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# FEEDBACK ON A MULTISCALE INVESTIGATION ON THE ACOUSTICAL PROPERTIES OF BIOBASED BUILDING MATERIALS

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## ABSTRACT

Acoustical performances of building elements including natural sustainable fibrous and granular materials are to date still poorly known, which limits their use and spread in the building market. In order to make progress on this aspect, an ambitious study was carried out in partnership between Cerema and CSTB. Several types of biobased materials have been considered, including vegetal wools (wood, flax, hemp, cellulose), but also vegetal aggregates or concretes (loose husks and hulls, shiv, hemp concrete).

Experimental investigations were organized at the material scale (through measurements of physical parameters as well as sound absorption and transmission loss in normal incidence) and at building element scale (through sound absorption and airborne sound insulation in diffuse field conditions).

In a second step, the parameters evaluated at the material scale have been injected into a prediction software (based on a transfer matrix approach and integrating a spatial filtering method to take into account the finite size of building systems and a coupling with a SEA approach to take into account structural paths) in order to predict the acoustic performance of the building elements.

The idea of this presentation is to focus on the key results of this study and to develop the application of a roof with lost attics including loose vegetal particles.

## 1. INTRODUCTION

To date, the deployment of solutions based on biobased materials is affected by a lack of knowledge regarding their acoustical performance (at the material and system scales), which complicates the task of project management during the design phase of a building. The project manager does not have the necessary elements to properly integrate these biobased solutions into the building. Moreover, the actors are generally small sized, poorly structured trade unions and do not always have a great knowledge of technical-regulatory issues and/or the necessary means to characterize and certify their products.

A study funded by the French Ministry of Ecology has been carried out two years ago involving Cerema and CSTB laboratories, to overcome this limited knowledge and to make the sector progress in the field of acoustics. A first step has been carried out in this context to provide a state of the art on the acoustic data available for biobased

materials [1-2]. In a second step, experimental characterisations as well as simulations have been performed, to evaluate and understand the acoustical behaviour of a large selection of bio-based materials, including vegetal wools, loose vegetal fibres or particles, hemp concretes and straws. This research was conducted at two levels, linking the material scale properties to the system scale performances [3].

In this paper, analyses focus on loose vegetal biobased materials (fibrous or particles) used in lost attic spaces. The first section deals with biobased material scale investigations such as their specificities and acoustical and mechanical characteristics. The second section presents the system-scale investigations (measurement and simulation methods) and finally the third and last section presents the obtained results.

## 2. BIOBASED MATERIALS

### 2.1 Overview

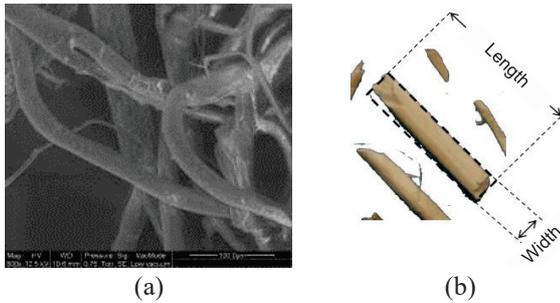
In France, biobased materials are characterised by a regulatory definition, as specified in the Decree of 19 December 2012 on the content and conditions for the award of the "biobased building" label [4]. These are materials derived from living organisms of animal (e.g. sheep's wool) or vegetal origin (e.g. wood, straw). An update study carried out in 2013 by the General Commission for Sustainable Development (CGDD) defines these biobased materials as "all biomass materials as opposed to traditional petroleum-based materials. They are either present in living organisms (plants or animals) or synthesized by them, or they are derived from products and by-products of cereals, oilseeds and protein crops, fibrous plants or wood."

### 2.2 Specificities of Materials

The biobased materials studied in this work are used as insulating materials and are considered as porous materials. The natural origin of biobased materials provides them, in addition to the specific characteristics of traditional porous materials, with several specificities that must be considered in order to understand and predict their acoustic behaviour at material scale.

These characteristics are mainly:

- their **strong anisotropy**, due to an elongated form of fibres and particles (see Fig. 1), organised in parallel planes, and leading to orthotropic behaviour;
- their **spread granulometric distribution**, which raises the question of the characteristic dimension to be retained in modelling approaches;
- finally, their **multiscale porosity**, distributed at three levels and according to different dimensions between and into the fibres or particles, and possibly in the binder.



