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Acoustical properties of hemp concretes for buildings thermal insulation

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Abstract
This presentation deals with the acoustical performance of hemp-lime and hemp-clay dedicated to building thermal insulation. The work is based on statistically robust experimental results from more than 100 hemp-clay samples, together with the analysis of a large hemp-lime database. A modelling approach is also developed to provide a general overview of the materials. In hemp-clay mixes, our experimental results show the concentration of hemp in a mix has a first order effect on the acoustical performance, while binder fluidity and clay type have no significant effect. Another conclusion of this study is that hemp-clay and hemp-lime behave acoustically in a same way. For both materials, experimental sound absorption and transmission curves can be modelled with a physical-based four-parameters approach. The close agreement between experimental measurements and modelling highlights the good level of understanding of the physical phenomena responsible for the acoustical behavior of hemp concrete. A classification is finally proposed in terms of density to be used as a general guideline to evaluate or optimize the acoustical performances of hemp-based concrete.

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1. Introduction

The use of bio-based materials for thermal insulation is a solution for reducing environmental impacts of the building sector, which represents 40% of the world-wide energy use [4, 10].

Hemp concretes are materials produced by mixing hemp particles (or shiv) with a binder (lime, cement, or clay). Figure 1 shows two hemp concrete construction techniques. Hemp concrete between 200 and 500 kg.m^{-3} can be used for building works by shuttering techniques, spraying or casted blocks, with or without a timber frame. In this range of densities, hemp concrete might be considered as an option for insulation purposes but density has to be reduced to 300 - 400 kg.m^{-3} to reach a thermal conductivity $\lambda \leq$ 0.065 W.m^{-1}.K^{-1}.

The use of clay instead of lime or cement as binder has several advantages (environmental impact, economic...). The main difference between theses binders is that the setting of clay is a reservible process, while

(a) (b)

Figure 1. Different construction methods associated to hemp-concrete density: Shuttering (a) and Spraying (b). Some pictures courtesy of Vincent Corbard.

the setting of lime and cement is irreversible. Although the thermal insulation provided by these materials is often recognized as a priority, their acoustic properties remain very important to ensure a high level of quality of life for the inhabitants. For this reason, sound dissipation in porous media has also been extensively studied in the literature [1]. For hemp-based concretes, the approach is made complex by the existence of multiple pores scales respectively in the binder, in the aggregates and between the aggregates. It appears that the acoustical properties are principally ruled by the interparticle pores scale [5], given the fact that intrabinder and intraparticle pores are masked due to a double porosity high contrast of permeability effect [11]. However, to our knowledge there is no literature concerning acoustical properties of light earth. Differences between hemp-lime and hemp-clay mixes could exist due to the different natures of the binders.

The present study focuses on acoustical investigations of hemp-clay at the material scale, in laboratory. In the frame of this study, experimental characterizations were performed in a density range well-suited for thermal insulation purposes: 200 to 360 kg.m^{-3}. The impact of different parameters (clay nature, binder viscosity, hemp/binder mass ratio and compaction level) were quantified. Hemp-clay can also be used for sound insulation purposes, without strong requirements on thermal insulation, for instance for interior partitions. For this reason, this study includes also some results up to 800 kg.m^{-3}, to produce a general understanding on how light-earth behaves and can be acoustically optimized. The results were interpreted with an acoustical theoretical model to obtain informations related to the meso-scale porosity that contributes to sound wave dissipation. Finally, hemp-clay and hemp-lime acoustical properties were compared and discussed.

2. Materials and Methods

2.1. Materials

2.1.1. Constituents

Two different earths with clay were used, both collected in Normandy (France). Both clays felt "highly cohesive" and without gravels, and were considered well adapted for light earth by a specialized craftsman. Clays were characterized to obtain their granulometry and clays activity. Interestingly, both clays have similar methylene blue values [3]. Clay 2 (gray) has a low fraction (6%) of very active clay, while clay 1 (red) has a high fraction (37%) of normally active clay. The fraction of gravel is low for both clays. They have a similar amount of sand (about 40%), but a different amount of silt that compensate the clay fraction. These clays were mixed with water to obtain sludges. These sludges were sieved with a 1.85 mm mesh size before being used with hemp as binders.

The shiv used was also produced in Normandy. Dust ratio is low: 0.3% in mass. The density measured following the RILEM procedure [2] is 90.9 kg.m^{-3}. Fibre content is 3.9% in mass, and fibres are short, smaller than 2-4 cm.

