Improving the sound absorbing performance of hemp fibrous material

Abstract

Compared to the traditional synthetic fibrous materials, natural fibres represent a more sustainable solution to be used in noise control engineering and acoustic treatments. However, while synthetic fibres have been studied for almost fifty years, the knowledge of natural fibres is still limited and needs to be improved. Natural fibres are affected by a large variability of the physical properties, which consequently causes a great uncertainty in numerical modelling and difficulties during the design process of acoustics treatments. This study highlights the possibility to enhance the acoustic performance of hemp fibrous materials through the manufacturing process, investigating how each treatments affects the material physical characteristics and its sound absorption coefficient. Moreover, a simplified model to evaluate the acoustic performance of hemp fibrous materials as a function of their density is proposed, in order to provide a practical tool to investigate and compare different solutions. The physical parameters numerically evaluated for a varying compression rate have been compared with the experimental results, measured at each stage of the production process on samples of several densities. The global reliability of the proposed approach is finally investigated by comparing the experimental sound absorption for normal incidence with the results obtained from the Johnson-Champoux-Allard model, implemented with the numerically evaluated material physical parameters.

Keywords: sustainability, hemp-fibrous material, sound absorption coefficient, material characterisation, JCA model

1. Introduction

As sound insulation and noise control became a primary concern in many industrial fields, several porous and fibrous materials have been developed, by using polymers and petroleum-based products. However, thanks to the global effort in pursuing the reduction of energy consumption, aiming to a more sustainable development, which will preserve resources for future generations, in the last decade sustainable material have been increasingly studied also within the field of noise control engineering. The sustainability of a material is generally considered in terms of resources usage, environmental impact, human health, and social equity. Moreover, the production process should require the least amount of energy consumption – green energy is preferable to non-renewable resources – and have the minimum manufacturing waste, or provide second life options for the wasted products. Besides, the traditional petroleum-based materials such as melamine and polyurethane foams, or polyester fibres, there are materials which, even though they are derived from natural or recycled products, need to be sealed since may contain substances impacting on human health if get in contact with the skin or are inhaled. On the other hand natural materials such as wood, coconut, kenaf and hemp fibres, other being obtained from renewable resources by means of a manufacturing process with a reduced impact on the environment, are also harmless for human health, since do not contain toxic substances [1, 2]. For these reasons, compared the traditional materials employed in building construction to improve the thermal and acoustic performances, natural fibres represent an eco-friendly sustainable solution. Hemp-based materials have been widely used in building construction, either in fibre-reinforced concrete, or other bio-composites, or as thermal insulation material [3] and again as tehrmo-mechanical reinforcement in gypsum plaster panels [4]. Moreover, recent studies have shown that natural fibres can also be employed for both sound insulation and sound absorption applications [5, 6, 7]. In the literature several acoustical model to investigate different kinds fibrous materials can be found. The most widely used empirical model for mineral and glass wool is probably the one developed by Delany and Bazley [8]. This model was later modified by Miki [9], providing alternative expressions for the complex wavenumber and the characteristic impedance. Other models have also been developed in order to investigate different fibrous, porous or granular materials, like, for example, the widely used Johnson-Champoux-Allard equivalent fluid model [10, 11] which takes into account both the visco-inertial dissipative effect and the thermal dissipative effect inside the material, or the alternative model propsed by Lafarge [12], or again the model specifically developed for polyester fibres by Garai and Pompoli [13]. While conventional fibrous materials have been thoroughly investigated and the physical parameters which affects their acoustic performance are well known, the knowledge of the physical characteristics of natural fibrous materials is still limited, as it is regarding the influence these might have on their acoustic performance. Moreover, the manufacturing process of natural fibres is not optimised in order to increase their acoustic performance; being generally produced in a lower amount compared to synthetic fibres, either in small enterprises, or sometimes even in artisan workshops, they are characterised by a significant variability of the fibres dimension and the other physical properties. The fact that the fibres' diameter distribution can not be arbitrary controlled like in the production process of synthetic fibres represents an issue for the evaluation of their acoustic performance, since all the acoustic models have been generally developed for homogeneous fibrous materials with a constant diameter [14, 15].

In this study an experimenatal investigation on the variety *Liptko* of the plant species *Cannabis Sativa* has been perfomed. Only few studies, recently published, on the characterisation of hemp fibres can be found in the literature [16, 17]. The aim of this work is to investigate some aspects which, to the authors best knowledge, have never been analysed before for this kind of fibrous material, even though they may have a significant influence on its acoustic behaviour. As it was noticed, rough hemp-fibrous materials exhibited a relevantly lower sound absorption compared to synthetic materials, such as polyester fibres. Therefore, the influence that the different stages of the manufacturing process have on the physical characteristics and how those affect the material's sound absorption have been analysed, in order to define the mechanical and chemical treatments that optimises the acoustic performance of such sustainable eco-friendly and fibrous material, which may be largely used in building construction. Furthermore, a simplified approach to characterised the physical parameters of hemp-fibrous material, which are required to evaluate their sound absorption coefficient, based on the knowledge of the fibres' radius and the material's apparent density, is proposed. The methodology makes use of a fluid dynamic model [18] to determine, from the experimental air flow resistivity, an effective radius of the equivalent homogeneous fibrous-material. Moreover, from the air flow resistivity and the absorption coefficient for normal incidence of the hemp fibrous material, measured at a given compression rate of the fibrous material, it is possible to define all the macroscopic parameters required as input data in the Johnson-Champoux-Allard (JCA) model. From this initial set of parameters, defined for a given density and thickness, the proposed methodology, based on Castagnède's model [19], allows to to investigate the material's physical parameters and consequently the sound absorption coefficient for any compression rate. The method was validated by comparing the numerical results evaluated at four different stages of the manufacturing process with the experimental data. In the next section the investigated material is introduced and different stages of the manufacturing process are described. In section 3 the basics of Johnson-Champoux-Allard model are summarised. The proposed methodology to characterised the material's physical parameter is given in details in section 4, while the main results are validated and discussed in section 5.