**Figure 1.** Example of vegetal fibres (a) and particles (b), highlighting the elongated forms responsible for the anisotropy of the associated biobased materials [5,6].

These specificities were taken into account to determine the most relevant models for each material and to evaluate the associated parameters [7].

### 2.3 Parameter Characterisations

A material-scale characterization is very important since the measured parameters can be then used as input data in simulation tools in order to estimate the acoustic performance for different building systems.

#### 2.3.1 Acoustical parameters

The acoustical characteristics of several biobased materials, including fibrous and granular materials, were evaluated by Cerema laboratory [3] such as:

- **Porosity  $\Phi$**  does not always correspond to open porosity due to the multiscale nature of the material (used according to [8]);
- **Resistivity  $\sigma$**  (in accordance with [9]);
- **Tortuosity  $\alpha_\infty$**  which can be relatively high for particles due to their shape and elongation and **viscous and thermal characteristic lengths  $\Lambda$  and  $\Lambda'$**  (accordind to [10, 11]).

Some results about loose fibrous and granular materials are presented in Table 1. Then, these parameters will be used as input data in an acoustic performance simulation software.

According to acoustical characterisation, loose vegetal wools are almost systematically very porous ( $\Phi > 95\%$ ) and characterized by a tortuosity  $\alpha_\infty$  of about 1, which is typical of more conventional fibrous materials and the resistivity naturally increases with density. Finally, the

characteristic lengths and thermal permeability are within the usual ranges of porous acoustic materials.

Regarding loose particles, these kinds of materials have lower porosities than fibrous materials (from 80 to 90% depending on the material) because they correspond to the interparticle porosities of the materials, the intraparticle pores not contributing to dissipation in this case [6]. Nevertheless, the most striking characteristic remains the significant tortuosity of the materials, directly linked to the quasi parallelepipedal shape of the particles (Fig. 1b).

Material		$\rho$ ( $\text{kg}\cdot\text{m}^{-3}$ )	$\Phi$ (%)	$\sigma$ ( $\text{Nm}^{-4}\text{s}$ )	$\alpha_\infty$ ( )	$\Lambda$ ( $\mu\text{m}$ )	$\Lambda'$ ( $\mu\text{m}$ )
Loose vegetal wools	Hemp	30	98.2	220	1.04	695	3 430
	Hemp/Cotton	40	97.4	2 380	1.00	100	530
	Hemp/Cotton (tested)	20	90.0	1 000	1.00	200	1 000
	Recycled cotton	30	98.0	5 415	1.00	95	140
	Cellulose wadding	35	97.7	6 290	1.00	55	100
	Cellulose wadding (tested)	30	98.0	4 000	1.00	70	100
Loose particles	Buckwheat hull	240	84.0	11 270	3.38	175	400
	Sunflower hull	105	93.0	2 320	2.63	280	3 400
	Small spelt husk	110	92.7	1 615	1.64	250	1 830
	Rice husk	100	93.3	2 690	1.89	220	700
Mineral wool		15	95.0	6 000	1.00	60	150

**Table 1.** Acoustical parameters of measured loose biobased materials.

#### 2.3.2 Mechanical parameters

About mechanical parameters, dynamic stiffness measurements have been carried out by CSTB laboratory in accordance with [12] in order to identify the elasticity and the damping of biobased materials (Young's modulus  $E$  and loss factor  $\eta$ ). But if in the case of relatively "flexible" materials this method is appropriate, it is not the case for loose materials: measurement results are very dispersed with a strong dependence to the material configuration and matter organisation. A dedicated setup must be developed to achieve better and meaningful characterisation in this case. Therefore, the mechanical properties of loose material have been deduced mainly based on the density and resistivity of material and considered identical and representative of the material type ( $E_{\text{fibrous}} = 0.03 \text{ MPa}$ ;  $E_{\text{granular}} = 0.25 \text{ MPa}$ ;  $\eta = 7\%$ ) [13].

