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Acoustic characterization of natural fibers for sound absorption applications☆

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ABSTRACT

Natural materials are becoming a valid alternative to traditional synthetic ones for sound absorption treatments. In particular, in recent years, natural fibers have been considered valid raw materials for producing sound absorbing panels at a reduced cost. Moreover, these fibers often have good thermal insulation properties, have no harmful effects on health, and are available in large quantities often as a waste product of other production cycles. Following a literature review of previous studies about the acoustic properties of some natural materials, this paper reports the acoustical characterization of the following natural fibers: kenaf, wood, hemp, coconut, cork, cane, cardboard, and sheep wool. The absorption coefficient and the flow resistance for samples of different thickness have been measured. By using existing theoretical models, this study also compares the measured behavior with the theoretically predicted behavior. This comparison shows the limits of theoretical models originally defined for porous materials with homogeneous fibers, when they are applied to natural materials. Finally, some suggestions for use of these natural fibers for sound absorption applications in buildings are reported.

1. Introduction

Sound absorption panels for room acoustic applications are generally composed of porous synthetic materials, such as rock wool, glass wool, polyurethane or polyester, which are expensive to produce and are generally based on petrochemicals. The growing awareness towards the environmental implications and health issues associated with these materials has increased the attention towards natural materials [1–3]. These are generally defined according to natural and renewable sources of their constituent materials, the low level of environmental pollution emitted during their production or to their low embodied energy [4,5]. However, there is still little knowledge about the sound absorption behavior of natural materials. In order to absorb sound, materials should have high porosity to allow the sound to enter in their matrix, and for dissipation. Pores isolated from other adjacent pores, also called “closed” pores, allow some level of sound absorption, but only “open” pores, which guarantee a continuous channel of communication with the external surface of the material, allow higher sound absorption properties [6]. Based on their microscopic configurations, porous absorbing materials have also been classified as cellular, fibrous, and granular [6,7]. Granular materials consist of relatively rigid, macroscopic bodies whose dimensions exceed those of the internal voids by many orders of magnitude, and in this they differentiate from cellular materials. Conversely, fibrous materials consist of a series of tunnel-like openings that are formed by interstices in material fibers; these fibers may be continuous filaments or discrete elongated pieces.

Fibers are often classified as natural or artificial. Natural fibers can be vegetable (kenaf hemp, wood), animal (wool, fur felt) or mineral (asbestos); whereas synthetic fibers can be mineral (fiberglass, mineral wool, glass wool) or polymer (polyester). Vegetable fibers are comprised mainly of cellulose [7] and can be categorized into:

- stalk or wood fiber (e.g. straw of wheat, rice, softwood or hardwood);
- bast fiber or skin fiber (e.g. flax, jute, kenaf, industrial hemp, ramie, rattan, and soybean);
- leaf fiber (e.g. sisal, palm, and agave);
- seed fiber (e.g. cotton and kapok);
- fruit fiber (e.g. coconut).

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The materials selected for this paper are mainly vegetable fibers, and derive from plant crushing to obtain basic components, which were then compressed in order to create sound absorbing panels. Among the materials with a fibrous structure investigated in this paper, there are kenaf, hemp, wood, cane, and coconut; for comparison, this paper also investigates cork, a cellular structure material, and wool, an animal fiber.

Natural fibers have been receiving increasing attention for acoustic uses [8–10]. A variety of natural fibers for building applications have started being commercialized already, but the majority of products investigated in this paper is still rarely used in building practice. Natural fibers are competitive materials thanks to their low density, good mechanical properties, easy processing, high stability, occupational health benefits, reduced fogging behavior, high quantity availability, low price, and reduced environmental impacts for their production [4,7]. Several authors have also shown that vegetable fibers may have a positive environmental impact thanks to the CO_2 absorption and sequestration during the growth of the plant [5]. However, other researchers have also questioned the real sustainability of natural fibers, in regard to the toxicity of the chemical products used for their cultivation or during the material transformation in building products. Fiber plants are often subject to fungi and parasites and are less resistant to fire than typical mineral fibers; moreover, they often need special treatments before being used, which reduce the inherent sustainability of the raw materials. These considerations suggest to pay attention to the environmental impacts of all the products used during the entire process of transformation of the natural fibers into building materials. Consequently, although natural fibers are often commercialized in panels or blocks created by using some binder, in this paper unprocessed natural fibers without the use of any binder are considered only. In this way, this paper analyzes the raw fibers without being influenced by a binder. Shape stability was obtained by compressing the raw material and compartmentalizing in small acoustically-transparent bags. The idea behind this approach was originally investigated by Iannace et al. [11], who created sound absorbing panels by putting unprocessed raw materials into jute bags, and will be discussed in the final section of this paper.

1.1. The environmental value of natural fibers

Different indicators to compare the environmental impacts of buildings materials have been proposed recently, such as the U.S. EPA TRACI categories. Zabalza Bribian et al. [4] considered the primary energy demand (in MJ-eq) according to the CED method, the global-warming potential (in kg CO_2-eq) according to the IPPC 2007 methodology, and the water demand for the building production (in litres). Most of the studies focused on just one of these indicators [12–17]. Doing environmental impact analysis of building materials, some studies considered the full life-cycle of the material, including raw material extraction, production, transport, construction, operating and management, deconstruction, recycling, and reuse; while others considered only the production of the material or the construction stage, and avoided the evaluation of the following phases since these are characterized by high uncertainties [15–17]. Another important aspect in any environmental comparison among building materials regards the considered functional unit. Previous evaluations have often been based on a unit of volume (1 m^3) or weight (1 kg). For thermal insulating materials, it is often common to use the quantity of material necessary to obtain a given thermal resistance as a functional unit. In this way, the environmental impact is considered according to the material performance; however, no study has been done so far using a sound-related performance as a functional unit.

Despite all the stated limits, and uncertainties in assessing the environmental impacts of building materials, there is a clear agreement about the high impact of conventional sound absorbing materials, which require much more industrial processing compared to natural fibers [17]. As an example, while the production of EPS or polyurethane emits 7 kg CO_2-eq/kg given the high consumptions of gas and petroleum, natural materials have shown impacts up to 98% less [4]. Similarly, Asdrubali reported the embodied energy in processed materials having a thermal resistance of 1 m^2 K/W, and showed negligible embodied energy for reed, below 50 MJ for coconut, cork, and kenaf fibers, around 75 MJ for hemp, and almost 100 MJ for mineralized wood fibers [2,15]. This result also confirms that the binder may highly affect the environmental impacts of natural fibers.

Consequently, this study decided to avoid an LCA comparison among the different fibers, and to focus only on natural products that are available as “waste” or secondary products of other production processes. The abundancy of these fibers produced in any way poses a problem for their disposal, and their use in the building industry would avoid their incineration, further reducing the environmental impact. This selective criteria may sound strange for some fibers such as the sheep wool; however, it must be pointed that due to the widespread use of synthetic fabrics, sheep wool in several European regions has seen its market shrink, and it is nowadays often a waste product to burn [18]. The production of wool products will convert this waste into a cheap material, with economic and social benefits. Similarly, obtaining cork in the forests and farms in the south of Europe would be an ecological production, as the cork is extracted without damaging the tree. This in turn would continue to contribute to the maintenance of an ecosystem of high value that would probably disappear without an economic use of cork trees [15]. This means that an evaluation of the primary energy demand in cork would not account sufficiently for the benefit of creating a building material from it. Finally, fibers were selected according to their antimicrobial properties and their resistance to mold, mildew, and insects with minimal processing.

2. Sound absorption of porous materials

A literature review about acoustic studies of natural materials showed a variety of experiences often focused on the production and acoustic characterization of one or a few materials in each study. In this paper, the characterization and the comparisons among several fibers are reported.

