hemp concrete having a width of 26 cm encasing a timber frame stores 35.5 kg carbon dioxide over a reference period of 100 years, and proves the ecological interest of this material. Moreover, as shown in [2, 3, 4, 5] it features very interesting properties from mechanical, thermal and acoustical points of view, so that it can qualify as a multifunctional material.

The acoustical behaviour of hemp concrete has already been the object of several studies. The effect of the binder content in the formulation was observed in [3]. Furthermore, the effect of density, particles size distribution, type of binder, and water content was succintly discussed in [5]. A first approach has been developed to model its acoustical properties in [5], and this model has been improved to highlight the effect of the multiple scales of porosity existing in the material in [6].

The porous microstructure of hemp concrete is quite complex, because it is composite and has a natural origin. Therefore, pores have dimensions distributed through three scales, with the inter-particle pores having a size ranging between $1mm$ to $10mm$ (See Figure 1 (a)), intra-particle pores having sizes varying between 10 and 60 μm (See Figure 1 (b)) [7, 8], and with intra-binder pores having a characteristic size of 1 μm. In [6], it is shown that the contrast of permeability existing between the inter-particle pores and the intra-particle pores is high enough so that only the inter-particle pores take part into the acoustical dissipation of hemp concrete.

The other difficulty concerning hemp concrete, and shiv (loose hemp particles), is the parallelepiped shape of the aggregates and their particle size distribution. Indeed, the acoustical properties of spherical aggregates having same size is now well known and modelled [9, 10].

(a) (b)

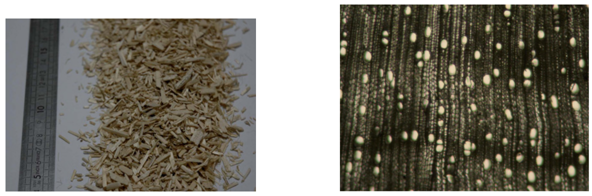

Figure 1: Photographs showing mix of hemp particles S_A ((a) shows the characteristic dimension of the particles and (b) shows the intraparticle porosity)

In the case of granular media with a particle size distribution and a non-spherical shape, not much has been done.

Studies investigated and modeled the effect of pore size distribution. Arbitrary and log-normal pore size distributions have been studied by [11] and [12], by extending the Biot theory [13, 14]. These authors showed that the pore size distribution has a noticed effect on the acoustical properties, and it has also be shown that this effect is greater than the change in pore shape. Besides, in our case, it is necessary to understand the effect of the particle size distribution on this pore size distribution. The progress concerning the modelling of the relationship between these parameters has been reviewed in [15] and a strong dependance is shown between porosity, particle shape and particle size distribution.

Finally, the influence of the shape of particles on the acoustical properties is also a key question. Usually, non-spherical shape of particles is considered empirically and using a shape factor [16]. Numerical works have been realized by imputing the shape and configuration of non-spherical particles, for instance with spiky particles [17]. However, parallelepiped shape such as hemp particles have not been investigated.

The article focuses on five different types of shiv called S_A to S_E and having different origins. The aim is to highlight the effect of particle size distribution, particle shape, and multi-scale porosity of shiv, on the acoustical properties. It is organized in three sections. The direct characterization methods are first described. Then the modelling approaches used to model this material are presented and compared. Some of the models enable to complete the characterization process in an indirect way. These indirect characterized parameters are discussed to explain the acoustical behaviour of the material. Finally, the effect of the shape and particle size distribution are discussed.

2 Experimental results - Direct characterization

2.1 Particles size distribution of the shiv

The hemp particles were first characterized by a particles size distribution analysis. Hemp particles shape is assumed to be parallelepiped. So, to describe perfectly a bed of particles, one has to know the distribution of length, width and thickness. This is particularly difficult and could only be made using 3D tomography.

We developed in the lab a more accessible method based on image analysis. This method first developped by Ceyte [18] enables to know the distribution of length and width of the particles.

This data have been compared to log-normal distributions, and a perfect agreement has been found as described by Figure 2.