### 3. BUILDING ELEMENT SCALE INVESTIGATIONS

#### 3.1 Acoustic Performance Characterisations

##### 3.1.1 Lost attic space with roof system

In a building, according to [14], the sound insulation by lost attic  $D_{2m,n\text{ attic}}$  (see Fig. 2), similar to a buffer room, can be calculated as follows:

$$D_{2m,n\text{ attic}} = D_{\text{outdoor} \rightarrow \text{attic}} + D_{\text{attic} \rightarrow \text{room}} \quad (1)$$

with

$$D_{\text{outdoor} \rightarrow \text{attic}} = R_{\text{roof}} + 10 \log_{10} \left( \frac{A_{\text{attic}}}{S_{\text{roof}}} \right) \quad (2)$$

$$D_{\text{attic} \rightarrow \text{room}} = R_{\text{ceiling}} + 10 \log_{10} \left( \frac{A_0}{S_{\text{ceiling}}} \right) \quad (3)$$

where  $R_i$  is the sound reduction index of the  $i$  building element [dB],  $S_i$  is the area of the  $i$ -th building element [ $\text{m}^2$ ],  $A_0$  is the reference equivalent sound absorption area ( $10\text{m}^2$ ) and  $A_{\text{attic}}$  is the equivalent sound absorption area in the attic space [ $\text{m}^2$ ] calculated as

$$A_{\text{attic}} = S_{\text{roof}} \alpha_{\text{roof}} + S_{\text{attic}} \alpha_{\text{attic}} \quad (4)$$

with  $\alpha_i$ , the sound absorption coefficient the  $i$  building element.

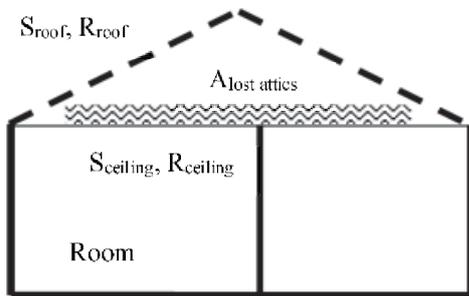


Figure 2. The sound insulation under roof (lost attics).

If  $R_T$  is considered as the equivalent sound reduction index of the whole element (roof + attic) then:

$$D_{2m,n\text{ attic}} = R_T - 10 \log_{10} \left( \frac{S}{A_0} \right) \quad (5)$$

with  $S$ , the area of ceiling.

In a laboratory, the sound reduction index  $R_T$  is measured with an area  $S_{\text{labo}}$  of  $15 \text{m}^2$  for all elements (roof, attic, ceiling). From Eqn. 1 and Eqn. 5, a calculated sound reduction index  $R_T$  can be obtained as:

$$R_T = R_{\text{roof}} + R_{\text{ceiling}} + 10 \log_{10} (\alpha_{\text{roof}} + \alpha_{\text{attics}}) \quad (6)$$

So, to evaluate  $R_T$ , it is necessary to know the sound reduction index  $R$  and the sound absorption coefficient  $\alpha$  of the roof and the ceiling (i.e. insulation material place on

the ceiling for thermal reasons) systems. Regarding roofs, these performances will be taken of the AcouBAT software database. Regarding the ceiling element, required performance data are obtained from measurements carried out in the part of biobased material study [3].

##### 3.1.2 Lost attics systems

In the French study carried previously out on the acoustical performance of biobased materials [3], ceilings separating a liveable room from an undeveloped attic have been considered and characterised, in the acoustics test laboratory of CSTB (LABE, European Laboratory of Building Acoustics), without roofing system in terms of sound reduction index  $R$ , according to [15]. The ceilings, of dimensions  $4.2 \times 3.6 \text{m}^2$ , consist of a  $12.5 \text{mm}$  thick plasterboard fixed by a metallic structure on a wooden frame ( $160 \text{mm} \times 60 \text{mm}$  purlins, with a spacing of  $500 \text{mm}$ ) and a  $350 \text{mm}$  layer of loose biobased insulating materials (see. Fig. 3).

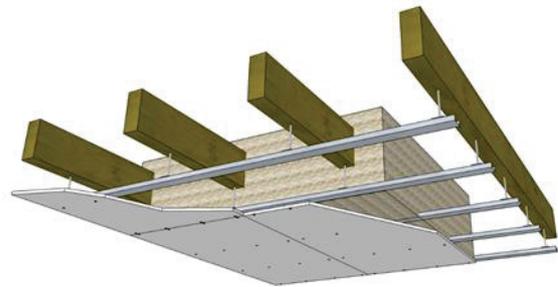


Figure 3. Schematic drawing of a lost attic with insulating biobased material.

Then, the same loose insulating materials used with ceiling have been characterised in reverberant room in terms of sound absorption coefficient  $\alpha$ , according to [16], for dimensions  $3.6 \times 3.0 \text{m}^2$ .

