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Acoustical Characterization and Modeling of Sustainable Posidonia Fibers

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Featured Application: The purpose of the article is to evaluate the use of a sustainable material obtained from marine plants (*Posidonia oceanica*) as sound-absorbing material.

Abstract: This article presents the results of an acoustic characterization of fibers obtained from Posidonia Balls (scientific name: Aegagropiles), produced by a marine plant (*Posidonia oceanica*) that is widespread in the Mediterranean Sea and can be found on beaches in large quantities, particularly following storm surges. The aim of this research is to evaluate the possible use of these fibers as eco-sustainable sound-absorbing materials and to define an acoustic model for the optimization of sound-absorbing panels made from these fibers. Experimental tests were conducted to measure airflow resistivity and sound absorption for different densities of loose fiber samples. From these experimental tests, the five physical parameters of the Johnson-Champoux-Allard model were calculated to obtain an analytical formulation of the acoustic behavior of the fibers depending on their density. To the author's knowledge, this is the first time that an article has been published on acoustic data relating to the sound-absorbing performance of loose *Posidonia oceanica* fibers and that an analytical model has been presented that allows for the acoustical design of panels of different thicknesses and densities made with this material. An interesting aspect of this material is that the lignin fibers are ready for acoustic application due to the natural cleaning process of the waves and salt water. Furthermore, the methodology consists of a hybrid method between the experimental characterization of some parameters (i.e., different densities) and the numerical inversion of the acoustic data for other parameters. This is an effective solution that has rarely been adopted in other studies on sustainable materials.

Keywords: Posidonia fibers; natural fibers; sustainable porous material; sound absorption; acoustical modeling

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1. Introduction

Research on sustainable sound-absorbing materials is being increasingly developed under the objectives of the Ecological Transition Plan, which aims to progressively reduce CO_2 emissions on a global level. The assessment of the environmental sustainability of these materials includes the use of renewable resources for their production, the processes that reduce the release of polluting particles into the environment and, potentially, the ability of these materials to absorb polluting particles (for example CO_2 during the growth of plants). We can therefore identify two main aspects concerning the environmental sustainability of sound-absorbing materials: the constituent material and the production process that allows the final product to be obtained. Analysis relating to the end-of-life of the product must also be added to these aspects, together with the possibility of recycling the product to create a new material. An objective analysis can be obtained with LCA (Life Cycle Assessment) methodology, which measures the environmental impact of a product by analyzing all phases of the product life in analytical form. It is thus possible to obtain comparative tables of the different types of materials in relation to their environmental sustainability.

Sound-absorbing materials can be divided into different categories based on the origin of the material they are made of:

- Vegetal origin: mainly materials with a fibrous structure, obtained from specially cultivated plants (cotton, hemp, flax) or from production waste from other processes (wood fibers, coconut fibers); in some cases (e.g., cork) the materials can also have a cellular structure;
- Animal origin: for example, sheep's wool or goose feathers;
- Mineral origin: the production of these materials is based on the availability of natural mineral resources, which by definition are non-renewable; they can have a fibrous structure, such as mineral wool (amorphous silicate obtained from a mixture of rocks and other inert materials) and glass wool (amorphous silicate obtained from a mixture of glass and sand), or cellular structure such as pumice or perlite;
- Synthetic origin: materials that require chemical processes (typically polymerization) to obtain open-cell foams such as polyurethane, polyethylene, melamine, or fibrous materials such as polyester. To produce synthetic materials, it is necessary to use non-renewable fossil resources; therefore, environmental sustainability is lower than the first two categories unless recycled materials are used in the production process.

More generally, a different category may include recycled materials obtained from end-of-life materials, regardless of their nature. This category includes felts obtained from textile fibers (recycled clothes), granulates obtained from recycled tires, and polyester fibers obtained from recycled plastics (PET).

If the analysis is narrowed down to materials of plant origin, there are hundreds of articles presenting acoustic results from sound-absorbing materials obtained from the most disparate types of plants: an exhaustive list can be found in several review articles, such as [1–3]. The natural fibers investigated can be obtained from processing waste from agricultural production (e.g., green tea residues [4], corn husk [5] and pineapple-leaf [6]), from specifically cultivated plants (e.g., hemp [7] and jute [8]), or from naturally occurring invasive plants that have no other applications (e.g., broom [9] and Yucca gloriosa [10]). For most of these plants, lignocellulosic fibers are obtained through chemical and mechanical processes, including maceration, water retting, carding, and alkaline treatment.

The acoustic results are often reported in terms of the sound absorption coefficient and therefore depend not only on the intrinsic properties of the fibrous material but also on its thickness and density. It would be very difficult to compare the data between different publications, and, in any case, this would not allow the real efficiency of the material to be determined. Efficiency is defined in this paper as the ratio between its performance and thickness or weight.