2.1.2. Mixes

Several hemp-clay mixes were prepared as described in Table I, using a conventional works sector mixer. Water to clay ratio was adjusted to obtain three viscosity levels, noted here "Very Fluid" (VF), "Fluid" (F) and "Viscous" (V).

The hemp/binder mass ratio was set up to 30%. Two mixes were prepared with a hemp/binder mass ratio of 25 and 40% to study the effect of this parameter. Three levels of compaction ("Low", "Intermediate" and "High") were defined in order to quantify the effect of a variation of the density of samples having the same composition. For repeatability purposes, the compaction level was controlled by measuring the mass of wet hemp-clay mix required to fill moulds having the same volume. Six samples were prepared for each mix, for a total of 102 samples.

Measurements were performed at dry state : samples were dried in an oven at 50 $^{\circ}$C until their masses got stabilized (daily variation lower than 0.1% over 72h).

2.2. Characterization methods

Assuming a rigid frame, two frequency-dependent properties fully describe the acoustical behavior of a porous material: the equivalent dynamic density ρ and the dynamic incompressibility modulus K (usually reduced to bulk modulus). A harmonic time dependence of type $\exp^{j\omega t}$ is considered in this paper, with $\omega = 2\pi f$ the pulsation, f the frequency and j^2=-1. Knowing the couple (ρ, K) and the thickness e of a sample, it is possible to compute the sound absorption coefficient α and sound transmission loss TL (assuming an homogeneous and isotropic material, having a limp or rigid behavior [14]) in normal incidence.

Visco-interial effects are described by Johnson *et al* model [9], while thermal dissipation is based on the cylindrical Zwikker & Kosten model [15]. This modelling approach is presented and validated in more details for hemp shiv in [7, 8].

In total, this model counts four parameters, estimated from the measured dynamic density ρ and bulk modulus K using the methodology presented in [7] and principally based on Olny and Panneton methods [12, 13]:

- the air flow resistivity σ (static resistance of the material to air flow, given in N.s.m^{-4}),
- the tortuosity α_∞ (sinuosity of the porous path),
- the acoustical porosity ϕ_{ac} (porosity acoustically active),
- the characteristic viscous length Λ (characteristic size of the interconnexion between pores, given in m).

All acoustical measurements were performed using a 100 mm diameter and 1.45 m length Kundt tube (frequency range 250-2 000 Hz), equipped with three microphones and a speaker.

The ratio $\frac{\alpha_\infty}{\phi_{ac}}$ as well as the viscous length Λ were calculated using the real and the imaginary parts of the dynamic density using an inverse analytical procedure described in [13]. Zwikker-Kosten model was then used to predict the real part of bulk-modulus [15]. The acoustical porosity ϕ_{ac} was deduced from

Clay	Binder viscosity	Hemp/Binder mass ratio	Compaction level	Code	Average dry density (kg.m^{-3})
1	Viscous (V)	0.25	Intermediate	$1\_V\_0.25\_Inter$	292.6 ± 4.4
		0.4		$1\_V\_0.4\_Inter$	269.5 ± 3.8
1	Very Fluid (VF)	0.3	Low	$1\_VF\_0.3\_Low$	195.8 ± 3.4
			Intermediate	$1\_VF\_0.3\_Inter$	243.4 ± 4.1
			High	$1\_VF\_0.3\_High$	285.7 ± 2.7
	Fluid (F)		Low	$1\_F\_0.3\_Low$	215.7 ± 6.3
			Intermediate	$1\_F\_0.3\_Inter$	264.7 ± 8.8
			High	$1\_F\_0.3\_High$	308.9 ± 2.9
	Viscous (V)		Low	$1\_V\_0.3\_Low$	223.7 ± 8.0
			Intermediate	$1\_V\_0.3\_Inter$	280.9 ± 8.2
			High	$1\_V\_0.3\_High$	328.8 ± 1.7
2	Very Fluid (VF)	0.3	Low	$2\_VF\_0.3\_Low$	209.4 ± 2.1
			Intermediate	$2\_VF\_0.3\_Inter$	258.5 ± 3.9
			High	$2\_VF\_0.3\_High$	309.2 ± 6.2
	Viscous (V)		Low	$2\_V\_0.3\_Low$	233.3 ± 5.9
			Intermediate	$2\_V\_0.3\_Inter$	295.8 ± 4.6
			High	$2\_V\_0.3\_High$	347.7 ± 8.1

Table I. Characteristics (composition and compaction level) of hemp-clay mixes.

the minimization of the discrepancy between this prediction and the measurement of K. Knowing the ratio $\frac{\alpha_\infty}{\phi_{ac}}$ and the acoustical porosity ϕ_{ac}, the tortuosity α_∞ was finally calculated.