Useful parameters to compare the sound-absorbing characteristics of fibers, and hence predict their behaviour, are the diameter, the length, and the regularity of the fibers. Electronic microscopy techniques have shown that the diameter of natural fibers tends to be larger than the diameter of synthetic fibers, and that natural fibers have more irregular shapes and diameters compared to synthetic fibers. This microscopic structure prevents theoretical sound absorbing models from being accurate [6,20,21]. Arenas and Crocker reported the average diameter for some natural fibers: 8–33 μm for cotton, 21 μm for kenaf, 16–38 μm for wood, and 22 μm for hemp [6]. For the latter, Oldham et al. found a diameter of 93.9 μm, and an airflow resistivity of almost 1400 Pa s/m^2 [22], practically equal to that found in the present paper. Finally, the wool, the only animal fiber considered in this paper, has a fiber diameter equal to 37 μm when used as a raw material and 63 μm when used as a wool batt, with an airflow resistance double for the fibers with small diameter [22].

Several models for predicting the sound absorption mechanisms in the interior of porous materials exist, and are generally differentiated based both on the distinctive absorption mechanism and the type of pores. A porous material exposed to incidental sound waves allows the air molecules within the pores of the material to vibrate and, by doing it, it transforms some energy into thermal and viscous heat. At low frequencies, these energy losses are isothermal and unfortunately limited, while at high frequencies, they are adiabatic and are generally more important. In fibrous materials, most of the energy is absorbed by scattering from the fibers and the consequent vibration of them.

Existing sound absorbing models aim to describe the characteristic wave impedance and the characteristic sound propagation constant using some basic physical properties of the materials, such as the porosity, the tortuosity, and the airflow resistance. Delany and Bazley proposed a very simple model for fibrous absorbent materials only employing the non-acoustical parameter of airflow resistivity for predicting the acoustical characteristics [23]. This model considers a porous layer as bulk material, with the rigid frame media of the material, so that the flow resistivity is sufficient to calculate the acoustical characteristics. Using a best-fitting approach to a large amount of experimental data for mineral fibrous porous absorbers, Delany and Bazley defined simple power–law relation for the z_c, the characteristic impedance, and k_c, the complex wave number or propagation constant [23]:

$$z_c = \rho_0 c \left(1 + 0.0571 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.754} - j0.087 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.732} \right) \tag{1}$$

$$k_c = \omega / c \left(1 + 0.0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.7} - j0.189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.595} \right) \tag{2}$$

where $\rho_0 c$ is the characteristic impedance (Pa·s/m), ω is the angular frequency ($\omega = 2\pi f$), c is the sound speed (m/s), σ the flow resistivity (Rayl/m), and f is the frequency (Hz).

Previous formulas were obtained over a well-defined frequency range ($10 < f/\sigma < 1000$) and with a porosity of the material close to 1, which means that a high fraction of pores should be present in the material in order to apply the Delany–Bazley model properly. In fact, at both lower and higher values of f/σ, Delany–Bazley state that there are theoretical reasons for expecting the data for rigid materials to normalise to other power–law relations, with progressive departure from their empirical relations. Moreover, the Delany–Bazley model was obtained from measurements on fibers with a diameter between 1 and 10 μm, and in fact although its simplicity, this model has shown some limits with thicker fibers [24–26]. Garai and Pompoli revised the Delany–Bazley model by experimenting polyester fiber materials with diameters ranging from approximately 20 to 50 μm, and proposed similar formulas to those of Delany–Bazley, but with different coefficients [24]:

$$z_c = \rho_0 c \left(1 + 0.078 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.623} - j0.074 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.66} \right) \tag{3}$$

$$k_c = \omega / c \left(1 + 0.121 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.53} - j0.159 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.571} \right). \tag{4}$$

The Garai–Pompoli equations have sometimes proved to be more accurate that the Delany–Bazely ones for the study of natural fibers, since these fibers show diameters and density of the closer to those considered by Garai and Pompoli. However, even the Garai–Pompoli equations were obtained using a best fitting approach to just a category of fibers, and in a limited frequency range. Many other authors, including Qunli, Miki, Mechel, Wang et al., have provided different coefficients for the previous formulas by using other empirical data and best fit modelling. A review of these models can be found in many acoustics handbooks, such as Crocker [27].

Parallel to best fitting empirical studies to sound absorption, a significant literature of theories and models has tried to understand the behaviour of porous material. Biot established an easy theoretical explanation for saturated porous materials which is still considered accurate enough [28]. Later, Attenborough [26] and Allard [29] improved the explanation of sound propagation in porous materials. In particular, Allard described a porous layer as a mixture of air and elastic frame, which could be modelled only by including some parameters, such as the bulk density, the fiber density, the Prandtl number of the air movement, the thermal characteristic length, and some elastic coefficients [29]. This model was later revised to consider the existence of different pore sizes, and to model the heterogeneity of real materials [30].

Models for predicting the characteristic impedance and wave number of porous materials with structures which are more complex than single fibers are generally developed using viscous and thermal effects and require much more detail to account for the interaction between the sound waves and both the micro-pores of the material, and the macro-structural behaviour.

In this paper, some materials which may expect to have a behaviour different from typical fibrous porous absorbers such as cork, cane, and the cardboard are investigated. In particular, for cane the pore structure arises from the space between individual non-uniform stems. Conversely, in the cardboard, large slit like pores, parallel to the airflow, result in a low airflow resistivity. Given the significant differences among existing models and the difficulty in modelling the highly inhomogeneity of natural thick fibers using these models, in this paper it was preferred an empirical approach often compared with the prediction of the Delany–Bazley model. Together with the common recognition of the validity of this model, this was also selected since it is reported in several standards, such as the EN 12354–6, Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 6: Sound absorption in enclosed spaces (Fig. 1).

3. Acoustic measurement setup

3.1. Sound absorption measurement

Sound absorption measurements were performed using the impedance tube method [31,32]. With this method it is possible to readily obtain measurements of normal incidence parameters using small samples that are easy to assemble and disassemble; moreover, from knowing the normal incidence properties, it is also possible to apply some corrective formulas to obtain an approximate value of the random incidence absorption coefficient. The procedure described in the ISO 10534-2 standard was followed [31]. The Kundt's tube had an internal diameter of 10 cm (which corresponds to an upper frequency limit of 2000 Hz), a length of 56 cm, and mounted two ¼" microphones, at a distance of 5 cm for measurements above 250 Hz (Fig. 2). The measurements were then repeated using a distance of 10 cm between the microphones, in order to measure the sound absorption below 250 Hz. In fact, the lower frequency of validity for a Kundt's tube should respect the condition $S > 0.05\ c/f$, where S is spacing between the microphones, c is speed of sound, and f the lower frequency. This means that a 10 cm distance between the microphones allows accurate data above 170 Hz. The following figures with the sound absorption results show measurements above 200 Hz only, however, the results also in the 125 Hz frequency band are reported in Table 2.