When evaluating the production process of a vegetable fiber material, the following need to be considered:

- The use of land for cultivation;
- The use of resources for plant cultivation (water, any chemical products, agricultural processing with non-renewable resources);
- The industrial processes necessary to transform the plant (or parts of it) into fibers, with the possible addition of binders to create panels of a certain shape;
- Transportation to the installation site.

Naturally, if the fibers are made from production waste (for example, wood processing waste or coconut waste), the first two points are not applicable (or rather, they fall on the primary products), while the last two are usually applicable.

If the fibers of a vegetable material are already available in nature, the sustainability of this material is very high, and its possible use is of great interest; a material of this type is present on the beaches of the Mediterranean: the so-called Sea Balls or Neptune Balls (scientific name: Aegagropiles), which are the result of the unraveling of the leaves of the

Posidonia oceanica. They are made up of an agglomeration of fibers bound together in an ellipsoid shape (Figure 1a,b).

Figure 1. Examples of Posidonia Balls (**a**,**b**) and "banquettes" on the beach (**c**).

Posidonia oceanica is an aquatic plant endemic to the Mediterranean Sea, and it belongs to the Posidoniacee family (Monocotyledonous angiosperms). *Posidonia oceanica* meadows occupy a surface area between 2.5 and 5 million hectares [11] and perform important ecological functions in the Mediterranean Sea, not only for biodiversity conservation but also for the mitigation of climate change, thanks to their role in carbon sequestration [12,13] and their ability to trap microplastics [14]. In the last few decades, there has been a widespread regression (from 13% to 50% [15]) of the meadows in Mediterranean coastal waters. Therefore, in view of their important ecological role, *Posidonia oceanica* meadows have been protected by European legislation through the Habitats Directive 92/43/EU, classified as a Priority Habitat and included as of "Least Concern" on the Red List of the International Union for Conservation of Nature (IUCN) [16].

The leaves of *Posidonia oceanica* are ribbon-shaped and can be up to one meter long. They are green in color when young and, as they age, turn brown and fall off due to the action of the waves. Research shows that Aegagropiles are formed by hydrodynamic movements and are made of different *Posidonia oceanica* plant fibers and sand grains [17–20]. The wave motion deposits them on the coast, where they are dried by atmospheric agents. These fibers are entirely processed by the sea, thanks to the action of the water and the waves. This frees the fibers from the vegetal material, creating ellipsoidal aggregates that end up on the beaches. During storms, large quantities of Posidonia leaves are torn off and deposited in large masses along the coast. The clusters, called "banquettes" (Figure 1c)—a few centimeters to several meters in thickness—can reduce the beach erosion rate [21], but if present in large quantities they are unwelcome to beach users. For this reason, in areas that welcome high numbers of tourists, large quantities of these materials are removed from the beaches before the summer season. Where it is not possible to do otherwise, they are sent to landfills as waste.

The alternative uses of Posidonia Balls currently being studied include recycling them for the creation of compost [22] or for the production of energy [23], after sieving out the sand present inside them, which is used for beach nourishment.

From an acoustic point of view, to the author's knowledge there is only one article in the literature that presents an analysis on the physical and acoustic characteristics and on the modeling of regular packets of these spheres as metamaterials. Apart from the present research, there is no other study on loose fibers with varying densities. An in-depth investigation of the structure of Aegagropiles and the characteristics of their fibers is reported in [24]. In general, the study shows that the shape, density, and size of the Aegagropiles can vary significantly, depending on the material included in the first nucleus on which the aggregate subsequently forms; another parameter that can vary their properties is the presence of sand inside—this too will have variable characteristics in terms of grain size and weight that can affect the overall density of the Aegagropiles. Variable densities between 100 and 400 kg/m^3 are detected in [18] (average value 220 kg/m^3).

The purpose of this article is to evaluate the possible use of Posidonia fibers as a sound-absorbing material, limiting mechanical and chemical treatments as much as possible, and to develop an analytical model that allows its acoustical properties to be optimized. To the author's knowledge, this is the first time an article has been published on acoustic data relating to the sound-absorbing performance of loose *Posidonia oceanica* fibers, and that an analytical model has been presented which calculates the size of the panels (density and thickness) made from this material. Acoustic applications of other marine plants have not been found in the literature; therefore, this is an innovative concept, particularly considering that the ocean covers 70% of the earth. Also, the methodology represents an effective solution that was first proposed by the author in [7,25]. It consists of a hybrid method between the experimental characterization of some parameters (i.e., density) and the numerical inversion of the acoustic data for other parameters.