3. Experimental results

Figure 2 shows typical results obtained for the sound absorption coefficient and sound transmission loss. These quantities are frequency-dependent. The following acoustical properties indicators were defined in order to facilitate the comparison between mixes: the frequency and level of the first peak for the sound absorption coefficient corresponding to the quarter-wave absorption, $f_{\lambda/4}$ and $\alpha_{\lambda/4}$, and the average level of the transmission loss on the range [250 Hz, 1 000 Hz], $TL_{[250,1000]}$.

Figure 3 shows the acoustical results (acoustical indicators and acoustical parameters) and the open porosity against the hemp concentration. This figure highlights a direct link between the results and the hemp concentration.

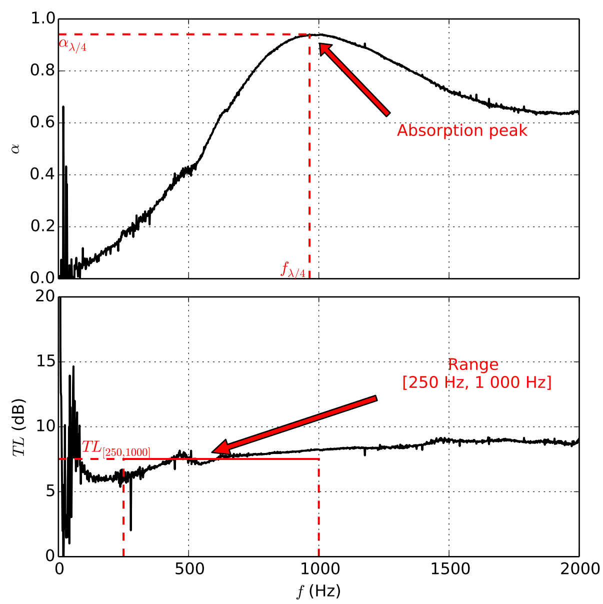

Figure 2. Example of results for the sound absorption coefficient α and sound transmission loss TL.

3.1. Effect of the compaction level

The variation of compaction within the explored range induces a density variation of 100 kg.m^{-3} in average. The effect of the compaction level is visible in all columns in Figure 3. Concerning the acoustical parameters, the porosities (ϕ_{open} and ϕ_{ac}) and the characteristic viscous length (Λ) decrease with higher concentration, while the resistivity (σ) increases. These effects are not surprising and result from a tightening of the particles in the material [7]. Besides, these variations of the acoustical parameters have a direct effect on the acoustical properties, and $f_{\lambda/4}$ and $\alpha_{\lambda/4}$ decrease with higher compaction while $TL_{[250,1000]}$ increases, which is in line with the typical behaviour of the acoustical model.

3.2. Effect of the binder viscosity

The effect of the binder viscosity level is visible in columns 1 and 2 in Figure 3. Unsurprisingly, the higher the viscosity, the higher the dry density. There is no visible effect of the viscosity of the binder on the level of the first absorption peak ($\alpha_{\lambda/4}$).