To reduce the possible gaps among the sample and the container, extreme care was taken to seal the border without creating local compression between the tube and the samples. In this way, the size of voids between the tested material and the

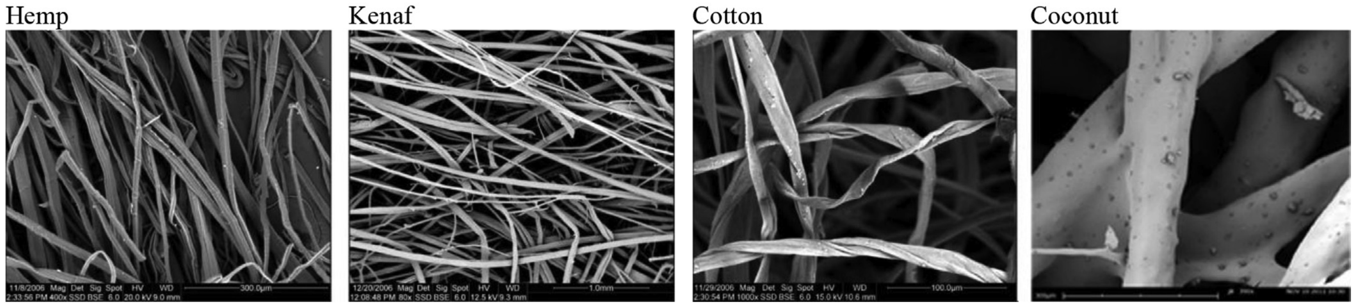

Fig. 1. Electronic microscopy images at different scales for some natural fibers. From left to right: hemp, kenaf, cotton, and coconut (images courtesy of Dr. Jesus Alba – Universitat Politècnica de València, Spain).

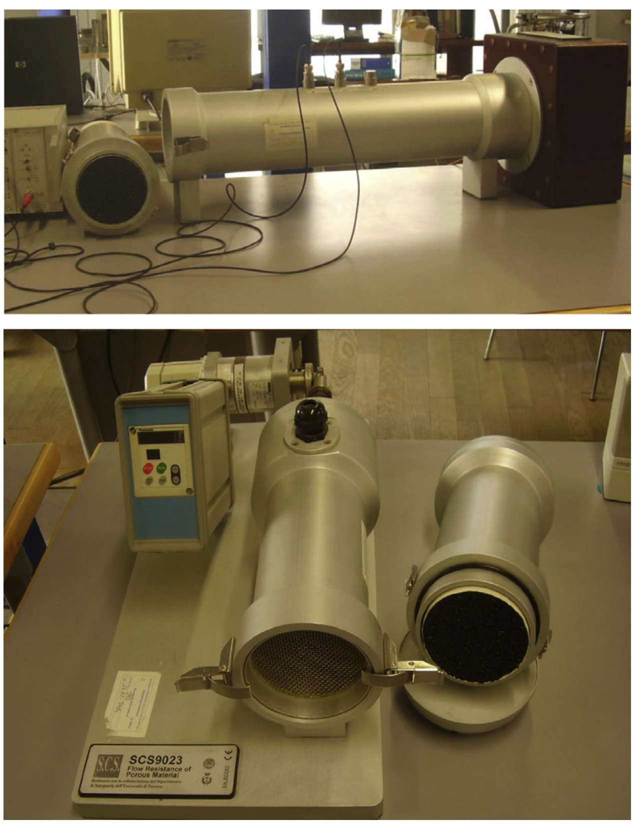

Fig. 2. Kundt's tube for the absorption coefficient measure (above) and airflow resistance measurement system at alternate airflow (below).

sample holder was reduced so that the circumferential effect discussed in Ref. [33] could be considered negligible. The effect of the irregularities in the samples, and in particular at the edges of them, was taken into consideration by repeating the tests with four different samples. For each sample, the measurements were repeated four times.

Known the sample thickness, the sound absorption measurement consisted in determining the complex wave number and from this to calculate the surface impedance (z_s) and the absorption coefficient (α) using the following expressions:

$$\alpha = 1 - |R|^2 \tag{5}$$

$$R = \frac{z_s - \rho_0 c}{z_s + \rho_0 c} \tag{6}$$

$$z_s = -jz_c \cot(k_c d) \tag{7}$$

where R is the sound pressure reflection coefficient, z_s is the surface impedance (Pa s/m), and d is the thickness of the sampled material (m).

The repeatability of the sound absorption measurements was high and the standard deviation at different frequencies was always below 0.1. For this reason, in the following figures of sound absorption, the standard deviation will not be plotted since it would decrease the readability of the sound absorption graphs.

3.2. Airflow resistance measurement

The airflow resistance is the resistance experienced by air as it passes through a material. As described in Section 2, the sound absorption of porous materials is highly dependent on their airflow resistance values. A low value indicates little resistance to air streaming through the material, whereas a too high value is

Table 1
Main properties of the materials studied in this paper.

Material		Density [kg/m^3]	Thickness [m]	Flow resistivity [Rayl/m]
Kenaf	(Light)	50	0.06	2700 (±290)
	(Dense)	100	0.04/0.06	3500 (±240)
Wood	(Fibers)	100	0.04	1600 (±300)
	(Mineralized)	260	0.03	1800 (±450)
Hemp		50	0.03	1400 (±170)
Coconut		60	0.04/0.06	1500 (±200)
Cork		100	0.03	1000 (±150)
Cane	(Mixed) (only wooden) (only bark)	400	0.04	850 (±130)
		470	0.04	1000 (±125)
		145	0.04	800 (±40)
Cardboard		140	0.115	250 (±50)
Sheep wool		40	0.04/0.06	2100 (±150)

Table 2
Sound absorption coefficient values of the materials studied in this paper.

Material		Thickness [m]	Frequency [Hz]					NRC
			125	250	500	1000	2000	
Kenaf	(Light)	0.06	0.09	0.19	0.33	0.68	0.90	0.55
	(Dense)	0.04	0.08	0.18	0.32	0.70	0.94	0.55
	(Dense)	0.06	0.10	0.30	0.61	0.99	0.95	0.70
Wood	(Fibers)	0.06	0.20	0.40	0.50	0.65	0.91	0.60
	(Mineralized)	0.03	0.05	0.10	0.10	0.20	0.40	0.20
Hemp		0.03	0.01	0.15	0.25	0.51	0.70	0.40
Coconut		0.05	0.10	0.20	0.34	0.67	0.79	0.50
		0.10	0.25	0.42	0.83	0.81	0.94	0.75
Cork		0.03	0.01	0.02	0.10	0.30	0.86	0.30
Cane	(Mixed)	0.04	0.05	0.10	0.35	0.54	0.58	0.40
	(Mixed)	0.08	0.10	0.21	0.56	0.52	0.68	0.50
	(Only wooden)	0.04	0.01	0.06	0.12	0.47	0.43	0.25
	(Only wooden)	0.08	0.07	0.15	0.46	0.39	0.66	0.40
	(Only bark)	0.04	0.10	0.12	0.38	0.64	0.62	0.45
	(Only bark)	0.08	0.10	0.26	0.63	0.54	0.89	0.60
Cardboard		0.10	0.10	0.27	0.48	0.54	0.66	0.50
Sheep wool		0.04	0.10	0.14	0.36	0.73	0.94	0.55
		0.06	0.15	0.28	0.66	0.95	0.94	0.70

generally assumed as an indication that the material pores are so close that airflow is obstructed, and hence low sound absorption may be expected [34–36].

Many authors have proposed empirical formulas for the determination of the airflow resistance of fibrous materials using values such as the bulk density of the material and diameter of the fibers. Bies and Hansen firstly presented a formula of this type for small fibers with a relatively uniform diameter, such as rock wool and fiberglass [34]. Later, Mechel formulated a revised porous model using airflow resistivity expressions according to the radius of the fibers and the porosity perpendicular to the direction of the fibers [37]. Similarly, Garai and Pompoli proposed a formula for the case of polyester fibers [24].