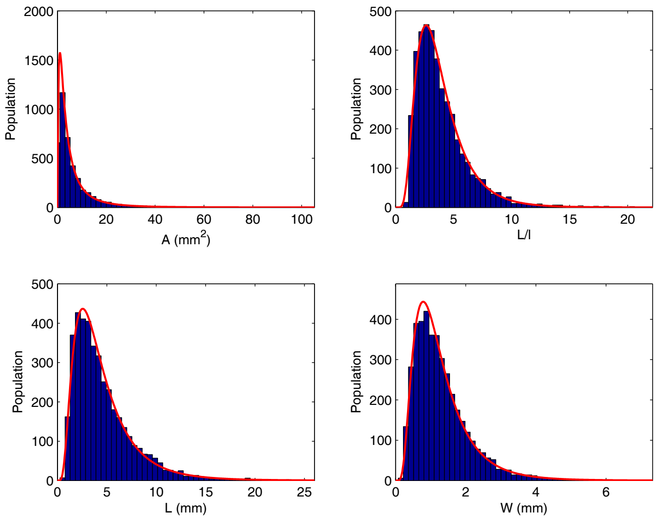

Figure 2: Particle size distribution of shiv S_A, population and associated log-normal distribution

These results enable to compare clearly the mean size of the particles and it appears for each parameter that the standard deviation does not vary a lot as a function of the shiv size.

2.2 Pore size distribution of the shiv

Using a similar method, the pore size distribution has then been investigated for different configurations of shiv. Photographs of shiv SA have been taken for two densities, a low density packing with $\rho = 100kg.m^{-3}$ and a high density packing with $\rho = 150kg.m^{-3}$. Then, an image analysis has been performed in Matlab to detect the pores and to evaluate their equivalent radii (radius of a circle having same area than the pores).

Figure 3 shows the pore size distribution. These pore size distributions have been modeled using a log-normal distribution and again, a very good agreement has been found. So, one can wonder if a granular material, whose aggregates are characterised by a log-normal size distribution, has a log-normal pore-size distribution. This will be discussed in Section 3.

Besides it appears on this figure that an increase of the density lowers the equivalent radius of the pores and its standard deviation. However, it is important to notice that in this case, we considered two extreme values of density, and the standard deviation does not change noticeably.

2.3 Open porosity

The open porosity ϕ is a function of the density knowing the frame density of the particles ρ_{frame} [5].

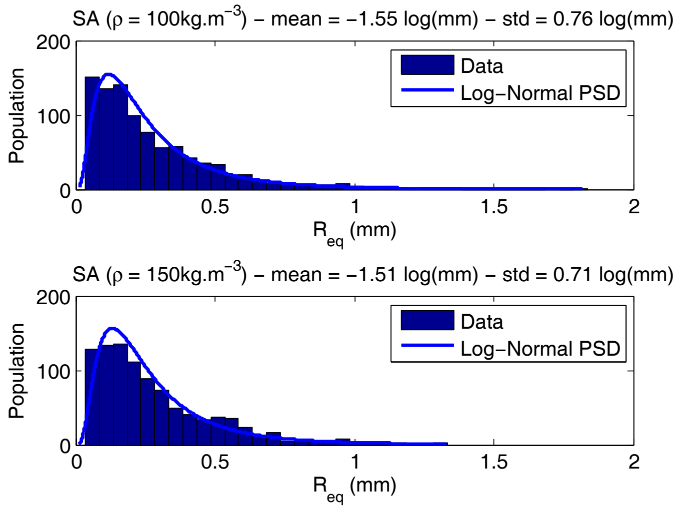

Figure 3: Pore size distribution of shiv S_A, population and associated log-normal distribution

These frame densities were measured for the five shiv on three different samples of mass M_{shiv} of 4 g to ensure the representativity of the sample. The volume of the frame V_{frame} of the shiv has been evaluated using air porosimetry [19].