2. Material and manufacturing process description

Hemp is a herbaceous plant of the species *Cannabis Sativa L.* The most inner part of hemp stems, often referred as the pith, is surrounded by woody-fibres known as hurds or shives. The most outer layer, which encloses the hurds, is made of bast fibres. By processing hemp stems two different products are usually obtained: namely the hurds and the fibres. While the first is used for composites productions, such as hempcrete or hemplime, the fibres represent the most valuable part of the stem and are used both in reinforced concrete, and especially to produce thermal insulating materials. On the other hand, this fibres do not provide an acoustic performance which can make them competitive with the more traditional fibrous materials. In other to increase the sound absorbing performance of this sustainable material, this study focused on the assessment of the influence on the acoustic properties of different manufacturing processes the hemp fibres may be subject to. The loose fibres obtained from *Cannabis Sativa L.* underwent subsequently thought four different treatments:

1. **01.CAR – Carding:** this mechanical process is made in order to break down and untangle long fibres, to remove the remaining traces of dirt and the shortest fibres [20].
2. **02.NaOH – NaOH alkaline treatment** ($5\%/h$)**:** this chemical procedure removes non-cellulose compositions in hemp bast and facilitates the fibrils extraction, improving the fibres quality [21, 22].
3. **03.WTC – Wide tooth combing:** a wide tooth comb is used in order to direct the fibres along a certain direction, reduce the amount of short fibres and eliminate the remaining non-cellulose components extracted by the alkaline treatment.
4. **04.FTC – fine tooth combing:** this last mechanical process is a further refinement of the previous step 03.WTC, in this case a fine tooth comb is used instead of the wide tooth one.

After each step of the manufacturing process, samples of hemp fibres have been sputter-coated in gold in order to be analysed with a scanning electronic microscope SEM. From the images reported in Figure 1, obtained by using a SEM ZEISS EVO M15 with accelerating voltage of 15 kV, one can see how each stages of the manufacturing process drastically changes the fibres diameters. A significant reduction of the mean diameter of the fibres is shown from step 01.CAR to step 04.FTC, moreover, the amount of coarser fibres decreases. Even though a large dispersion is still found in the diametres distribution, thus the determination of an effective, or weighted-averaged, radius [23] is not trivial and certainly affected by a significant uncertainty. The effective radius can be used to compute the material physical parameters of a fibrous materials, however, a highly uncertain esteem would provide inaccurate results. For these reason, in the proposed methodology a fluid dynamic effective radius determined, as described in the section 4, from the experimental air flow resistivity was used, rather than an effective radius esteem based on SEM images. In Table 1 are reported both the minimum and maximum radius and the effective fluid dynamic radius evaluated for each material.

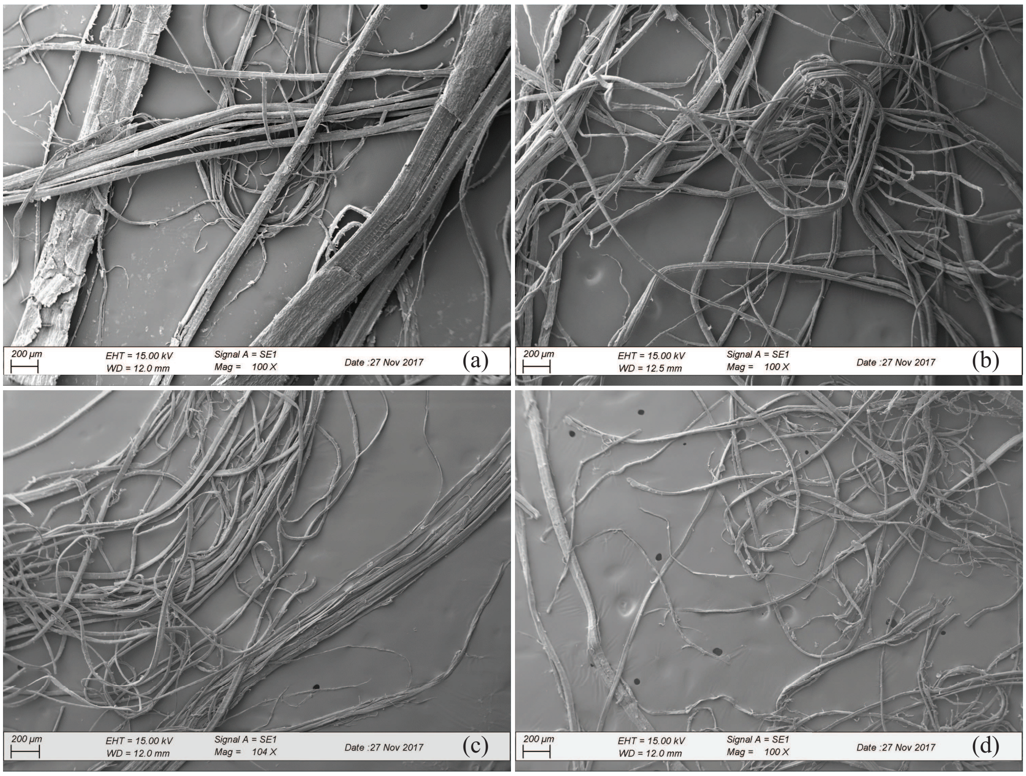

Figure 1: SEM images of hemp fibres: a) hemp fibres after carding process: 01.CAR; b) hemp fibres after alkaline treatment: 02.NaOH; c) hemp fibres after wide tooth combing: 03.WTC; d) hemp fibres after fine tooth combing: 04.FTC.