Given the lack of theoretical agreement, in this paper an empirical approach was selected consisting of the direct measurement of the airflow resistance. The procedures for measuring the airflow resistance have been standardized internationally [38], and consist of a continuous flow procedure or an alternate flow one. In the continuous flow procedure, the airflow is unidirectional and constant, while in the alternate flow, the airflow is alternated with a frequency of 2 Hz [38]. In both cases, the pressure difference between the two sides of the sample has to be measured. In this paper, the alternate method was preferred since it allows measurements over a higher number of cycles, and hence to average the results, reducing the uncertainty of the measured value. Moreover, the alternate method is more reliable in terms of the adiabatic compression of the air inside the volume since the equipment can easier be closed hermetically. The measurement device (Fig. 2) consisted of a cylindrical chamber closed with the material sample, a piston system pumping air inside the chamber, while a pressure microphone measured the pressure level inside. As suggested in the ISO standard, for each sample, ten measurements were performed for four different air velocities (0.5, 1, 2, and 4 m/s) in order to determine the airflow resistance.

To obtain the airflow resistivity (measured in Pa $\cdot$s/m^2 or Rayl/m), it was necessary to multiply the airflow resistance (measured in Pa $\cdot$s/m^3) by the sample thickness. It is important to state that the uncertainty associated with the flow resistivity measurement is generally large due to density change, presence of non-laminar air flow (so dependent on the different air movement speeds), low pressure differences on the two sides of the sample, and inaccuracy in thickness determination [39–43]. Although the existence of an international standard for the airflow resistance measurement, the high uncertainty of this measure has recently led to suggest alternative methods, which however have also shown significant limits [39–41].

Table 1 reports the values of the density, thickness, and air flow resistivity together with the standard deviation of the selected materials as obtained from ten different measurements. The density was measured using a graded tube in which the material was included and then water was added up to a certain volume. In this way, the weight of the material was calculated based on the assumption that the water occupied all the porosity of the material. It is evident by looking at the standard deviation values that according to the extrapolation process for the flow resistivity measurement and to the significant inhomogeneity of the samples, the measurements suffer high uncertainty. The dense kenaf and the mineralized wood showed the highest flow resistivity, while the cardboard, which had long open channels parallel to the airflow movement, showed a particularly low flow resistivity. The cane, which was the heaviest material, with a density up to 470 kg/m^3 for the only wooden samples, also showed a low flow resistivity, as a consequence of the large voids among the wood chocks.

4. Acoustic characterization

4.1. Kenaf

The kenaf fiber, scientifically known as *hibiscus cannabinus*, is obtained from the stem of the plant. Kenaf is widespread in Africa, Asia, and India, where it is generally used for making bags. The British imported kenaf into Europe before it diffused in North America. Kenaf panels are commercially available as semi-rigid panels of different density and thickness. During the fabrication process, the kenaf fibers are often mixed together with some polyester fibers to increase their rigidity.

Pure kenaf samples of 4 cm and 6 cm thick and of different density were tested. The measured values of the sound absorption coefficient were high at medium and high frequencies, but the absorption coefficient assumed low values at low frequency (Fig. 3). An increase in the density from 50 kg/m^3 to 100 kg/m^3 increased the absorption coefficient up to 0.94 in the frequency band of 2000 Hz (Table 2). The tests also showed that doubling the density of the material has comparable effects to increase its thickness, as evident by the almost perfect overlap between the curves of the sample 100 kg/m^3 dense and 4 cm thick, and the sample 50 kg/m^3

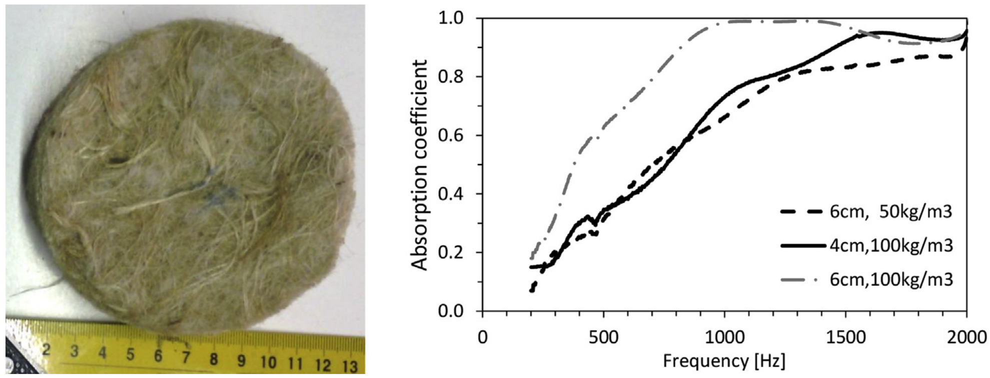

Fig. 3. Absorption coefficient of kenaf samples with different density and thickness.

dense and 6 cm thick. These results agree with similar investigations reported in Ref. [21].

Comparing the experimental results with the theoretical predictions as reported in Table 3, it emerges that the theoretical model predicts an almost linear increase of the sound absorption up to 1000 Hz, followed by a reduction of the sound absorption to 0.7 or 0.9 at 2000 Hz depending on the sample thickness, and then an increase to values above 0.9 at higher frequencies (Table 4).

The comparison with the measurements showed that:

- for the 50 kg/m^3 dense and 6 cm thick sample, the theoretical model is pretty accurate and the largest error is in the band of 500 Hz;
- for the 100 kg/m^3 dense and 4 cm thick sample, the theoretical model underestimates measured values in all the frequency bands, but in particular, below 1000 Hz.
- for the 100 kg/m^3 dense and 6 cm thick sample, the theoretical model underestimates measured values especially below 1000 Hz, but the prediction at high frequency is generally accurate (predicted absorption at 2000 Hz 0.92 against a measured value of 0.95).

4.2. Wood

Panels of wood fiber may be produced by processing the waste of wood works. The dried row material is then cut and weakened. The addition of binder is common in many processed wood products in order to give more shape stability, but it results in significantly increase in airflow resistivity. Wassilief found that pure wood fibers without any binder have similar absorption coefficient to mineral fibers, with values as high as 0.9 at high frequency [36].

The results of acoustic measurements in Fig. 4 show high values of the sound absorption above 500 Hz, with a particularly high absorption above 1650 Hz. These measurements confirmed that the wood fiber is a good absorbing material even without the addition of binder, although without a binder, the wood fibers need to be contained in packages in order to be used practically in building applications.

Comparing the experimental results with the theoretical predictions, it emerges that the theoretical model is accurate in the frequency bands of 1000 Hz and 2000 Hz (error of 3% and 14% respectively); however, the low frequency prediction suggested significantly lower values than the measured ones.

4.3. Mineralized wood

Mineralized wood fibers are commercialized in different types depending on the binder and the manufacturing process. Semi-rigid panels are often made with crushed wood fibers impregnated with cement. The final product is robust, easy to transport and to install, but rarely light as evident by Table 1 which shows that the density of the mineralized wood panel was 2.6 times higher than the density of the wood fibers described in Section 4.2. Mineralized wood is often

Table 3
Sound absorption prediction for the different materials according to the Delany–Bazley model.