Among the tested shiv, the frame density ranges between 870 and 1350 $kg.m^{-3}$. These values for frame density have the same order as in [5]. This leads to open porosity ranging between 85% and 95% decreasing lineary as a function of the density of the bed.

2.4 Air flow resistance

The air flow resistivity, noted σ, has been estimated from the low frequency range of the imaginary part of the dynamic density ρ_{eq}.

The validity of this estimate has been checked by performing direct measurement, following standard ISO9053 on shiv S_A and gives satisfactory results. The measured resistivities range between 1000 and 9000 $N.m^{-4}.s$, and increase with density and for shiv having smaller particles such as S_E.

The evolution of resistivity can be modelled as a function of the inter-particle porosity and the characteristic size of the shiv, as presented in [6], and using models derived from self consistent methods. So, concerning resistivity, shiv present same behaviour than packings of spheres having the same characteristic size.

2.5 Tortuosity

Finally, tortuosity has been evaluated using a flight time method. This method described in [20] consists in measuring the time delay between the incident and the transmitted waves using a 48 kHz ultrasound wave.

We can observe that for all shiv, the tortuosity is considerably high in comparison to spherical particles for which this parameter ranges usually between 1 and 1.5 [21]. Here the tortuosity of hemp particles ranges between 1.5 and 3.5, and increases in a linear way with density. Such values can be attributed to the parallelepiped shape of the particles and to the particles size distribution.

Modelling the evolution of tortuosity of such packings is quite complicated since no model enables to take into account a parallelepiped shape. Some numerical predictions could be done as for example in [17] by describing the exact geometry of the particles: this is one of the outlooks of the authors. In [6], an empirical model is used and a shape factor accounts for the shape and size distribution of the particles.

2.6 Acoustical properties

The different shiv were tested in a B&K type 4106 impedance tube having a diameter of 10 cm in the frequency range of 150 - 2000 Hz. The loose particles were deposited in the tube which was held vertically and shaken to get the desired density with a constant sample thickness of 5 cm. The diameter of the tube and the thickness of the samples have been chosen to ensure a low ratio between the characteristic sizes of the particles and the tested sample, so that the properties of the granular mixes are not affected by the shape of the containing tube.

The shiv were characterized using a three microphone method [22] to enable the measurement of the intrinsic properties of the material: the equivalent dynamic density ρ_{eq}, which accounts for visco-inertial effects and the equivalent bulk modulus K_{eq}, which accounts for thermal effects. These two frequency-dependent properties describe fully the material, and enable to compute sound absorption α and sound transmission loss (TL) as a function of the thickness. Furthermore, viscous and thermal parameters can be determined from these intrinsic properties, using the indirect characterization relationships developed by Olny and Panneton [23, 24].

3 Modelling approaches

3.1 Description of the models

Acoustical properties of porous materials can be predicted, under rigid frame hypothesis, from their intrinsic properties ρ_{eq} and K_{eq} [25].

As explained in [6], shiv is a packing of porous particles. So a double porosity approach is used to take into account the properties of the intra-particle pores and of the inter-particle pores. In [6], the analysis of the experimental data enabled to show that the contrast of permeability existing between these two networks of pores is big enough, so that, in the tested frequency range, we are in the case, described in [26], of a very high contrat of permeability with no pressure diffusion between inter-particle and intra-particle pores.

As a result, the intra-particle network does not take part into te acoustical dissipation and the intrinsic properties of shiv ρ_{eq} and K_{eq} can be described accurately by computing the intrinsic properties of the inter-particle network ρ_{inter} and K_{inter} as described by Equations 1 and 2.

$$\rho_{eq}(\omega) \approx \rho_{inter}(\omega) \quad (1)$$

$$K_{eq}(\omega) \approx K_{inter}(\omega) \quad (2)$$

The models decribed in the following enable to compute these intrinsic properties from acoustical parameters such as the porosity and the resistivity of the inter-particle network.

3.1.1 Traditional approach for porous media

Some general models have been developped and can be used to describe porous materials such as granular, fibrous or foam materials. Here, we use Johnson et al. model [27] for the visco-inertial effects and Zwikker and Kosten model [28] for the thermal effects.