2. Materials and Methods

2.1. Description of the Samples of Aegagropiles

Aegagropiles of different sizes were collected on the beaches of southern Sardinia. The collected material was found in dry sand, free from humidity. Once harvested, it was left out in the sun for several days to eliminate any residual humidity. Each Aegagropile appears as a very dense interweaving of fibers with a well-defined geometric shape similar to an ellipsoid. The samples have a flattened shape in one direction, while in the other two the semi-axes have similar dimensions to each other (Figure 2a). The collected Aegagropiles vary in density, which ranges from 85 to 180 kg/m^3.

The woven fibers were manually separated from these Aegagropiles, and the internal sand was removed by sieving. The loose fibers obtained were used for the physical and acoustic analyses described in the following paragraphs (Figure 2b).

A preliminary microscopic analysis highlighted the presence of fibers with a diameter between 70 and 110 μm, with some larger fibers reaching up to 300 μm in diameter. However, they were actually made up of several fibers that had not been disrupted by the action of water or atmospheric agents (Figure 2c).

It is important to underline that the aims of this study do not include evaluation of the variability of the fiber properties of Aegagropiles collected from different sites, which are characterized by different wave motion conditions, coastal settings, aging processes, and weather conditions, depending on the season. This would certainly be of interest if the intention is to industrialize a sound-absorbing acoustic product made from *Posidonia oceanica* fibers.

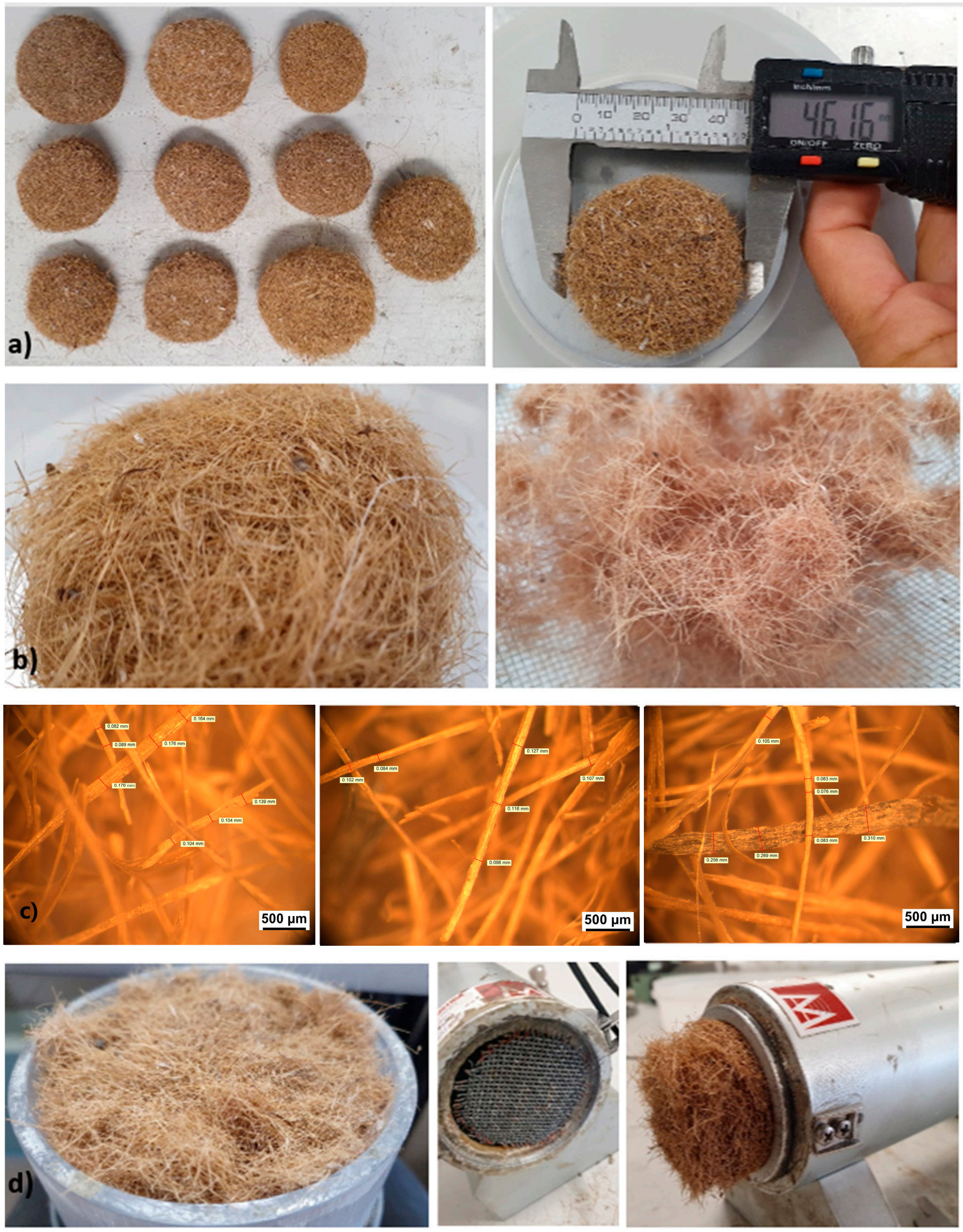

Figure 2. Collected Posidonia Balls (**a**), fibers obtained from the aggregates (**b**), microscope pictures of the fibers (**c**), fibers inside the sample holders for the measurement of airflow resistance (**left**) and sound absorption at normal incidence (**right**). In the center, the front grid for the compression of the sample (**d**).