3. Acoustical model for sound absorption

For a great variety of fibrous and porous materials excited by an incident acoustic wave, it is possible to assume their solid frame to be rigid, either due to the high value of the elastic modulus, or the high density, or again because of special test conditions. These media can be described as equivalent fluids, characterised by an effective density ρ and an effective bulk modulus K. The well known Johnson-Champoux-Allard (JCA) equivalent fluid model [10, 11] is based on five macroscopic parameters:

- *airflow resistivity* - σ [Ns/s^4]: it is the resistance of the material to an airflow passing through it. The airflow resistivity is determined as:

$$\sigma = \frac{\Delta p}{h v_{airflow}} \tag{1}$$

where Δp is the pressure drop across the medium while $v_{airflow}$ is the airflow rate passing through the medium of thickness h.

Table 1: Minimum and maximum radius of the hemp fibres determined from SEM images at each stage of the manufacturing process and equivalent effective radius based on a fluid dynamic analysis.

	01.CAR	02.NaOH	03.WTC	04.FTC
$r_{min,SEM}$ [μm]	5.33	5.86	4.56	2.39
$r_{max,SEM}$ [μm]	176.55	52.5	50.05	56.65
$r_{effect,FD}$ [μm]	27.31	29.30	22.74	18.41

- *open porosity* - ϕ [−]: it represents the fractional amount of air volume within the interconnected pores in the medium. It can be evaluated as the ration between the air volume V_{fluid} and the total volume V_{total} of the investigated material.

$$\phi = \frac{V_{fluid}}{V_{tot}} \tag{2}$$

- *tortuosity* - α_∞ [−]: this dimensionless quantity evaluate the sinuous fluid paths through the material. It is defined as:

$$\alpha_\infty = \frac{\frac{1}{V}\int_V v^2 \mathrm{d}V}{\left|\frac{1}{V}\int_V \vec{v}\mathrm{d}V\right|^2} \tag{3}$$

  where v is the microscopic velocity of an inviscid fluid within the pores and V is the equivalent homogeneous fluid volume.

- *viscous and thermal characteristic lengths* - Λ, Λ' [μm]: this two quantities describe the viscous forces and the thermal exchanges between the solid frame and the saturated fluid contained in it. Their influence is significant at high frequencies. They are defined as:

$$\Lambda = 2\frac{\int_V |v(r)|^2 \mathrm{d}V}{\int_S |v(r)|^2 \mathrm{d}S} \tag{4}$$

$$\Lambda' = 2\frac{\int_V \mathrm{d}V}{\int_S \mathrm{d}S} \tag{5}$$

  where V is the volume of the fluid contained within the pores and S is the interface surface between the solid frame and the fluid.

The effective density ρ of the porous material, which is associated to the inertial and viscous forces, can be determined as:

$$\rho = \frac{\alpha_\infty \rho_0}{\phi} + \frac{\sigma}{\mathrm{j}\omega}\sqrt{1 + \frac{4\mathrm{j}\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}} \tag{6}$$

where ρ_0 is the air density and η its viscosity. The effective bulk modulus K takes into account the thermal exchanges between the frame and fluid. It can be determined using the formulation:

$$K = \frac{\gamma P_0}{\phi}\left[\gamma - (\gamma - 1)\left(1 + \frac{8\eta}{\mathrm{j}\rho_0 \omega N_{Pr} \Lambda'^2}\sqrt{1 + \frac{\mathrm{j}\rho_0 \omega N_{Pr} \Lambda'^2}{16\eta}}\right)^{-1}\right] \tag{7}$$

being N_{Pr} the Prandtl number, γ the specific heat ratio and P_0 the static pressure. From the equivalent density and the equivalent bulk modulus, both complex quantities, the characteristic impedance Z_c and the complex wavenumber k_c can be computed:

$$Z_c = \sqrt{\rho K} \tag{8}$$

$$k_c = \omega \sqrt{\frac{\rho}{K}} \tag{9}$$

Considering a porous material of thickness h place on a rigid reflecting boundary the surface impedance for normal incidence Z_s can be determined as:

$$Z_s = -\mathrm{j} Z_c \cot(k_c h) \tag{10}$$

the normal incidence sound absorption coefficient α_n is finally evaluate as:

$$\alpha_n = \frac{4\mathrm{Re}\left\{\frac{Z_s}{\rho_0 c_0}\right\}}{\left|\frac{Z_s}{\rho_0 c_0}\right|^2 + 2\mathrm{Re}\left\{\frac{Z_s}{\rho_0 c_0}\right\} + 1} \tag{11}$$

where c_0 represent the speed of sound in air.

4. Proposed methodology

4.1. Single density material characterisation

In order to determine all the five physical parameters of the hemp fibrous material at each stage of the manufacturing process, required as input data in the JCA model, an approach based on an equivalent effective radius as been used. Considering a fibrous material with homogeneous fibres, the physical properties can be determined from the fibres radius r. Based on a fluid dynamic analysis, Tarnow [24] derived a relationship between the constant fibres radius r and the air flow resistivity σ, considering randomly distributed fibres and an air flow perpendicular to their axes:

$$\sigma = \frac{4\pi\eta}{b^2\left[0.64\ln\left(\frac{b^2}{\pi r^2}\right) - 0.737 + \frac{\pi r^2}{b^2}\right]} \tag{12}$$

the coefficient b can be computed from the ratio between the fibres density ρ_g and the density of the fibrous material ρ_w as [18]:

$$b = r\sqrt{\pi\frac{\rho_g}{\rho_w}} \tag{13}$$

Therefore, being the air flow resistivity an easily measurable quantity, the effective radius r of an equivalent homogeneous material with single diameter fibres can be computed using a simple minimisation algorithm based on Eq. (12). To this purpose, samples of loose hemp fibres, resulting from each manufacturing process described in the section 2, were tested in the acoustic laboratories of the University of Ferrara. For each sample the air flow resistivity σ was measured by means of the alternate flow method, as described in the EN 29053:1993 standard [25]; moreover tha the normal incidence sound absorption coefficient α_n was measured by using a well-established transfer function method in an impedance tube, according to the ISO 10534-2:1998 [26]. The cylindrical samples were prepared by compressing the loose hemp fibres into