Material		Thickness [m]	Frequency [Hz]						NRC
			125	250	500	1000	2000	4000	
Kenaf	(Light)	0.06	0.09	0.20	0.42	0.73	0.87	0.92	0.55
	(Dense)	0.04	0.05	0.12	0.27	0.53	0.81	0.84	0.45
	(Dense)	0.06	0.08	0.21	0.47	0.8	0.92	0.96	0.60
Wood	(Fibers)	0.06	0.09	0.20	0.37	0.63	0.80	0.85	0.50
	(Mineralized)	0.03	0.05	0.09	0.16	0.27	0.45	0.63	0.25
Hemp		0.03	0.05	0.09	0.16	0.26	0.44	0.59	0.25
Coconut		0.05	0.08	0.15	0.27	0.48	0.70	0.71	0.40
		0.10	0.17	0.35	0.62	0.84	0.85	0.93	0.65
Cork		0.03	0.05	0.08	0.14	0.23	0.39	0.53	0.20
Cane	(Mixed)	0.04	0.06	0.10	0.17	0.28	0.47	0.53	0.25
	(Mixed)	0.08	0.12	0.22	0.38	0.62	0.70	0.78	0.50
	(Only wooden)	0.04	0.06	0.11	0.18	0.31	0.50	0.57	0.30
	(Only wooden)	0.08	0.12	0.23	0.41	0.66	0.71	0.81	0.50
	(Only bark)	0.04	0.06	0.10	0.17	0.28	0.47	0.52	0.25
	(Only bark)	0.08	0.12	0.22	0.38	0.59	0.70	0.77	0.45
Cardboard		0.10	0.12	0.20	0.34	0.51	0.57	0.65	0.40
Sheep wool		0.04	0.06	0.13	0.24	0.43	0.69	0.74	0.40
		0.06	0.09	0.20	0.39	0.68	0.84	0.88	0.55

Table 4
Sound absorption coefficient difference between measured (Table 2) and predicted (Table 3) values.

Material		Thickness [m]	Frequency [Hz]					Average absolute difference of values
			Δ 125	Δ 250	Δ 500	Δ 1000	Δ 2000	
Kenaf	(Light)	0.06	–	5%	21%	7%	−3%	7%
	(Dense)	0.04	−60%	−50%	−19%	−32%	−16%	35%
	(Dense)	0.06	−25%	−43%	−30%	−24%	−3%	25%
Wood	(Fibers)	0.06	−122%	−100%	−35%	−3%	−14%	55%
	(Mineralized)	0.03	–	−11%	38%	26%	11%	17%
Hemp		0.03	80%	−67%	−56%	−96%	−59%	72%
Coconut		0.05	−25%	−33%	−26%	−40%	−13%	27%
		0.10	−47%	−20%	−34%	4%	−11%	23%
Cork		0.03	80%	75%	29%	−30%	−121%	67%
Cane	(Mixed)	0.04	17%	–	−106%	−93%	−23%	48%
	(Mixed)	0.08	17%	5%	−47%	16%	3%	18%
	(Only wooden)	0.04	83%	45%	33%	−52%	14%	46%
	(Only wooden)	0.08	42%	35%	−12%	41%	7%	27%
	(Only bark)	0.04	−67%	−20%	−124%	−129%	−32%	74%
	(Only bark)	0.08	17%	−18%	−66%	8%	−27%	27%
Cardboard		0.10	17%	−35%	−41%	−6%	−16%	23%
Sheep wool		0.04	−67%	−8%	−50%	−70%	−36%	46%
		0.06	−67%	−40%	−69%	−40%	−12%	46%

considered a non-fibrous material since the binder may make the material compact and dense. However, the mineralized wood considered in this paper has limited cement, and the strips of wood joined together with high porosity were clearly separated (Fig. 5).

The results of the absorption coefficient measurements revealed very low values at low and medium frequencies (0.1 at 500 Hz), and modest values at higher frequencies (Fig. 5). These results discourage the use of this material for sound absorption, although it may be a valuable option in noise insulation applications.

As expected with mineralized wood, the Delany–Bazely model cannot be applied with accuracy. Wassilieff presented a comprehensive review of the acoustical characteristics of mineralized wood [36], and demonstrated how their properties may be better predicted using the Attenborough's model [26]. To use the Attenborough's model, non-acoustic parameters were obtained from Ref. [45]. Both the Delany–Bazley model and the Attenborough one were unable to predict the resonance of the material at low frequency, but they both showed low values of absorption similarly to the measured ones. The difference between measured and predicted values was limited only at low frequencies. The inaccuracy of the theoretical models may also be justified by the inhomogeneity of the material, which clearly emerged in the high standard deviation of the airflow measurements.

4.4. Hemp

The hemp fiber, scientifically known as *cannabis sativa*, derives from the textile hemp whose low quality fibers cannot be used for textile applications. The plant grows in temperate zones, and it is generally available in large quantities. Insulating panels are produced by treating the hemp fibers with soda or boron salts to improve the fire behavior; then the material is subjected to heat setting to form a more robust panel. Processed hemp fibers contain no toxic substances, and do not entail risks for the health neither during the processing nor during the useful life of the panels.

The hemp fiber has good thermal and acoustic properties [22]. In particular, results in Fig. 6 show that the values of the absorption coefficient at medium and high frequencies were discrete, whereas at low frequency, the coefficients resulted negligible. The results of the sound absorption coefficient of the hemp was generally lower from those reported by Oldham et al. [22], who found absorption values above 0.4 at 500 Hz, 0.75 at 1000 Hz, and 0.95 at 2000 Hz for a sample 5 cm thick. In particular, the main differences resulted at high frequency, since above 2000 Hz the absorption reported by Oldham et al. was always above 0.9, while in the present study, its value remained below 0.8.

The comparison between the measured and predicted values of the sound absorption showed that the theoretical values were always significantly lower than the measured ones, with errors of 67%, 56%, 96% and 59% in the frequency bands of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz respectively. The high percentage errors were also given by the low absolute absorption, but in general, it is seems that the measured values of the air flow resistivity of the hemp was too low, and led to underestimate the theoretical

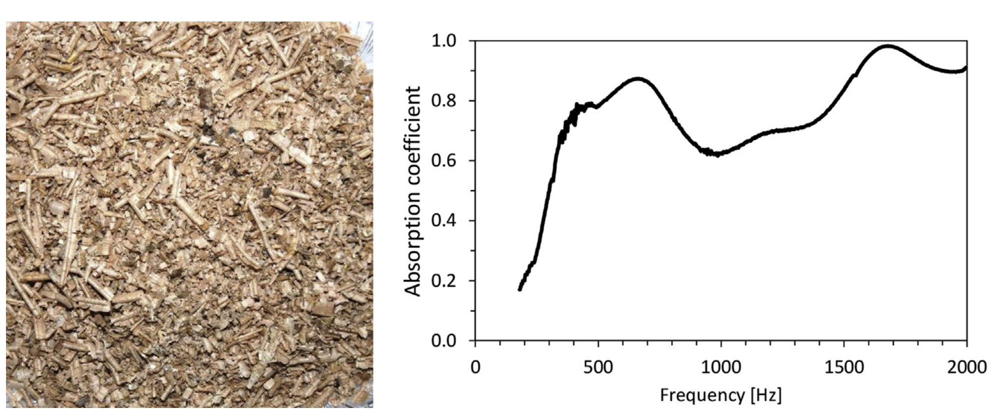

Fig. 4. Absorption coefficient of wood fiber 6 cm thick.

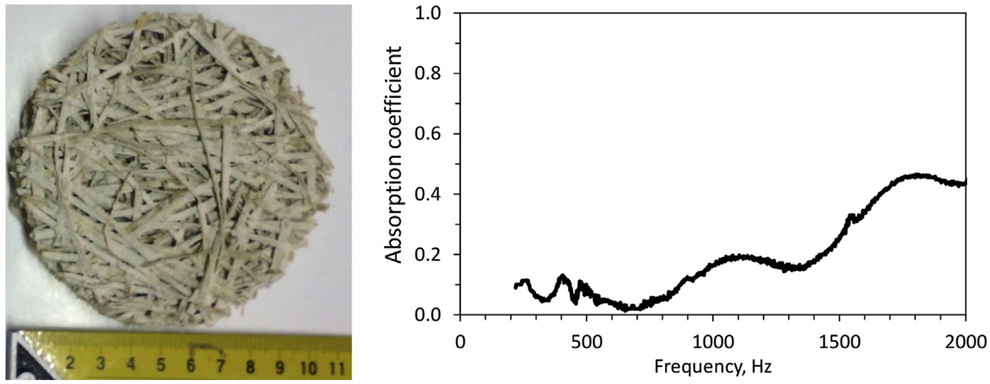

Fig. 5. Absorption coefficient of mineralized wood fiber 3 cm thick.

predictions of the sound absorption of this material.