2.2. Experimental Characterization

The following experimental measurements were carried out on loose fibers obtained from Aegagropiles:

- Porosity by the air volume compression method [26];
- Airflow resistivity according to ISO 9053-2 [27], as the density of the loose fibers varies (range from 65 to 191 kg/m^3);

- Sound absorption at normal incidence according to ISO 10534-2 [28], as the thickness and density of the fibers vary (range from 48 to 210 kg/m^3).

The experimental tests aim to determine the variation of the physical and acoustic parameters of the fibrous material as a function of the apparent density of the fibers.

The equivalent dissipative fluid model proposed by Johnson-Champoux-Allard (JCA) [29,30] was used, which describes complex effective density ρ and the complex effective bulk modulus K as a function of five physical parameters: porosity ϕ, tortuosity α_∞, airflow resistivity σ, and viscous and thermal characteristic length Λ and Λ':

$$\rho(\omega) = \frac{\alpha_\infty \rho_0}{\phi} + \frac{\sigma}{i\omega}\sqrt{1 + \frac{4i{\alpha_\infty}^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}} \tag{1}$$

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

where ρ_0 is the density and η the viscosity, P_0 the static pressure, and γ the specific heat ratio of air.

From the complex effective density ρ and the complex effective bulk modulus K, the characteristic impedance Z_c and the complex wavenumber k_c can be computed as:

$$Z_c = \sqrt{\rho K} \tag{3}$$

$$k_c = \omega \sqrt{\frac{\rho}{K}} \tag{4}$$

Considering a homogeneous porous material of thickness h placed on a rigid boundary, the surface impedance for normal incidence Z_S can be determined as:

$$Z_S = -iZ_C \cot(k_c h) \tag{5}$$

and the normal incidence sound absorption coefficient α_n as:

$$\alpha_n = \frac{4Re\left(\frac{Z_S}{\rho_0 c_0}\right)}{\left|\frac{Z_S}{\rho_0 c_0}\right|^2 + 2Re\left(\frac{Z_S}{\rho_0 c_0}\right) + 1} \tag{6}$$

where c_0 is the speed of sound in air.

In the following subsections, the procedures for deriving the density dependence of the five physical parameters are described.

A schematic diagram of the procedure proposed in this article is shown in Figure 3.

2.2.1. Porosity

Porosity ϕ was experimentally measured using the air volume compression method [26] for a single apparent density ρ_a, inserting the fibers of measured weight into a cylindrical specimen and measuring their thickness and therefore, the apparent volume.

The method (Figure 4) involves the compression at constant temperature of the air inside a container in which the porous sample to be measured is positioned and is based on Boyle's law for ideal gases. Since pV = const., by measuring the absolute pressure p_0 before compression and the absolute pressure p_1 at the end of the compression, when the compression volume ΔV is known it is possible to calculate the volume of air present in the container as:

$$V_0 = \frac{\Delta V p_1}{(p_1 - p_0)} \tag{7}$$

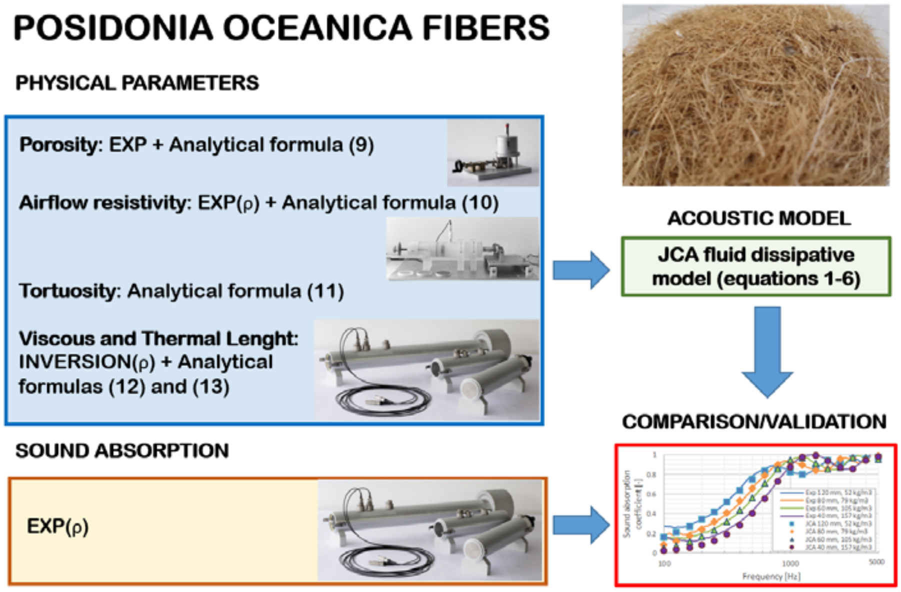

Figure 3. Schematic diagram of the procedure for the characterization of Posidonia fibers and acoustic modelling.

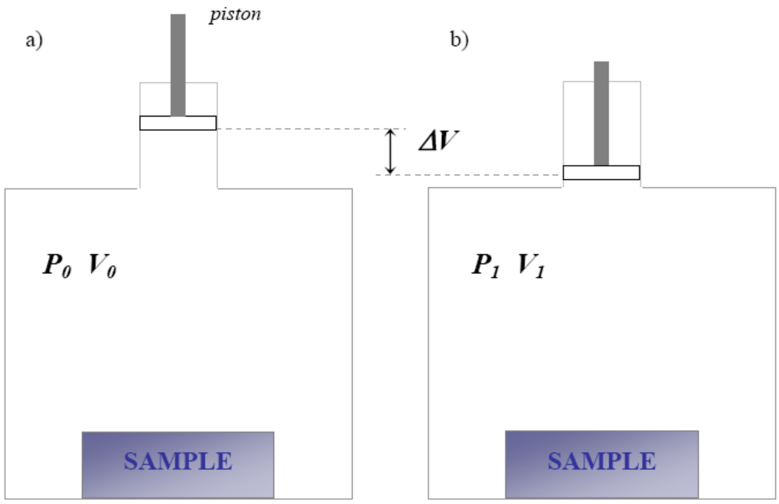

Figure 4. Schematic diagrams of the porosity measurement system based on the air volume compression method: (**a**) before the compression, (**b**) after the compression of know volume ΔV [26].

The volume V_0 thus calculated is equal to the difference between the known volume of the container V_c and the volume occupied by the fibers V_m. Once V_m has been calculated, it is possible to calculate the density of the material constituting the fibers by dividing the total weight of the fibers M_m by the previously calculated volume V_m:

$$\rho_m = \frac{M_m}{V_c - \frac{\Delta V p_1}{(p_1 - p_0)}} \tag{8}$$

A fiber density of 1518 kg/m^3 was obtained from the pressure detected inside the device at the end of a compression of known air volume with (7) and (8).

When the density of the fibers is known, it is possible to calculate the porosity for each bulk density using the following equation:

$$\phi = 1 - \frac{\varrho_a}{1518} \tag{9}$$

The porosity values in the density range of the experimental measurements are shown in Figure 5.

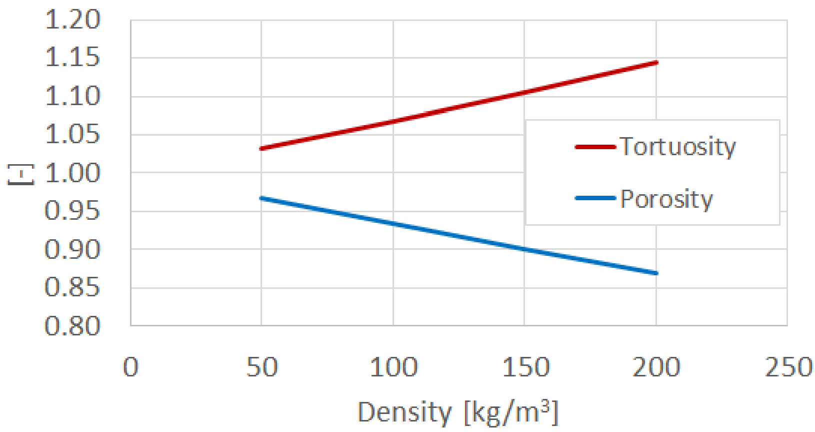

Figure 5. Porosity and tortuosity values as a function of the apparent density of the fibers, calculated with (9) and (11).

2.2.2. Airflow Resistivity

The airflow resistivity σ was measured with testing equipment with ISO Standard 9053-2 [27] by progressively compressing 20 g of fibers placed in a cylindrical sample holder (range from 65 to 191 kg/m^3). The apparent density was calculated as a function of the weight of the fibers (constant) and the occupied volume (variable in relation to the thickness of the sample).