Figure 2: Investigated hemp fibres: a) loose hemp fibres; b) a fibrous material sample is created within the test rig; c) metallic mesh used to restrain the fibres in the sample holder.

the sample holder, of each measurement test rig, as shown in Figure 2. A coarse metallic mesh was used to restrain the fibres when compressed in order to obtain samples with a constant density and also to prevent any leakage around the edge. For each processing stage three different measurements have been performed, each time the sample was removed and reinserted in the test rig. The fibrous material porosity ϕ was computed from the mass of lose hemp fibres, the volume of the sample holder it was contained within and the density of the fibres, according to the relationship:

$$\phi = 1 - \frac{\rho_w}{\rho_g} \tag{14}$$

where ρ_w represent the density of the fibrous material and ρ_g the density of the fibres, which was estimated from the literature: $\rho_g = 1300\ \mathrm{kg/m^3}$. The tortuosity can be eveluated as a function of the material porosity as [27]:

$$\alpha_\infty = \left(\frac{1}{\phi}\right)^{0.7659} \tag{15}$$

It is possible to estimate the thermal characteristic length Λ' as a function of the mean square radius of the hemp fibres r [19], evaluated from the measured air flow resistivity using Eq. 12 as:

$$\Lambda' = b - r \tag{16}$$

By knowing these four physical parameters, the viscous characteristic length Λ can be finally evaluated from the measured absorption coefficient α_n by using a well established inversion method [28].

4.2. Material characterisation varying the compression rate

The analysis was further extend investigating the possibility to compute the physical parameters of hemp fibrous material with a arbitrary compression rate. For example the formulations developed by Castagnède et al. [19], either for 1D and 2D compression, allow to evaluate all the five physical parameters for any compression rate $n = \rho_{w,(n)}/\rho_{w,(0)}$ by knowing the material characteristics for a given density $\rho_{w,(0)}$ and thickness $h_{(0)}$. The great advantage of this approach is certainly represented by the fact that it can be easily applied in practical contexts, requiring few simple experimental measurements. However, it should be mentioned that the linear relationships, developed for 1D compression, have been validated only for material with high internal porosity within the range $\phi = 0.944 \div 0.995$. In fact, it has been proved [29, 30] that Castagnède formulas for 1D compression provide reliable results when a small compression rate and highly porous materials are considered, although it may inaccurate to investigate high density materials. Moreover, this approach does not take into account the variation of the fibres orientation due to the compression, which has been prove to have a significant influence on the physical properties of the material [30]. Nevertheless, Castagnède model due to its simplicity and and straightforward applicability represents a good starting point to define an empirical tool to be used in order to characterise hemp fibres, which have never been systematically analysed before from an acoustic point of view. To this purpose, the linear relationships associated to mono-axial 1D compression, to define the physical parameters of the JCA model, have been used, even though a correction coefficient has been introduced as exponential of the compression rate in the formulation of the air flow resistivity. Instead of the linear relationship proposed by Castagnède for 1D compression, the compression rate rate n is raised to the power of $A = 2.1337$. Such coefficient was determined though a least square minimisation of the percentage error between the computed air flow resistivity and the experimental data, measured on samples of five different thickness for each investigated material. Indicating with the subscript $_{(0)}$ the initial set of physical parameters, determined as described in the previous section, and with the subscript $_{(n)}$ the material properties evaluated for any given compression rate n, Castagnède relationships have be reformulated as:

$$\sigma_{(n)} = n^A \sigma_{(0)} \tag{17}$$

$$\alpha_{\infty,(n)} = 1 - n\left(1 - \alpha_{\infty,(0)}\right) \tag{18}$$

$$\Lambda_{(n)} = \frac{\Lambda_{(0)}}{n^{1/2}} + r\left(\frac{1}{n^{1/2}} - 1\right) \tag{19}$$

$$\Lambda'_{(n)} = \frac{\Lambda'_{(0)}}{n^{1/2}} + r\left(\frac{1}{n^{1/2}} - 1\right) \tag{20}$$

The material's porosity was determined as ratio between the material density and the fibres density, as provided in Eq. (14). The hemp fibrous material was characterised for any compression rate within the range $n = 0.5 \div 2$, starting from the physical parameters determined as a function of the fluid dynamic effective radius for the material with density $\rho_{w,(0)} = 88$ kg/m^3 and thickness $h_{(0)} = 40$ mm.

5. Results and validation

The way in which each manufacturing process, presented in section 2, affects the acoustic performance of the material has been analysed by comparing the normal incidence sound absorption coefficient α_n, measured on samples of loose hemp fibres at the four different stages of the process, with identical density $\rho = 88$ kg/m^3 and thickness $h = 40$ mm. The sound absorption measurements were performed, as described in section 4, three times for each sample; the experimental deviation is reported as a shaded area around the average curve of the associated absorption coefficient. As shown in Figure 3 there is not a relevant difference between the fibres only carded 01.CAR and the fibres which also went through the alkaline treatment 02.NaOH. In