All these measurement results are presented in Sec. 4.1.1.

#### 3.2 Acoustic Performance Prediction Method

##### 3.2.1 Simulation tool

Acoustic performance of a building element is predicted using a transfer matrix method (TMM) [7, 17] implemented in AcouSYS software developed and commercialized by CSTB. The different layers of constant thickness constituting the structure can be solid, fluid, porous (according to the generalized Biot-Allard theory [18]) or viscoelastic. This tool can be used to predict sound reduction index, impact sound level, sound absorption, rainfall noise, propagation constants and turbulent boundary layer noise. Moreover, a method of spatial windowing is used to take into account the finite dimensions of the studied systems [19], when subjected to air-borne excitation.

### 3.2.2 Calculation hypothesis

The calculations were performed only on the ceiling systems in order to evaluate the effect of different type of loose biobased insulating materials. The roofing systems were not modelled.

Structural connexions due to framing elements in ceiling system (metallic supports of ceiling boards or wooden beams) are not taken into account for simplicity.

A contact is considered between loose insulating materials and plasterboards (since the insulation material rests on the plasterboards layer). Thus, the mechanical parameters of the insulating material may have an impact on acoustic performance as the skeleton of the porous material is excited. This situation corresponds to the standard assumption for this type of system. However, since mechanical parameters have been difficult to obtain for this kind of materials (see Sec. 2.3.2), values typical of similar materials have been used.

A parametric study was carried out (not presented here) and emphasizes that, in this system case, acoustic performance is influenced principally by the acoustic parameters (mainly the airflow resistivity which strongly impacts the slope of the performance curve), and that the mechanical parameters (elasticity) do not influence significantly the general appearance of the curve because of their low value.

Nevertheless, it is important to note here that the hypotheses regarding the mechanical properties of the materials (Young's modulus  $E$  and damping factor  $\eta$ ) remain to be lifted and that it is fundamental to characterize them in order to ensure the relevance of the predictions for other kind of building systems. As mentioned before, these properties can be assessed based on [12], although for loose materials this method should be adapted.

To sum up, the input data for the insulating materials considered in the present work, used in AcouSYS prediction software are the mechanical and acoustical parameters presented in Sec. 2.3.

## 4. RESULTS

### 4.1 Measurements on Lost Attic Systems

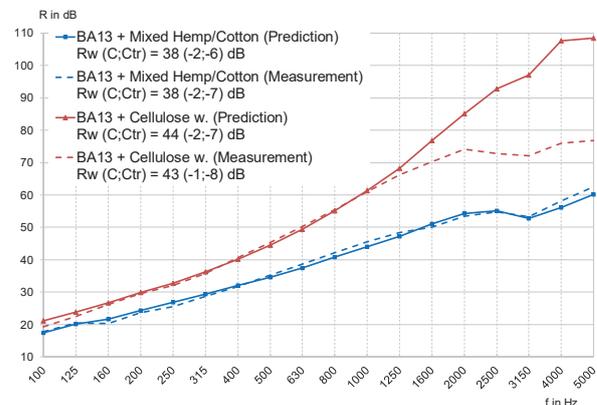
#### 4.1.1 Calculation/measurement comparisons

In this section, the results of laboratory measurements and associated simulations obtained on lost attic systems with biobased insulating materials are presented.

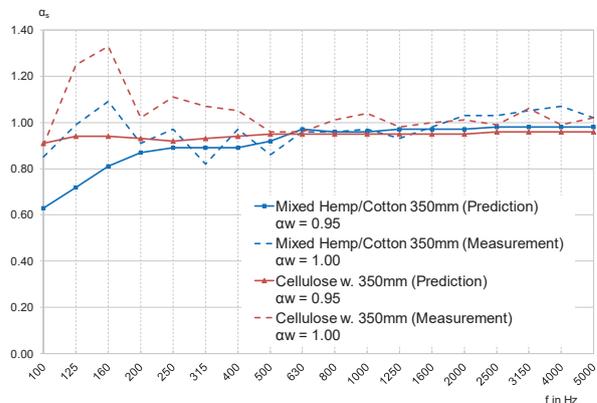
Fig. 4 illustrates the comparisons of the measured and simulated sound reduction indices for the ceiling and Fig. 5 shows the associated sound absorption coefficient for each kind of loose vegetal wools investigated.

The experimental results show a greater sound reduction and a better sound absorption for cellulose wadding filling, which is related to the greater resistivity of this material.