Preliminary tests showed that disassembling and reassembling the 20 g fiber sample from the sample holder and repeating the airflow resistivity measurements gives practically identical results. For this reason, average values were not considered in the calculations, nor is a statistical analysis of the results presented.

Figure 6 shows the experimental values of airflow resistivity with respect to the apparent density of the fibers; to extend the experimental data to all bulk densities, an interpolation curve was calculated, using the relationship proposed in [31]:

$$\sigma = \frac{\eta}{(2a)^2} \frac{\sqrt{1-(1-\phi)}}{0.21\left(\frac{0.71}{1-\phi} - 3\sqrt{\frac{0.71}{1-\phi}} + 3 - \sqrt{\frac{1-\phi}{0.71}}\right)} \tag{10}$$

where a is the effective radius of the fibers and η the viscosity of air.

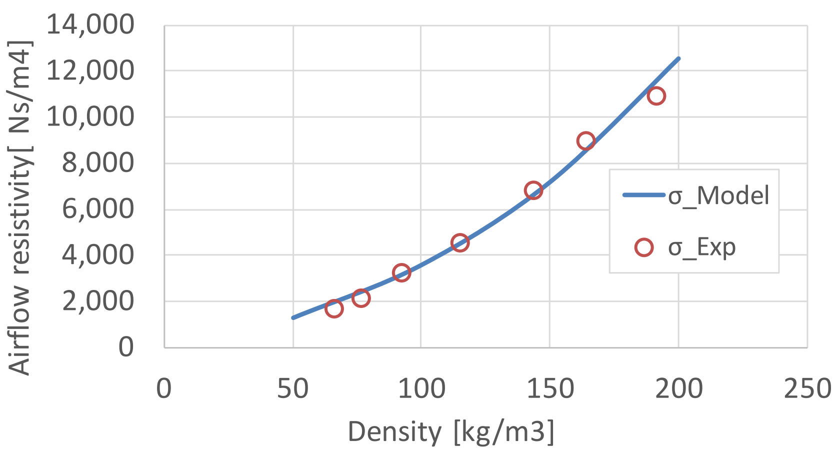

Figure 6. Comparison between the experimental airflow resistivity values and analytical model (10) with a = 40.1 µm.

In relation to the experimental data, using Equation (10), the equivalent radius of the fibers *a* was minimized; this radius *a* was found to be equal to 40.1 µm.

The resulting average percentage difference between the experimental airflow resistivity and that calculated with Equation (10) was equal to 5%, with a maximum value of 8%.

2.2.3. Normal Incidence Sound Absorption Coefficient

The experimental sound absorption measurements were conducted according to the ISO Standard 10534-2 in a 45 mm diameter standing wave tube, in a frequency range between 100 Hz and 4300 Hz.

Ten grams of fibers were inserted inside the sample holder; the thickness was varied by compressing the fibers between the rigid bottom of the sample holder and a metal mesh fixed to the tube on the side of the sample exposed to the acoustic field (Figure 2d). In this way, various samples of decreasing thicknesses and increasing densities were obtained, varying between 48 kg/m^3 and 210 kg/m^3.

Preliminary tests showed that disassembling and reassembling the 10 g fiber sample from the sample holder and repeating the acoustic measurements gives practically identical results. For this reason, average values have not been considered in the calculations, nor is a statistical analysis of the results presented.

Figure 7 shows the experimental curves for some combinations of density and thickness.

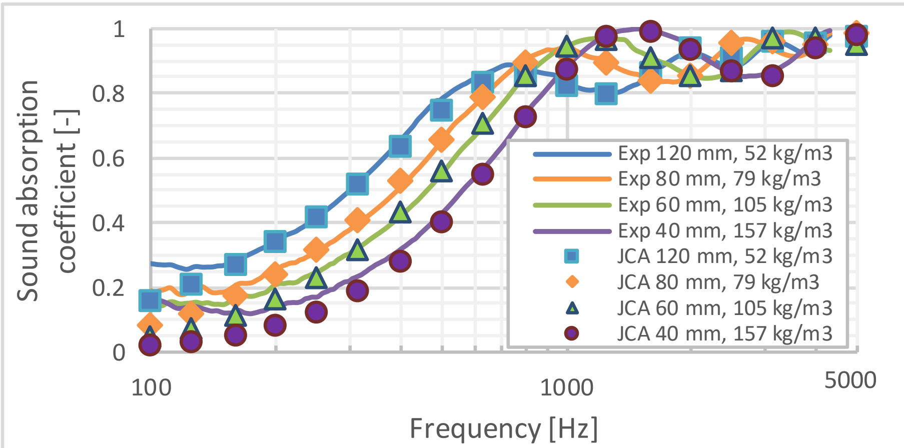

Figure 7. Comparison between the experimental measurements (Exp) and analytical model (JCA) for four different combinations of thickness and density (constant sample weight).