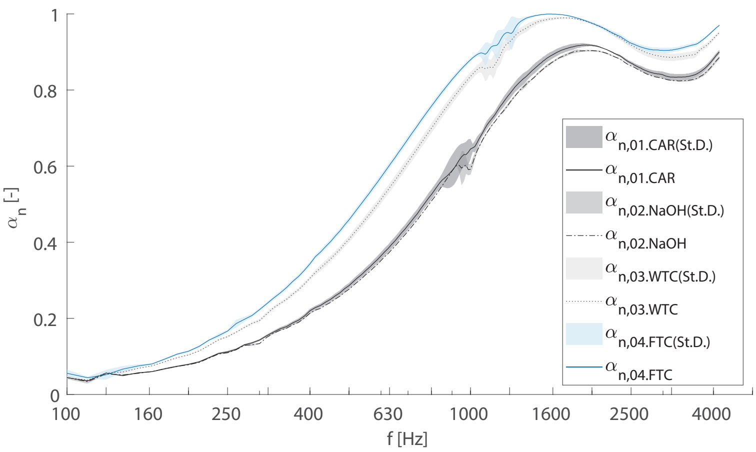

Figure 3: Normal incidence sound absorption coefficient measured on hemp fibres samples, with thickness h = 40 mm and density ρ_w = 88 kg/m^{3}at the four different stages of the manufacturing process.

fact, even though the sound absorption coefficient associated with the 02.NaOH fibres is slightly lower than the values related to the carded fibres 01.CAR, these differences are barely noticeable and the two curves almost match within the entire frequency range. On the other hand, the wide tooth combing 03.WTC significantly increases the sound absorption of the material. Moreover, the acoustic performance of the hemp fibrous material is further enhanced after the fine tooth combing treatment 04.FTC, which allows the natural fibrous material to match the normal incidence sound absorption of traditional synthetic fibres.

The characterisation methodology described in the previous section was validated by comparing the physical parameters, computed for a varying compression rate n, with experimental results. The initial set of material properties computed as a function of the effective radius, derived from the experimental the air flow resistivity $\sigma_{(0)}$, and function of the normal incidence sound absorption coefficient $\alpha_{n,(0)}$; both measured on samples of hemp fibres 40 mm thick, with a density of $\rho_{(0)}$ = 88 kg/m^3, is provided in Table 2. In order to validate the results, additional measurements have been made on the hemp fibrous material at each stage of the manufacturing process. In particular, a total of five different densities ρ_w were experimentally tested within the range $\rho_{w,i}$ = 58.7 ÷ 140.8 kg/m^3, obtaining hmep firous samples with a thickness varying from h = 60 mm to h = 25 mm. For each sample the normal incidence absorption coefficient and the air flow resistivity were experimentally measured as described in section 4. Moreover, the materials' tortuosity α_∞ was assessed from an ultrasonic experimental method [31], while the viscous Λ and thermal characteristic lengths Λ' have been evaluated by using well consolidated inversion techniques [28].

In Figure 4 the experimental air flow resistivity, measured on samples of the fibrous material, with five different densities, after each processing step, is shown. Results consistent with the sound absorption coefficients, shown in 3, are found. In fact, for all the investigated densities the fibres resulting from the process 04.FTC exhibit the higher air flow resistivity, while the

Table 2: Physical parameters of the hemp fibrous materials used as initial data set to characterise the material properties at varying compression rate

	01.CAR	02.NaOH	03.WTC	04.FTC
$h_{(0)}$ [mm]	40	40	40	40
$\rho_{(0)}\left[\mathrm{kg/m^3}\right]$	88	88	88	88
$\phi_{(0)}$ [−]	0.93	0.93	0.93	0.93
$\sigma_{(0)}\left[Pas/m^2\right]$	5536.13	4920.17	7883.65	12503.29
$\alpha_{\infty,(0)}$ [−]	1.055	1.055	1.055	1.055
$\Lambda_{(0)}$ [μm]	109.78	115.46	59.61	50.10
$\Lambda'_{(0)}$ [μm]	160.00	170.81	135.56	109.44

lowest values are associated with the fibres resulting from the alkaline treatment 02.NaOH; this behaviour is more emphasised as the density increases. A rising high of the air flow resistivity is thus associated with an improvement of the material's absorption coefficient. The experimental air flow resistivity, plotted together with the error bars, which represent the experimental standard deviation, are compared in Figure 4, with the air flow resistivity computed for a varying compression rate $n = 0.5 \div 2$, according to Eq. (17). For each material a good agreement is found between the experimental results and the curve computed using the formulation proposed in this paper $\sigma_{i,(n,A)}$. The results obtained from the linear model proposed by Castagnède for 1D compression is also reported as a dotted line $\sigma_{i,(n,1D)}$, in order to demonstrate how it is not suitable for this kind of material, providing inaccurate results, which progressively deviate from the experimental evidence as the density increases.

On the other hand, Castagnède equation for 1D compression provides a good approximation of the experimental tortuosity, as shown in Figure 5. Even though, the curve obtained from the linear relationship for 1D compression slightly deviates form the experimental results at the highest densities, it should be considered that such differences are comparable with the experimental standard deviation, reported as error bars.

It was not possible to measure the viscous and the thermal characteristics lengths, these quantities were thus determined, for each material, by using a consolidated inversion technique, minimising the difference between the experimental sound absorption coefficient and the results obtain from the JCA model.