From the comparison results, it appears that the predicted sound reduction index is very close to that measured (see. Fig. 4). The differences observed in the high frequencies between prediction and measurement for cellulose wadding insulation could be due to the assumption used to model the ceiling (no framing); they have however no influence on the overall performance of the system.



**Figure 4.** Comparison between measurement and simulation of the sound reduction index  $R$  of a ceiling with loose fibre insulation materials (mixed hemp/cotton fibres and cellulose wadding).



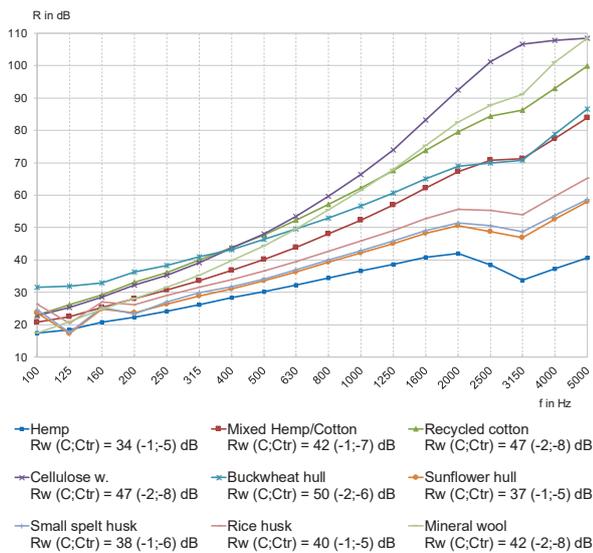
**Figure 5.** Comparison between measurement and simulation of the sound absorption coefficient  $\alpha$  of loose fibre insulation materials (mixed hemp/cotton fibres and cellulose wadding).

Regarding the sound absorption coefficient (see Fig. 5), it should be noted that overall the frequency behaviour is similar between measurements and predictions. The measured sound absorption coefficients show values greater than 1 with a maximum of one third of an octave 160 Hz due to the finite size of the system tested in the laboratory and the side effects which are not taken into account in the modeling.

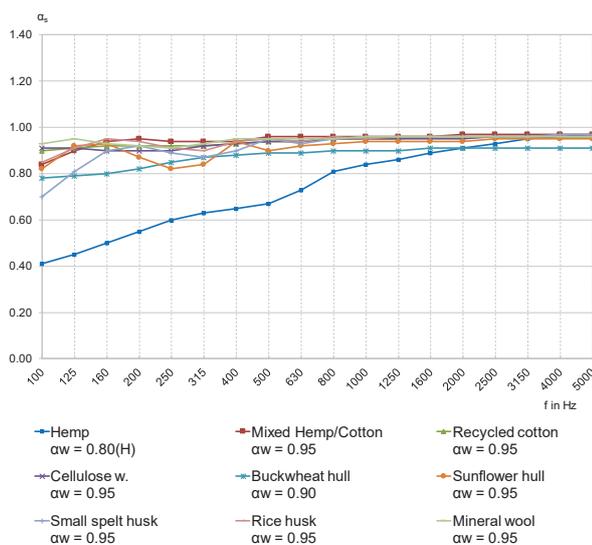
#### 4.1.2 Extrapolation of results

From the calculation/measurement comparisons above, which have shown fairly good correlations, extrapolations of acoustic performance are made with the loose biobased materials whose characteristics are presented in Tab. 1.

Fig. 6 illustrates the sound reduction index calculated for the ceiling (composed of a single plasterboard layer of 12.5 mm in thickness) with different loose biobased materials compared to a standard mineral wool and Fig. 7 shows the associated calculated sound absorption coefficient. The insulating material have a thickness of 350 mm (thickness usually required commonly implemented for thermal reason).



**Figure 6.** Simulated sound reduction index of a ceiling (single plasterboard layer) with different loose biobased insulating materials and a standard mineral wool.



**Figure 7.** Simulated sound absorption coefficient of different loose biobased insulating materials and a standard mineral wool (thickness of 350 mm).