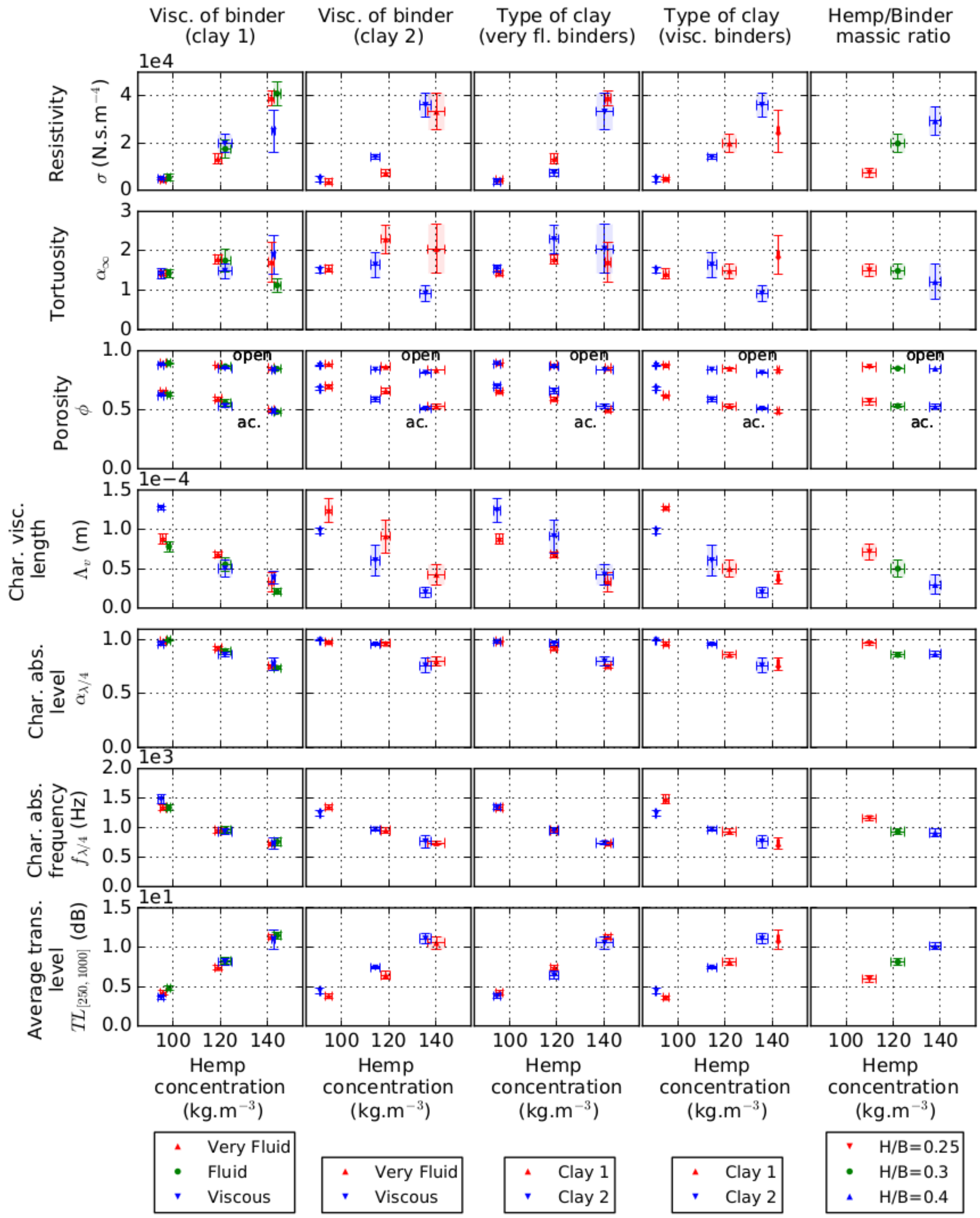

Figure 3. Mean properties indicators and acoustical parameters of hemp-clay samples plotted against the hemp concentration. Each point represents an average value over 6 samples per mix, and the bars represent the standard deviation.

3.3. Effect of the type of clay

The effect of the type of clay is visible in columns 3 and 4 in Figure 3. Clay 2 and clay 1 results are similar, with a density offset of about 20 kg.m^{-3}. This shift is consistent since the water amount required to reach the same viscosity is slighlty higher for clay 1 than for clay 2. Thus, clay type does not seem to have a significant effect on the acoustical performances (for the tested clays). This was not obvious since this binder was likely to affect the microstructure, similarly to the hemp concretes presented in [6].

3.4. Effect of hemp/binder mass ratio

The effect of the hemp/binder mass ratio is visible in column 5 in Figure 3. The proportion of hemp in mixes affects all indicators and parameters. Samples were manufactured with an identical wet mass, so the compaction level was adjusted to fit all the material into the mould (the higher the hemp content, the higher the compaction applied). Unsurprisingly, there is no direct correlation between the mass density and the resistivity (σ). Indeed, a sample with H/B $= 0.4$

can have a resistivity twice higher than a sample with H/B = 0.25, due to different compaction levels.

4. Discussion

4.1. Acoustical performances of hemp-clay

Hemp-clay can be produced with a large range of manufacturing parameters (density, ratio between constituents, nature of the constituents, building technique...). The present study was focused on the range 200 - 360 kg.m^{-3}. But, in a preliminary study, hemp-clay samples with densities ranging from 229 to 821 kg.m^{-3} were analysed in the Kundt tube. An overview of the available spectrum of performances is presented Figure 4. It shows hemp-clay can result in a large assortment of possible acoustical performances, concerning sound absorption (α) as well as transmission loss (TL).