This approach has been chosen first since it enables with a reduced number of parameters to predict with accuracy the physical phenomena happening into the porous medium. Besides, it has been presented and applied successfully to hemp shiv and hemp concretes in several papers [5, 6].

3.1.2 Mono-sized spherical granular material approach

The second model investigated in this study is dedicated to granular media, which is more adapted to the porous nature of shiv. This kind of materials have been extensively studied by Boutin and Geindreau. In [9], these authors developed a model to predict the acoustical properties of mono-sized spherical aggregates. A very good agreement has been found between this model and numerical predictions for aggregates having a spherical shape. Besides, it has already been used for packings of porous grains [29].

This model is used here to investigate the differences between shiv and packings of spherical particles having same size, and to discuss the effect of the shape and distribution of particles on the acoustical properties.

3.1.3 Log-normal pore size distribution approach

Finally, a third model has been considered. This model is also developed for granular material but takes into account the distribution of pore size. A general model could be used to describe arbitrary pore size distribution [30]. For the case of our shiv, we use the Padé approximants of this general model, presented in [30].

This approach has been chosen to take into account the log-normal distribution of pore size and particle size existing in shiv and to investigate the effect of such distribution.

3.2 Indirect characterization of the inter-particle parameters

The inter-particle porosity ϕ_{inter} has been evaluated by adjusting the Zwikker - Kosten model [28] on the measurement of the real part of the bulk modulus. It can then be modelled as a function of both the density of the shiv and the apparent density of the particles $\rho_{particle}$.

Then, in order to model the dynamic density and the bulk modulus using Johnson et al. and Zwikker and Kosten models, inter-particle tortuosity and viscous length, respectively $\alpha_{\infty inter}$ and Λ_{inter} have been indirectly characterized from the real and imaginary parts $\Re(\rho_{eq})$ and $\Im(\rho_{eq})$ of the dynamic density measurement using the analytical method presented in [24].

The values of tortuosity measured with this method are close to the previous ones which were obtained using the direct ultrasound technique. However, it is possible to see differences, especially for shiv S_E and for high densities. In these cases, the ultrasound tortuosity is greater than the inter-particle tortuosity. This difference can be explained by the existence of the two scales of porosity as shown in [31].

It is also possible to see that inter-particle viscous length is affected by the shape and size distribution of particles. In [6], it is shown that shiv have smaller viscous length than mono-sized spherical aggreagates of same inter-particle porosity and characterstic size, and that the existing models are not suitable for this material.

3.3 Deduction of standard deviation of pore size distribution and effective pore size from the log-normal approach

For the log-normal approach, the standard deviation has first been evaluated so that the modeled sound absorption fits the measured one. Values range between 0.5 and 1. This range corresponds to the order of magnitude found experimentally in Section 2.2.

Compared to other media, these standard deviations are pretty high. In [32], glass beads, coustone and foam have been modeled using the log-normal approach and the characterized standard deviation range between 0.22 and 0.44. In our case the shape and size distribution of hemp particles is responsible for this big increase of the standard deviation of pore size compared to glass beads.

For a media having identical circular pores, the resistivity σ can be evaluated from the radius of the pores R_{pores} using Equation 3 [12, 33], where $l_{eff} = R_{pores}$ for circular pores.

$$\sigma = \frac{8\alpha_{\infty inter}\eta}{\phi_{inter} l_{eff}^2} \tag{3}$$

In the present case with a log-normal distribution of pore size, the effective pore size l_{eff} takes into account the standard deviation of the pore-size std_{pores} and we have: $l_{eff} = \left\langle R_{pores}^2 \right\rangle e^{2(std_{pores}\log(2))^2}$.

The characteristic size l_{eff} of the pores decreases with the density. We also notice that l_{eff} is very close from Λ_{inter} which can be interpreted as an estimate of the size of interconnection between pores [27].