4.5. Coconut

The palm plant is typical in tropical regions, and its fruit fiber (coconut) has generally been used in applications where robustness is demanded. Coconut fiber is obtained from the mesocarp, the thick fibrous layer that covers the shell of the nut, and it is produced as a waste of an agricultural production. If green coconuts are harvested, white or green fibers may be extracted, while the fiber is brown when it is obtained by harvesting fully mature coconuts. After extraction, the fibrous husks are soaked in pits or in nets in a water to swell and soft, and then are dried. Longer bristle fibers are generally tied into bundles, while mattress fibers are compressed and packed into large bales, from which the samples described below were composed. This paper only used brown fibers. The coconut fiber has excellent characteristics of thermal insulation and sound absorption [10,44]. In building panels, the coconut fiber is often mixed with binders to improve the characteristics of rigidity, anti-fungus, and flammability [46,49]; however, in this paper, pure fiber without any binder was tested only.

The coconut fiber has a mean diameter of 250 μm, being a big fiber if compared with typical mineral or other natural fibers. del Rey et al. measured an airflow resistivity for coconut samples of 1.9 cm thick and 128 kg/m^3 dense was 2.6 kNs/m^2; similarly for samples of 2.9 cm thick and 100 kg/m^3 dense was 1.9 kNs/m^2, and for samples of 4.2 cm thick and 80 kg/m^3 dense was 1.2 kNs/m^2 [42]. That study also proved large differences in the airflow resistance for measurements done with different measurement methods, and attributed the differences to the non-homogenous composition of the material.

The raw coconut fiber resulted in a good sound absorption coefficient at both low and medium frequencies, although in thicker layers, the behavior was much more remarkable (Fig. 7). Comparing the results of the present study with literature data [10,42], it emerges that the fibers used in this study were softer, had lower airflow resistance, and higher sound absorption. Al-Rahman et al. [47] recently presented measurements done on 50 mm thick date palm fibers treated with latex, and showed an absorption coefficient of around 0.9 from 1.3 to 4.2 kHz. The results are comparable with those in Zulkifli et al. [48] or by Fouladi *et a*l. [10], who studied a coir-based samples produced using fresh coconut husk with or without the addition of a binder. Fouladi's study proved that the sample with the binder had a significant reduction in the absorption coefficient. Moreover, the sample without the binder closely followed the Biot-Allard model, while the sample with the binder was better predicted by using the Delany–Bazley model [10].

The prediction using the Delany–Bazley model (Table 3) proved sufficiently accurate:

- for the sample 5 cm thick, the theoretical model was generally accurate in the frequency bands of 2000 Hz (error 13%), while the prediction was less accurate at lower frequencies;
- for the sample 10 cm thick, the theoretical model was highly accurate in the frequency bands of 1000 Hz and 2000 Hz (errors 4% and 11% respectively), while at low frequency, the measured resonance absorption at 500 Hz was neglected in the theoretical model, although this model was able to estimate a modest absorption in this frequency band.

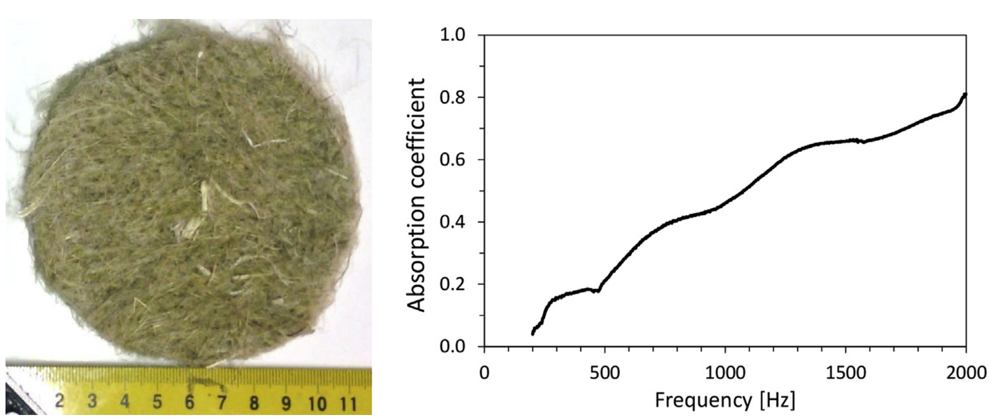

Fig. 6. Absorption coefficient of hemp fiber 3 cm thick.

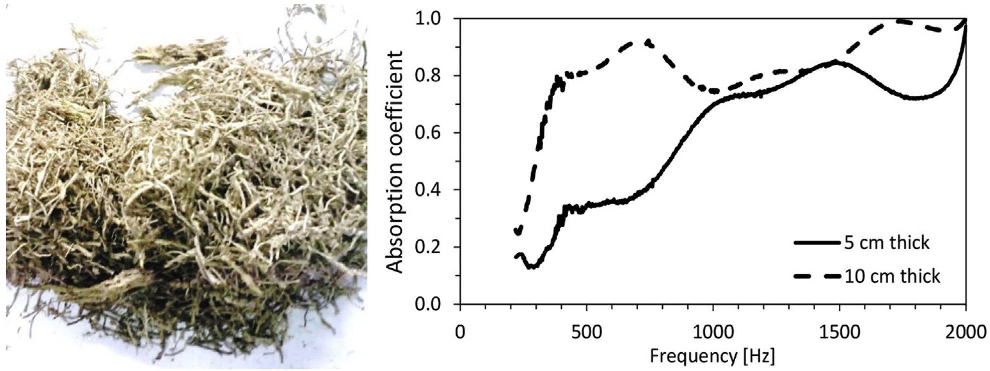

Fig. 7. Absorption coefficient of coconut fiber, 5 and 10 cm thick.

4.6. Cork

The cork oak an evergreen oak species reaching a height of 20 m is the raw material for the production of cork products. Cork oaks grow mainly in Portugal, Spain, Tunisia, Morocco, Italy, France, and Algeria, with the European cork industry producing about 340.000 tons of cork per year [50]. The cork is composed of spherical light granules containing air. This property allows the panel to be light, elastic, and thermally insulating. The material is commercialized in semi-rigid panels of different size and thickness.

Fig. 8 shows that the absorption coefficient at low and medium frequencies is negligible due to the size of the cork grains. On the contrary, results up to 0.9 were obtained at 1600 Hz. This confirms that in order to obtain a cork panel with good sound absorption characteristics, it is generally necessary to adopt large thicknesses.

The prediction using the Delany–Bazley model was highly inaccurate. This was expected since the material has a cellular structure, and as a consequence the energy dissipation in its cavities is not taken into account by a model simply based on the airflow resistivity. The error in the prediction was significant through all the frequencies, although the theoretical model correctly estimated low values of sound absorption at low frequency. The drop in the sound absorption below 2000 Hz was also not predicted by the theoretical model, neither the Delany–Bazley model nor the Allard model. This last was used by taking literature data for the non-acoustical microstructural properties, but it did not improved the theoretical predictions appreciably.

4.7. Cane

The cane or reed, scientifically known as *arundo donax*, is a widespread plant that grows near water courses. It has a very fast growing process, which often creates conflicts with the agriculture, and for this reason, it is frequently cut, making the raw material widely available. Giant reeds usually reach 6 m in height and 2–3 cm in diameter, with 30–60 cm long leaves and 2–6 cm wide. The canes were cut and crushed in order to have a granular material, with an average size of 4 cm in length, 1 cm in width, and 0.3 cm thick (Fig. 9).