However, keeping in mind that at the low frequencies, or for materials with a low density, both the viscous and the thermal characteristics lengths have not a significant influence on the sound absorption coefficient, one soon realises that in these cases the inversion technique would not necessarily provide the best physical solution. In order to provide a sensitivity analysis of the JCA model to these quantities, as a function of the material density, the numerical results were compared with the all values of Λ and Λ' resulting from the minimisation algorithm which guarantee an absorption coefficient within the 3% of error with respect to the experimental value, plotted as a shaded area representing the standard deviation around the best fit results. The standard deviation found in the determination of the characteristic viscous length, as shown in

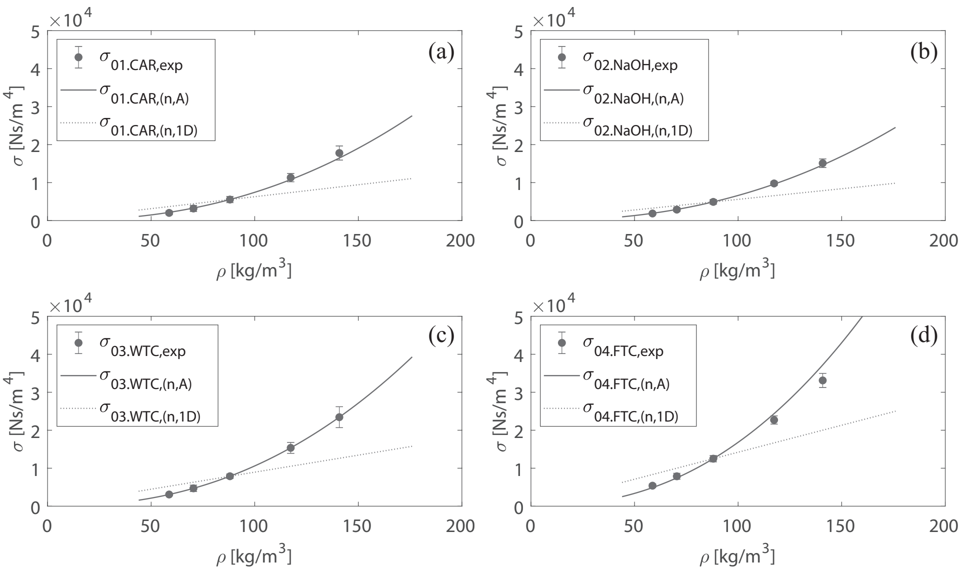

Figure 4: Experimental and estimated air flow resistivity evaluated at each stage of the manufacturing process on samples of various densities at the four manufacturing stages: (a) carding process: 01.CAR; (b) alkaline treatment: 02.NaOH; (c) wide tooth combing: 03.WTC; (d) fine tooth combing: 04.FTC.

Figure 6, is very limited for all the four materials, both for high and low densities. However, as the porosity increases the fluid viscosity influence is more significant and the standard deviation further decreases. The numerical curve for a varying compression rate $\Lambda_{(n,1D}$, given in Figure 6, is in good agreement with the experimental values of the material resulting from the two last manufacturing processes: 03.WTC and 04.FTC; although it significantly deviates from the characteristic viscous length evaluated from experimental data for the fibres which underwent only the first two manufacturing treatments: 01.CAR and 02.NaOH. An analogous situation can be drawn comparing the thermal characteristic length derived from the experimental data set and the numerical curve evaluated for a varying compression rate. As it was found for the viscous characteristic length, Castagnède equation for 1D compression provide an accurate approximation for the materials obtained from the last two manufacturing process: 03.WTC and 04.FTC, while relevant discrepancies are found for the materials at the first two stages: 01.CAR and 02.NaOH. However, by looking at results obtained from the inversion algorithm, considering all the solutions which provide an absorption coefficient within the 3% error, a huge standard deviation is found. This means that the thermal characteristic length does not significantly affect the sound absorption coefficient of materials with high porosity or with rough fibres. The numerical results, even though deviates for the best values solution, represented by black circles, is by far within the shaded area which represents the standard deviation obtained in the minimisation approach.

Finally, in order to determined whether the accuracy provided by this approach may guarantee a good approximation of the material acoustic performance, the experimental sound absorption form normal incidence α_n, measured at each stage of the manufacturing process for five different compression rates, was compared to the results obtained from the JCA model. The physical parameters estimated for a varying compression rate just presented were used as input

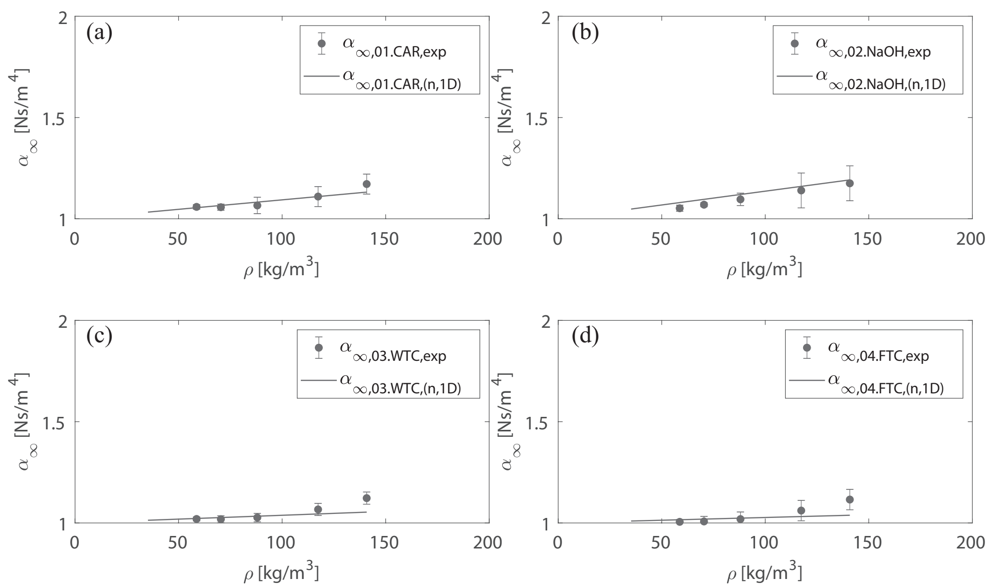

Figure 5: Experimental and estimated tortuosity evaluated on samples of various densities at the four manufacturing stages: (a) carding process: 01.CAR; (b) alkaline treatment: 02.NaOH; (c) wide tooth combing: 03.WTC; (d) fine tooth combing: 04.FTC.

data in the model. As shown in Figure 8 a good agreement is found between the numerical results and the experimental sound absorption for all the four materials at each of the investigated compression rates. Since the small discrepancies highlighted in some cases between numerical and experimental curves are comparable with the experimental standard deviation found between different measurements of the same sample, shown in Figure 3, it can be concluded that the characterisation approach investigated in this study provide an accurate estimation of the physical parameters required to describe the acoustic performance of hemp fibres materials using the JCA model.