#### 4.2 Estimates on Lost Attics with a Roofing System

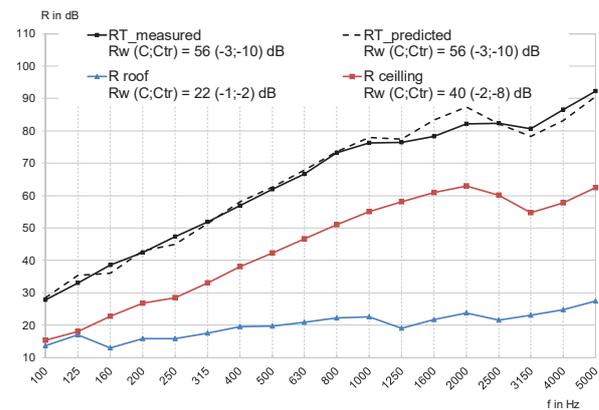
##### 4.2.1 Validation of the method

In order to estimate the acoustic performance of a lost attic system when a roof is integrated (see Eqn. 6, Seq. 3.1.1), a validation of the method is carried out on a configuration of insulated lost attic with a roofing system measured in laboratory. This complete system has to be evaluated in order to validate the acoustic performance against outdoor noise.

The measured system is constituted of concrete roof tiles on a wooden frame, an airgap of 540 mm and a ceiling composed of a 280 mm thick mineral wool placed on a single layer of 12.5 mm thick plasterboards.

Fig. 8 illustrates the recomposed sound reduction index of the complete system according to Eqn. 6 from the components (roof and ceiling performances) as well as the corresponding measured sound reduction index for the lost attic system with roof.

Based on this comparison, the re-composition method to evaluate the sound reduction index for a lost attic system with roof is validated. Thus, the estimate for other lost attic systems with roof and biobased insulating materials can be performed.



**Figure 8.** Comparison between measured and recomposed sound reduction index of a lost attic system with roof from ceiling and roof acoustic performances.

##### 4.2.2 Extrapolation of results

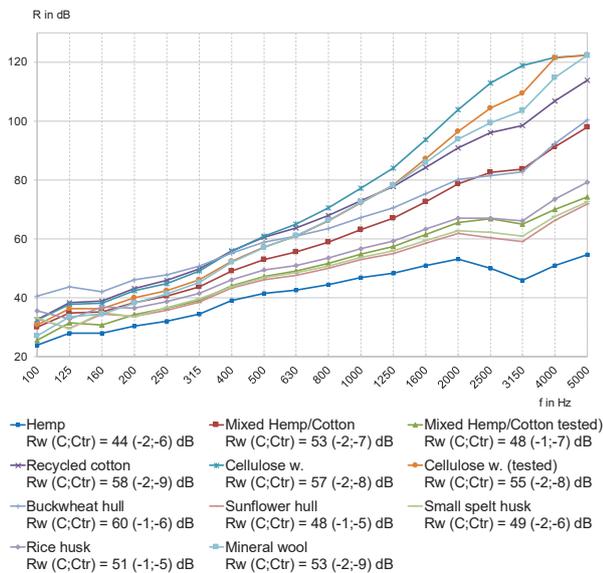
From Eqn. 6 and the validation performed in Sec. 4.2.1, an estimate of the acoustic performance of the lost attic systems studied in Fig. 6 (ceiling composed of a 350 mm thick insulating material placed on a 12.5 mm thick plasterboards) is carried out by considering several roof types (concrete, terracotta and slate tiles).

The estimated acoustic performances are shown in Tab. 2 and the predicted sound reduction indexes of the complete system for each insulating material are illustrated in Fig. 9, Fig. 10 and Fig. 11, depending on the roof tile nature.

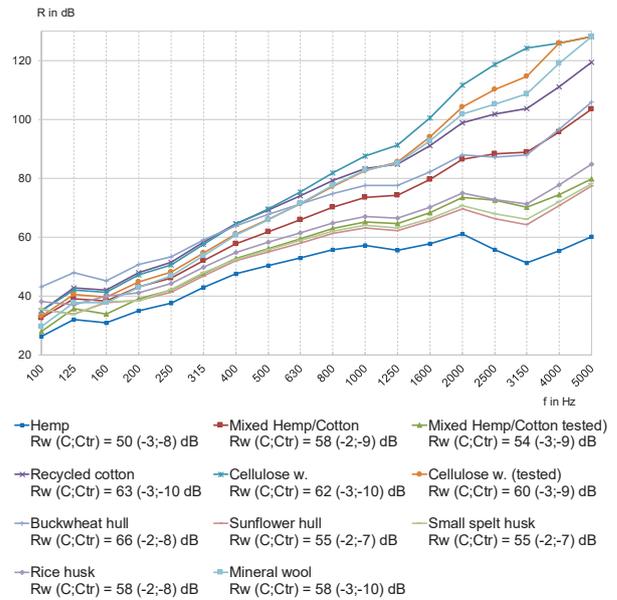
		$R_w+C_{tr}$ [dB]		
		Terracotta tiles + Lost attics	Concrete tiles + Lost attics	Slate tiles + Lost attics
350mm thick	Hemp	38	42	44
	Hemp/Cotton	46	49	52
	Hemp/Cotton (tested)	41	45	47
	Recycled Cotton	49	53	55
	Cellulose Wadding	49	52	55
	Cellulose Wadding (tested)	47	51	53
	Buckwheat hull	54	58	60
	Sunflower hull	43	48	49
	Small spelt husk	43	48	49
	Rice husk	46	50	52
	Mineral wool	44	48	50