The material is generally made from both the wood and the bark, although the excessive presence of bark was expected to reduce the sound absorption. In this study, three types of shredded material were considered: solely wooden parts (average length 4 cm, width 1 cm, and thickness 3 mm), mixed composed of wooden parts and the cortex with varying dimensions (the bark comes from the outer coating of the giant reed tuber), and only bark parts.

The absorption coefficient for the bark generally has a low value at low frequencies for the 4 cm thick sample, and only the test for 8 cm thick sample resulted in more significant sound absorption at low frequency. The test for the wooden part presents a strong resonance, which occurred at the frequency of 1250 Hz for the 8 cm thick, and 630 Hz for the 4 cm thick. Finally, the measurements obtained by mixing the wood parts and the bark ones have intermediate absorption values.

The comparisons between the theoretical prediction and the measured values show that:

- for the 4 cm thick bark sample, the theoretical model highly underestimates the absorption at middle frequency (0.17 predicted against 0.38 measured at 500 Hz, and 0.28 predicted against at 0.64 measured at 1000 Hz) while better predicts the

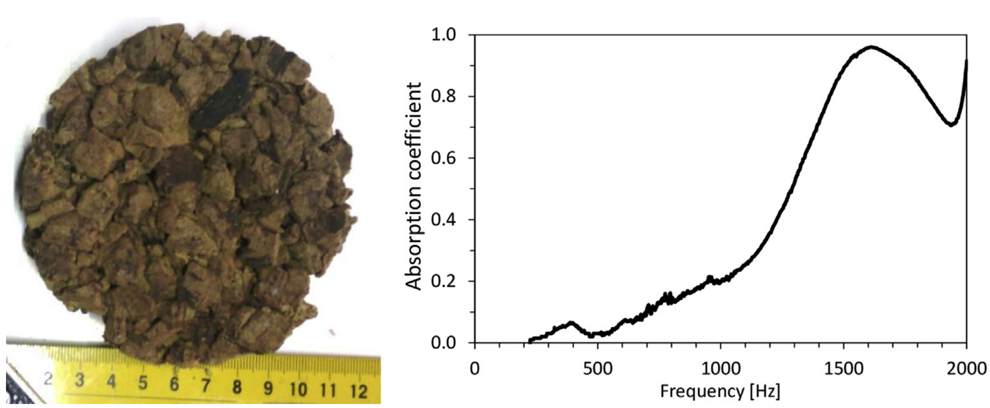

Fig. 8. Absorption coefficient of cork 3 cm thick.

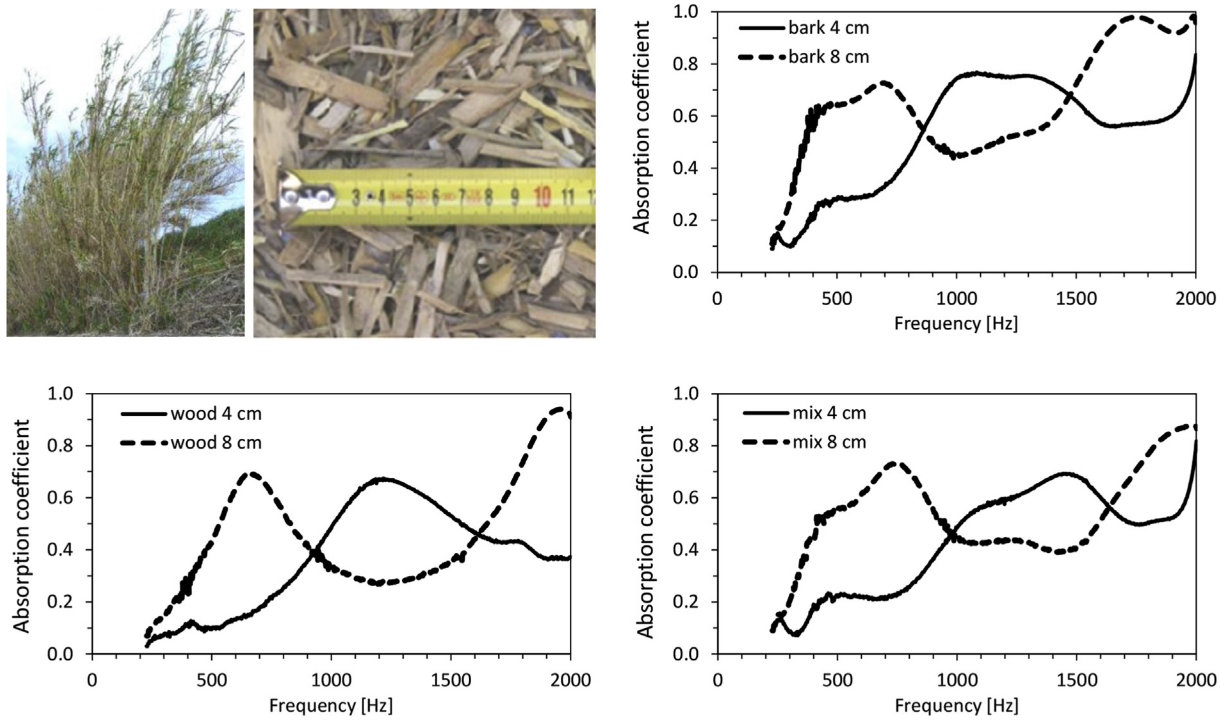

Fig. 9. Absorption coefficient of bark, wood and mix of water canes, 4 and 8 cm thick.

behavior at low and high frequency; on the other side, for the 8 cm thick sample, the theoretical prediction generally improved;

- for the wood sample, the theoretical model showed a linear increase in the sound absorption from low to high frequencies for both the 4 cm and 8 cm thick samples, but the theoretical model was unable to predict the resonances measured in the impedance tube;
- for the mix (bark plus wood) sample, the theoretical model poorly predicted the behavior of the thin sample, while behaved more accurately for the thicker sample.

4.8. Cardboard

Cardboard is produced by recycling papers, and it is a light material, largely available worldwide, and generally cheap. The main limit of this material is its poor fire performance which obliges fire retardant treatments, reducing the material sustainability [2,19]. In order to perform acoustic tests, the material was mounted so that the veins were arranged with tubes parallel to the impedance tube. This allowed the sound waves to propagate through the material, as clearly shown by the low value of the airflow resistivity of this material in Table 1. Testing hollow canes, Oldham et al. proved dissipative losses in empty tubes. The cardboard was expected to behave similarly [22].

Results of the sound absorption coefficient of the cardboard samples show that the material has a good absorption coefficient at medium and high frequencies, but below 400 Hz the sound absorption reduces significantly (Fig. 10). The theoretical predictions obtained by applying the Delany–Bazley model show values significantly lower than the measured ones, especially at low frequency. In fact, the low airflow resistivity for such a thick sample (11.5 cm) shows that the behavior of cardboard cannot be considered rigid and porous, while it is possible to assume that the internal surface of the cardboard cavities plays a significant role for the sound absorption of this material.

4.9. Sheep wool

Since ancient times, the sheep wool has been used for clothing thanks to its excellent thermal insulation properties. However, in the last years, there has been a scarce use of wool, and the product in excess is often burnt or buried. Wool is generally composed of many different amino acids, which form long chains. The coiled springs of wool molecular chains contribute to the fiber resilience, which has already been considered for acoustic applications [18,22]. As it grows from the sheep skin, wool naturally groups into staples which contain thousands of fibers of different kinds. In case of fire, the wool is self-extinguishing and does not emit toxic substances; however, this material can be attacked by moths or parasites, so it needs some chemical treatments before being used in buildings.