6. Conclusion

A study regarding the acoustic performance of hemp fibrous materials and the physical parameters by which this is affected has been presented. It was analysed how to optimise the manufacturing process in order to obtain a natural, sustainable and renewable fibrous material, which can provide an sound absorption coefficient comparable to the one provided by traditional synthetic fibres. An experimental investigation on hemp-fibres identified the influence of each stage of the manufacturing process both on the acoustic performance and on the physical characteristics of the fibrous material. It was shown that an alkaline treatment (02.NaOH) performed on the material after the carding process (01.CAR) does not significantly affect neither its acoustic performance neither its physical properties, such as the airflow resistivity for example; unless this is followed by two combing processes, the first one made with a wide tooth comb while the second with a finer one, which allow to improve the material acoustic performance, by increasing air flow resistivity and reducing the effective radius of the fibres. From a physical point of view

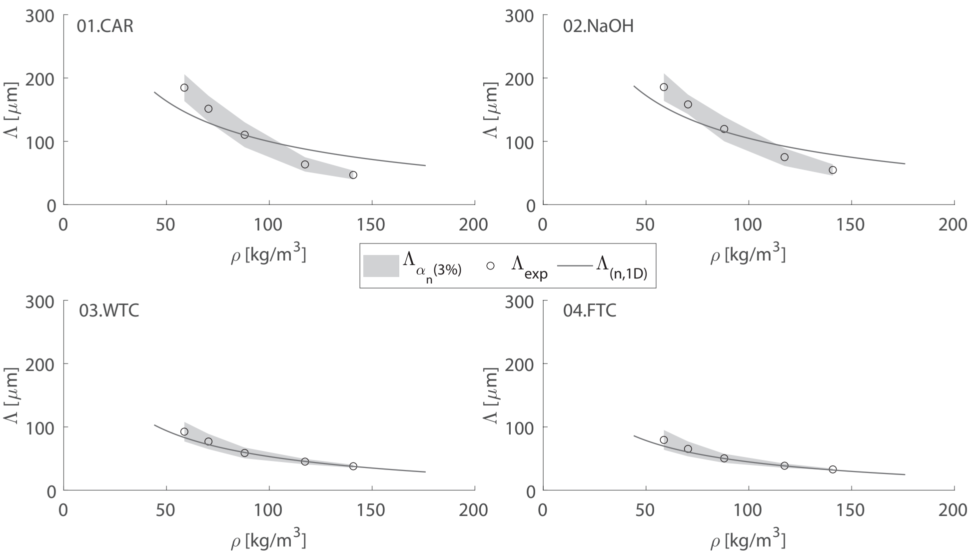

Figure 6: Experimental determined from inversion technique and estimated characteristic viscous length evaluated on samples of various densities at the four manufacturing stages: (a) carding process: 01.CAR; (b) alkaline treatment: 02.NaOH; (c) wide tooth combing: 03.WTC; (d) fine tooth combing: 04.FTC.

these processes remove the non-cellulose components extracted by the alkaline treatment. The physical parameters required to describe the hemp fibres using the JCS equivalent fluid model were characterised after each manufacturing procedure. Since natural fibres are characterised by large variability of the diameters distribution, the proposed approach is based on the concept of effective equivalent fluid-dynamic radius, derived from the experimental air flow resistivity by using the model developed by Tarnow. Besides, a simplified methodology to investigate the acoustic performance of hemp fibrous materials, as a function of the material density, was then proposed, providing an useful tool to compute and compare the sound propagation into the material with different degrees of compression. Characterising the hemp fibrous material at the given density the five physical parameters, used in Johnson-Champoux-Allard model for porous medium, it was possible to evaluate the properties of the material for a varying compression rate with good accuracy, by using the simple model developed by Castagnède for mono-axial compression. However, in order to consider also materials with a high compression rate, i.d. high density and low porosity, or aspects which are not take into account in this simplified model, such as the fibres orientation, the 1D linear equation provided to compute the air flow resistivity was modified by introducing an exponential correction coefficient. Such term was determined from the experimental airflow resistivity measured on hemp fibres samples at different compression rates by means of a minimisation algorithm. At each manufacturing stage, all of the investigated parameters numerically evaluated were validated by comparison with the experimental results, measured on hemp fibres samples with five different densities and thicknesses. More specifically, the air flow resistivity, the tortuosity and the normal incidence sound absorption were directly measured, while the viscous and thermal characteristic lengths were determined