The purpose of these measurements is twofold:

- To obtain for different fiber densities an experimental curve to be used to calculate the missing physical parameters (viscous and thermal characteristic length) through an inversion procedure (Section 2.2.4);
- To obtain experimental data to validate the proposed analytical model (Section 2.2).

2.2.4. Analytical Calculation of Further Physical Parameters

To calculate the acoustic parameters of the loose fibers in relation to their density using the formula (Section 2.2.1), it is necessary to know the variation of the physical parameters of the model with respect to density.

In addition to porosity (Section 2.2.1) and airflow resistivity (Section 2.2.2), the following physical parameters were calculated:

- Tortuosity α_∞ using the analytical formula proposed in [31] as a function of the porosity:

$$\alpha_\infty = \left(\frac{1}{\Phi}\right)^{0.9574} \tag{11}$$

- Viscous and thermal characteristic length Λ and Λ' using the inversion technique [32] starting from the experimental acoustic measurements described in Section 2.2.3 and assuming the validity of the JCA equivalent dissipative fluid model. For each measurement of acoustic absorption relating to a specific density and thickness, the values of porosity, tortuosity, and airflow resistivity were fixed in the relationships (9), (10), and (11). The values of Λ and Λ' were calculated through a procedure of inversion, minimizing the difference between the experimental absorption curve and the one calculated with the JCA model. The values of the viscous and thermal characteristic lengths obtained are shown in Figure 8 as a function of the apparent density; subsequently, to extend the results to any density through an analytical formulation, the following exponential interpolation equations were obtained:

$$\Lambda = 0.066(1-\phi)^{-1.309}\ [\mu\text{m}] \tag{12}$$

$$\Lambda' = 0.790(1-\phi)^{-0.745}\ [\mu\text{m}] \tag{13}$$

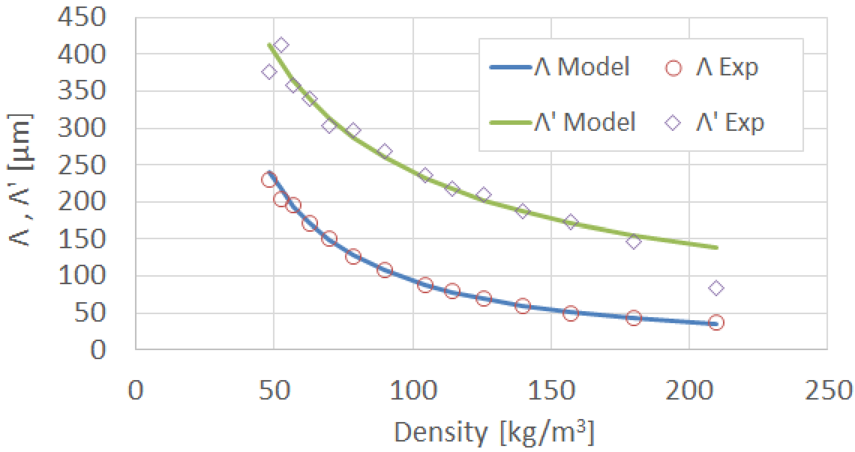

Figure 8. Comparison between the values of Λ and Λ' obtained by inversion from the experimental measurements and interpolation curves (12) and (13).

Figure 8 compares the interpolation curves and the experimental values as a function of the apparent density.

The resulting average difference between the values of Λ and Λ' obtained with the inversion technique and the analytical Formulas (12) and (13) is 2% and 8%, respectively.

3. Results

The analytical model presented in Section 2 allows the normal incidence sound absorption coefficient to be calculated for any combination of thickness and apparent density of Posidonia fibers.

To verify the reliability of the method, the absorption curves of several different experimentally tested combinations of thickness and density were calculated with the analytical model.

Table 1 shows the physical parameters calculated as a function of density using the Formulas (9)–(13).

Figure 7 presents the comparison between the experimental and calculated sound absorption curves; very good correspondence can be seen between the analytical model and the experimental measurements.

From Figure 7, it is evident that the Posidonia fibers have promising sound-absorbing properties in a wide range of densities.

Table 1. Physical parameters of the JCA model calculated with the proposed analytical relationships.

Thickness [mm]	Density [kg/m^3]	Porosity [-]	Airflow Resistivity [Ns/m^4]	Tortuosity [-]	VCL [μm]	TCL [μm]
40	157	0.90	7867	1.11	52	171
60	105	0.93	3871	1.07	88	232
80	79	0.95	2455	1.05	128	287
120	52	0.97	1356	1.03	217	388

Thanks to the analytical model, the sound absorption can be compared as the bulk density varies for a constant thickness (for example, 50 mm); in Figure 9, the variation of sound absorption can be seen as the density increases from 50 kg/m^3 to 200 kg/m^3.