The sheep wool is an excellent sound-absorbing material, thanks to micro-cavities of which it is composed [22]. The value of the absorption coefficient resulted high at medium and high frequencies, with a fairly homogenous behavior (Fig. 11). An increase in the thickness of the sample led to a significant increase of the sound absorption, mainly at middle frequency. The wool fibers act as very effective sound absorbers, although the absorption obtained in this study was generally higher than that reported in Ref. [22], especially at high frequency: at 2000 Hz, an absorption of 0.95 was obtained in this study versus a value of 0.7 reported in Ref. [22]. This study found values more similar to those in Refs. [18], which reported an absorption coefficient of 0.9 from 800 Hz to 2 kHz.

The theoretical predictions obtained by applying the Delany–Bazley model show values lower than the measured ones, especially at middle frequencies. For example, at 500 Hz, 1000 Hz

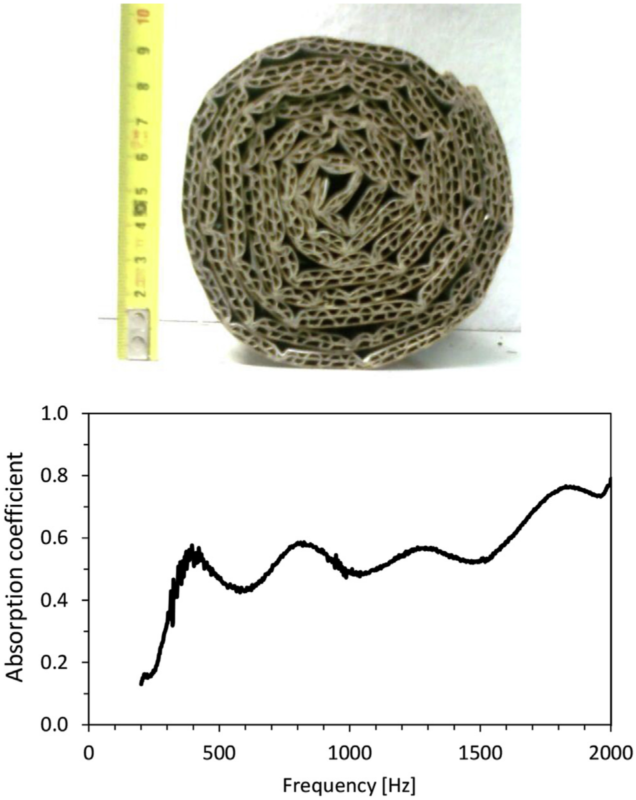

Fig. 10. Absorption coefficient of recycled cardboard 11.5 cm thick.

and 2000 Hz, the measured values were 0.66, 0.95, and 0.94 respectively for the 6 cm thick sample, while the Delany–Bazley model predictions were 0.32, 0.67, and 0.83 respectively. However, by applying literature data to the Mechel's model [37], it would give values of 0.36, 0.70, 0.87 respectively, with a substantial reduction of the error. Similarly, also for the thinner sample, the Mechel's model would give a better prediction than the Delany–Bazley model.

5. Discussion and conclusions

The measurements carried out on samples of natural fibers have shown that -similarly to traditional porous materials-these fibers have good sound absorption coefficients, especially at medium and high frequencies. Moreover, by increasing the material thickness, it is possible to obtain significant sound absorption also at low frequencies, when otherwise other strategies such as adding air gaps or perforated plates would be necessary.

This paper has reported normal sound absorption measurements, since only the impedance tube technique was adopted. However, random incidence would have given higher absorption values. The reader should hence refer to the several formulas recently proposed for obtaining the random sound absorption from the normal one, basing on the data reported in Table 1 and *i.e.* the material density, thickness, and flow resistivity [27].

It is also important to note that the materials investigated in this paper, were directly realized by the authors in their research laboratory. The lack of binder addition to any of the previous materials, except for the mineralized wood, has clearly influenced the acoustic behavior of the samples. Although, it is clear that further research should be done to standardize the manufacturing process for sound absorbing treatments with these natural fibers, the idea behind this paper was the possibility to create sound absorbing treatments using natural fibers only.

In a previous study, giant reeds of sweets water were cut using a small mil, dried and shredded [11]. The insertion of the natural fiber in jute bags, a material acoustically transparent, has recently made possible to realize aesthetically acceptable sound absorbing panels (Fig. 12). The scope of this approach is the realization of environmental friendly, acoustically efficient, and cheap absorbent panels.

Although theoretical models allowed to predict the general trend of the fibers behavior, for some of the materials studied in this paper, the prediction was not accurate. The main limit that emerged during the tests, is the high inhomogeneity of natural materials, which cannot be simplified using theoretical models alone. Moreover, natural fibers do not conform easily to multi-porosity models, such as that developed by Horoshenkov et al. [25]. The approach to define the constants of the Delany–Bazley model by fitting the coefficient in the equation (1) ad (2) to the measurement results also seemed inappropriate, since the measurement results depend on the considered sample and the production processes, so that the reproducibility of the results could not be guaranteed using different fibers or production processes.

Table 2 also reports the values of the sound absorption for the different materials in the frequency octave-bands of analysis, together with the Noise Reduction Coefficient (NRC). This is the arithmetic average of the absorption coefficients determined at the octave band of 250 Hz, 500 Hz, 1000 Hz and 2000 Hz, rounded to the nearest multiple of 0.05. The NRC is often used as a synthetic indicator to represent the sound energy absorbed by a material. The values of the NRC are hence useful to compare the different sound absorbing materials. The NRC values were generally high, and allowed to recognize the sheep wool and the coconut as two highly promising sound absorbing materials. The measured NRC values agreed with those predicted by the theoretical model for the less dense kenaf and for some types of canes; in all the other cases, the measured NRC showed values higher than the predicted ones. This

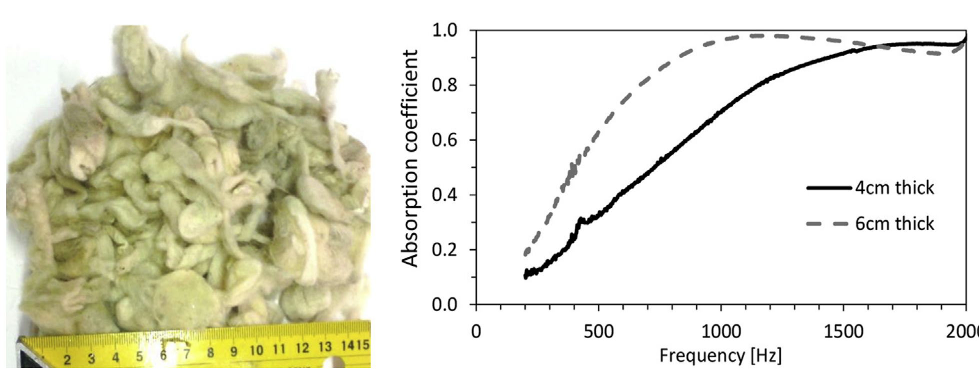

Fig. 11. Absorption coefficient of sheep wool 4 and 6 cm thick.

Fig. 12. Jute bags in which the loose natural material could be inserted to obtain sound-absorbing panels.

confirms that natural fibers represent a valid option for sound absorption treatments. For this, it is important to increase the awareness about the environmental advantages of these products. Finally, similarly to LCA analysis of thermal insulating materials, the authors hope that future comparisons among different sound absorbing materials will be based using as functional unit the material mass that allows a given sound absorption effect, as it could be represented by the absorption based on the synthetic NRC values.

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