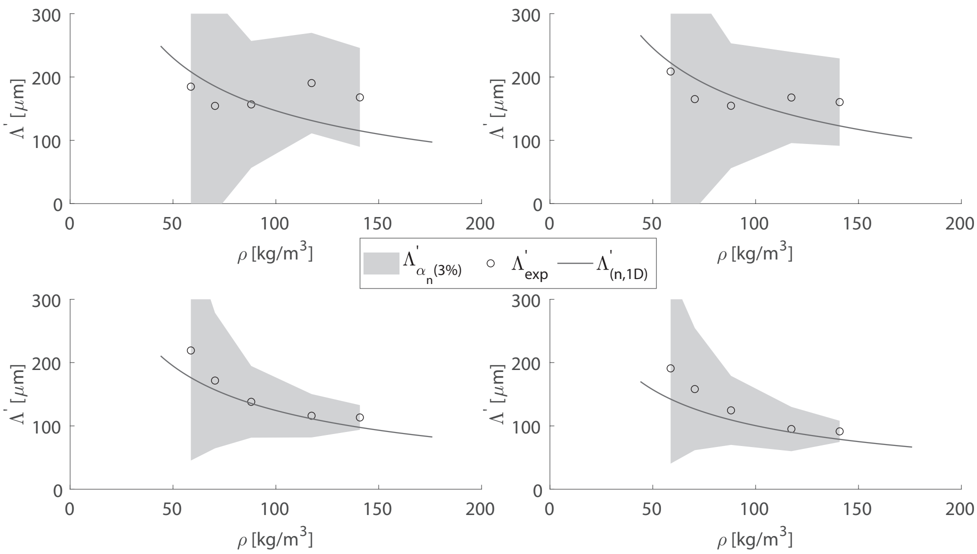

Figure 7: Experimental determined from inversion technique and estimated characteristic thermal length evaluated on samples of various densities at the four manufacturing stages: (a) carding process: 01.CAR; (b) alkaline treatment: 02.NaOH; (c) wide tooth combing: 03.WTC; (d) fine tooth combing: 04.FTC.

from the experimental data set using an inversion technique. The validation highlighted a good agreement between the results obtained from the proposed methodology and the experimental physical parameters. Due to the simplified and practical nature of the proposed approach some discrepancies were found, especially at the highest densities. However, the differences found between the experimental and numerical results were comparable with the experimental standard deviation obtained from different measurements of the same sample. Moreover, numerically evaluated parameters used as input data in the Johnson-Champoux-Allard model provided a very good approximation of the experimental sound absorption coefficient measured at each stage of the manufacturing process on materials with five densities. The proposed model can be certainly refined in the follow-up of this project, even though this simplified approach represents a simple and reliable tool to analyse the acoustic performance of hemp fibrous materials, which was never investigated before.

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We would like to ...

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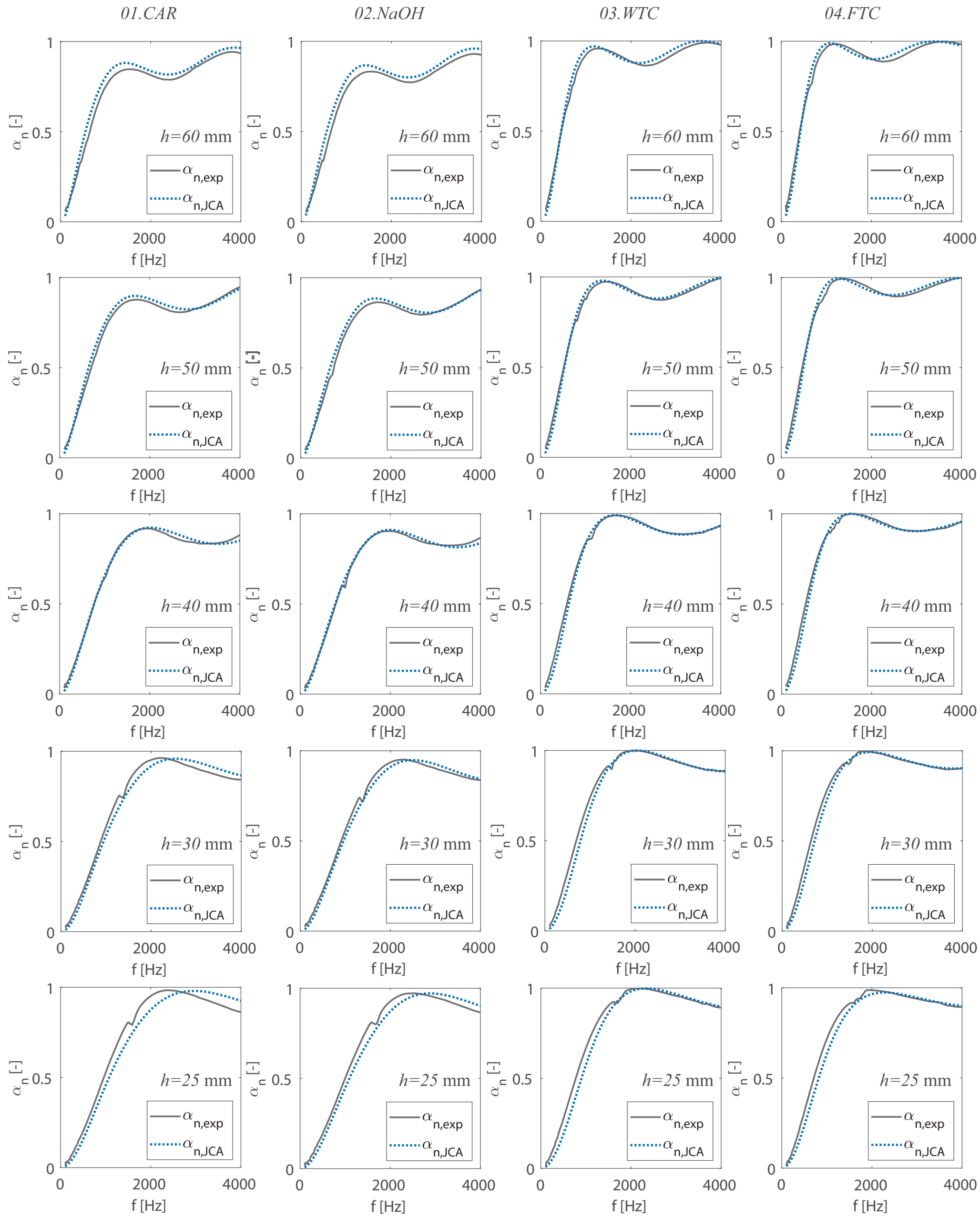

Figure 8: Comparison between numerical and experimental normal incidence sound absorption coefficient of the hemp fibrous material at each stage of the manufacturing process, for different compression rate.