**Table 2.** Estimated acoustic performances of lost attic system with several roof types (concrete, terracotta and slate tiles) and loose biobased insulating materials.

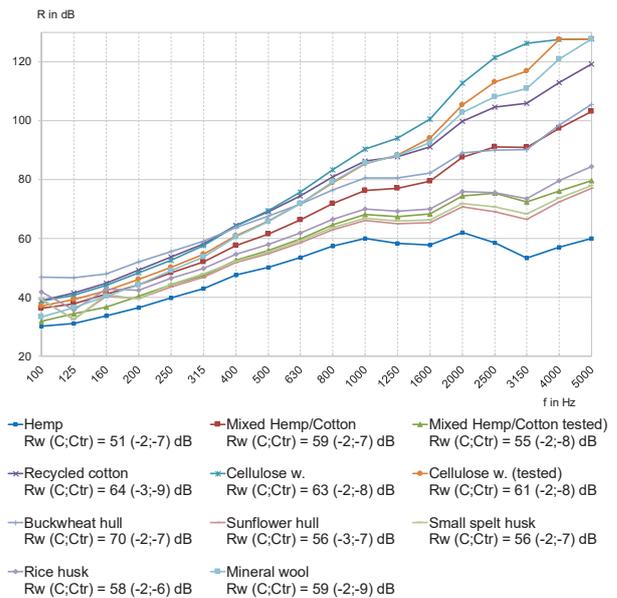
According to the results, the performance hierarchy is in keeping with the system without roof (see. Fig. 6). In addition, the acoustic performances  $R_w+C_{tr}$  are higher in the case of a roof with slate tiles due to a better sealing between tiles, and the acoustic performances  $R_w+C_{tr}$  with concrete tiles are higher than with terracotta tiles due to the greater mass of the material.



**Figure 9.** Predicted sound reduction index of a lost attic system with a terracotta tile roof system for different loose biobased insulating materials and a standard mineral wool.



**Figure 10.** Predicted sound reduction index of a lost attic system with a concrete tile roof system for different loose biobased insulating materials and a standard mineral wool.



**Figure 11.** Predicted sound reduction index of a lost attic system with a slate tile roof system for different loose biobased insulating materials and a standard mineral wool.

For information, the same investigations have been carried out with an under-roof screen installed behind tiles, as it is usually the case. Although improving the acoustic performance at high frequencies, the contribution of such a screen does not improve the single number acoustic performances  $R_w+C_{tr}$  presented in Tab. 2.

## 5. CONCLUSION

A large experimental campaign has been previously carried out on biobased materials to get a better understanding the acoustical behaviour of these materials [3]. The present study focuses on a part of this past experimental campaign and mainly on the evaluation of acoustic performance of lost attic space systems with roof when integrating loose biobased materials as thermal insulation layer.

Once the characterization of the acoustic parameters for various loose biobased materials (fibrous and granular forms) has been obtained, these characteristic properties were injected into a calculation model (AcouSYS software) in order to estimate and compare the acoustic performances of ceiling systems measured in laboratory. A good agreement has been found between the experimental data and simulations, and result extensions have been applied to other loose biobased materials with or without consideration of a roofing system.

All results show that building systems integrating biobased materials have the same levels of acoustical performances that other similar systems with more conventional material, such as mineral wool.

This work highlights also the need for further studies in this field, to investigate more deeply some of the results at material and system scales, one priority being a better determination of the mechanical parameters of these loose materials and their durability with time.

## ACKNOWLEDGEMENT

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