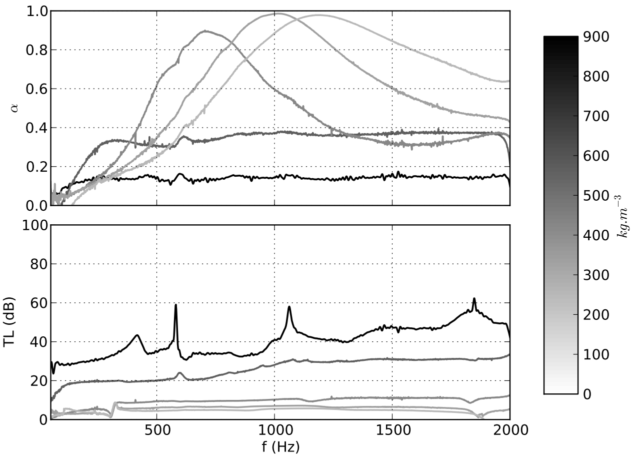

Figure 4. Range of performances achieved with hemp-clay mixtures. Formulations having densities of respectively 229, 306, 386, 517 and 821 kg.m^{-3} (lines are darker for heavier samples).

4.2. Hemp-clay versus hemp-lime

The modelled sound absorption and transmission loss of three classes of densities of hemp-clay are compared in Figure 5 to hemp-lime samples of similar densities (modelling performed using rigid frame approach). Their averaged densities and acoustical parameters are given in [3].

The shapes of hemp-clay and hemp-lime sound absorption at a given density are similar. A density increase affects the same way both materials: absorption peak moves to lower frequencies with a lower amplitude. Interestingly, these similar shapes are obtained while hemp-clay samples have a larger resistivity σ (up to a factor of 10), smaller porosity ϕ_{ac} and characteristic pores sizes α_∞. Another difference is that

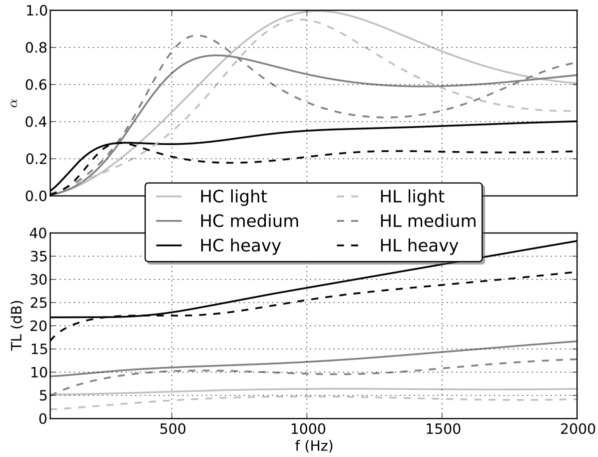

Figure 5. Comparison of hemp-clay (HC) and hemp-lime (HL) modelled sound absorption and transmission loss for three classes of density (Lines are darker for heavier samples).

the absorption peak for hemp-lime is narrower. This might be due to the greater tortuosity α_∞ in hemp-lime than in hemp-clay, the difference being above uncertainty level. This difference might be related to the lower density of the binder in hemp-lime mixes (1 000 to 1 300 kg.m^{-3} in [5]) compared to the binder density in hemp-clay (1 600 to 1 800 kg.m^{-3}. A lower density could result in stronger microstructure clogging effects.

Concerning transmission loss, the larger resistivity of hemp-clay results in a greater TL, with a difference of 3 dB on average in the considered frequency range.

Conclusion

This experimental and modelling study provides a detailed knowledge of the acoustic performances of hemp-lime and hemp-clay at the material scale.

In hemp-clay concrete, our experimental results show the concentration of hemp in a mix has a first order effect on the acoustical performance, while binder fluidity and clay type have no effect. More globally, our paper demonstrates that hemp-clay and hemp-lime mixes acoustically behave in a similar way. Their densities are located in the same range, their absorption peak position and amplitude are similar due to a major contribution of the interparticle pores. To summarize, three different acoustical behaviors can be distinguished: below 375 kg.m^{-3} with a highly absorbent behavior, between 375 to 500 kg.m^{-3} with a strong dependence of the performance on the manufacturing process, and above 500 kg.m^{-3} with low sound absorption curve and transmission loss (TL) increasing with density. This classification can be used as a general guideline to evaluate or optimize the acoustical performances of hemp-based concrete.

The experimental sound absorption and transmission data were finally modelled with a physical-based four-parameters approach with a close agreement, which highlights the good level of understanding of the physical phenomena responsible for the acoustical behavior of hemp concrete.

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