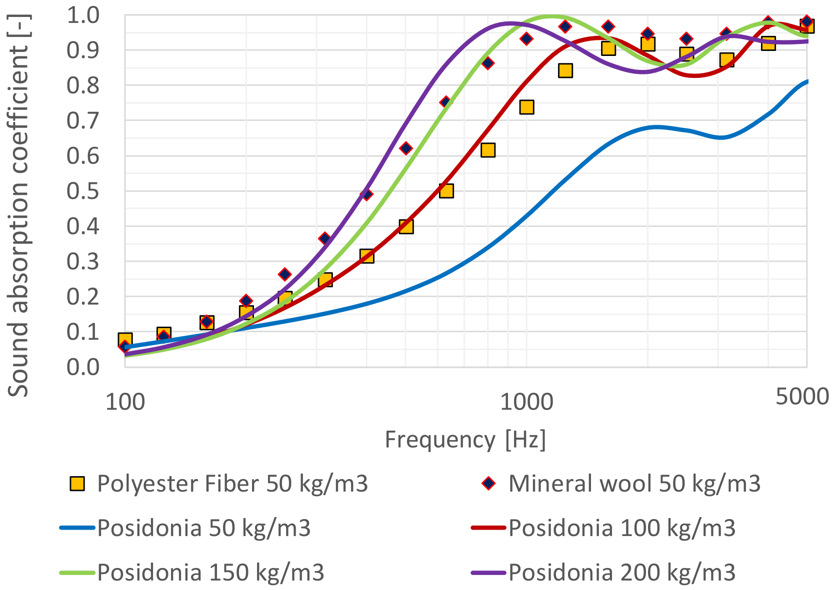

Figure 9. Absorption coefficient of Posidonia fibers as density varies (solid lines) and of two traditional sound-absorbing materials (dots: polyester fiber and mineral wool).

When comparing the acoustic performance of Posidonia fibers with traditional fibrous materials, analytical models present in the literature can be used, such as:

- The model proposed in [33] for polyester fibers;
- The model proposed in [34] for mineral fibers.

Figure 9 shows comparisons between polyester fibers and mineral fibers with commonly used densities (50 kg/m^3) with the same thickness of 50 mm.

As the figures show, due to their larger diameter, the Posidonia fibers have lower absorption at the same density of 50 kg/m^3. When the density of the fibers is increased to 100 kg/m^3, the performance of the polyester fibers (50 kg/m^3) is reached, and when it is increased between 150 and 200 kg/m^3, the performance of mineral wool (50 kg/m^3) is reached.

4. Discussion

Aegagropiles are very common plant materials on the Mediterranean coasts, which represent a potential problem—particularly during the tourist season—as their disposal can constitute a cost for local public administrations. However, they could be a useful resource for the production of sound-absorbing materials, particularly as the Aegagropiles fibers are found on the beach ready for use since they are naturally cleaned of any non-cellulosic components by the action of the waves and sea water. Only a mechanical treatment is necessary to separate the intertwined fibers of the Aegaropiles and to sieve out any sand trapped inside.

This research has shown that Posidonia fibers have potential applications in the acoustic field and that they can achieve absorption coefficients comparable with those of traditional materials such as mineral wool and polyester fibers. Depending on the degree of compaction of the fibers (and therefore on the density), it is possible to control the airflow resistivity of the material and consequently calculate the absorption curve as a function of the thickness of the material.

The analytical model presented showed a good correlation with the experimental acoustic measurements and constitutes a design tool for acoustic panels made with this sustainable material; this is of great importance since there are no acoustic models related to the density of this sustainable material in the literature. It should also be underlined that the proposed characterization method, a hybrid of experimental measurements and the numerical inversion of acoustic measurements, proved to be very efficient in obtaining an analytical model of the acoustic propagation in the material.

The large size of the fibers determines the need to use fiber densities higher than 100 kg/m^3, which is significantly higher than other traditional materials such as mineral wool or polyester fibers. The use of these materials is therefore recommended for applications where the weight of the panel is not a determining factor (such as on trains, cars, or airplanes), where a reduced environmental impact is sought. The lower acoustic efficiency of the material can be compensated for by its high sustainability and the reduced need for mechanical and chemical treatments, in addition to the fact that the waste material is reused—creating a circular economy.

The research, currently limited to fibers from Aegagropiles, could be extended to Posidonia leaves deposited on the beaches in the form of "banquettes", which represent a greater problem since they are larger in quantity. In this case, it would be necessary to study an industrial treatment to obtain the fibers from the leaves swept up onto the beaches.

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Conflicts of Interest: The authors declare no conflict of interest.

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