3.4 Ability of the models to describe shiv

The predictions of the three models are compared to data in Figure 4 for the example of shiv $S_A - \rho = 150kg.m^{-3}$. It appears that the general model and the log-normal model predict the acoustical properties very well. This is clearly not the case for the mono-sized granular model.

Indeed, all models give satisfactory results for the normalised bulk modulus K/P_0, but for the normalized dynamic density ρ/ρ_0, the real part is a lot underestimated using the mono-sized spherical model. As a result, the sound absorption α predicted with this model is far from the experimental one.

This can be attributed to the fact that the shape of the aggregates is not taken into account within this two-parameter model. It has been shown that tortuosity is very high for shiv in comparison to spherical particles, that is why the real part of dynamic density of shiv, especially sensitive to tortuosity, is greater than the dynamic density of spherical particles.

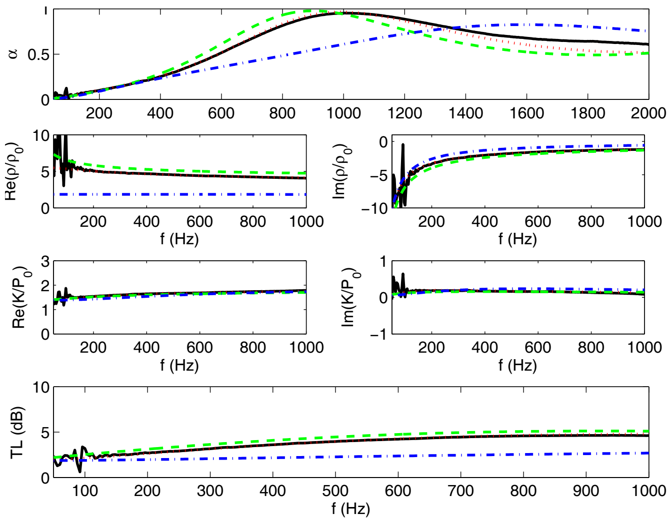

Figure 4: Modelling of shiv $S_A - \rho = 150kg.m^{-3}$ using the general model (...), the mono-sized spherical model (.−), and the log-normal model (−−), compared to data (−).

4 Effect of the shape and distribution of particles on the acoustical properties

It is pretty hard to distinguish the effect of the shape and the effect of the particle size distribution on the acoustical properties. This is partially due to the fact that both interact on the pore size distribution.

In Figure 4, the experimental sound absorption of shiv is compared to the modelling in the case of a packing of spheres having same characteristic size and same inter-particle porosity. This is a first way to notify the effect of shape and size distribution of hemp particles on the acoustical properties.

We constat for the different cases that the sound absorption of shiv is a lot better than mono-sized spherical granular media at low frequencies, and that it is a bit lower or equal to it at higher freqencies. This is explained by the increased tortuosity, that moves the first absorption peak towards the lower frequencies.

Concerning sound insulation, the transmission loss of shiv is greater than the transmission loss of the equivalent mono-sized spherical granular media.

So, this comparison shows that for a same inter-particle porosity and characteristic size, shiv provides a better transmission loss in the whole frequency range and better sound absorption for the low frequencies. This is interesting in the cases where shiv is used in a loose way in buildings, for instance in attics.

5 Conclusion

In this study, the acoustical properties of hemp particles, eco-friendly aggregates mainly dedicated to building applications, are investigated. The acoustical modelling of this material leads to several difficulties, such as the existence of pores at multiple scales, the size-distribution and the parallelepiped shape of the particles.

It is first highlighted in this paper that particle-size and pore-size distributions can be perfectly described by log-normal distributions. Besides, a clear influence of shape and size-distribution of particles is observed on the acoustical parameters. For instance, the tortuosity of shiv is very high compared to monosized spherical aggregates.

Three modelling appproaches are finally compared and enable to show the influence of shape and size-distribution of particles on the acoustical properties. For shiv, sound absorption is shifted towards the lower frequencies while transmission loss is higher than for monosized spherical aggregates.

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