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Influence of fineness, length and hollow section of fibers on acoustic absorption

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Abstract

A fibrous material is characterized by its fineness, flexibility and high length/fineness ratio and it is used to reduce noise in indoor rooms due to their porous structure. The aim of this work is focused on investigating the structure of two different fibers (acrylic and polyester) from the analysis of the macrostructural parameters, such as fineness, length and cross-section (solid or hollow). Furthermore, the degree of influence of these parameters on the average sound absorption has been investigated. The sound absorption coefficient of fibers is measured at normal incidence in the impedance tube. In acrylic fibers, results showed that the fineness of the fiber has a significant influence on the sound absorption compared to the length of the fiber. In polyester fibers, hollow fibers have a better acoustic behavior compared to solid fibers.

Keywords

Fibers, fineness, length, cross-section, sound absorption coefficient

Fibers are raw materials that can be classified under different criteria such as the origin (natural, chemical) or their properties (conventional, technical).[1] The fiber properties can be analyzed according to their macrostructure or their microstructure. The macrostructure is directly related to the geometric parameters of the fiber. The microstructure is related to the internal structure of the fiber and it studies how the atoms are bonded and the macromolecules are arranged into a crystalline or amorphous structure.

Different parameters are directly related to the fiber macrostructure: fineness, thickness, crimp and cross-section.[2] The most important dimensional features to characterize fibers are length and fineness. The length depends on the fiber nature. Cotton fiber length is shorter than that of wool, whereas silk is the longest among natural fibers, as it is a filament. However, chemical fibers can be as long as desired as they are generally produced as a filament (long length) and cut to the desired length. Fineness is defined as the ratio between fiber mass and fiber length and it is not easy to measure because the cross-section of fibers can vary and show different shapes, as can be seen in Figure 1. Before 1960, fineness was measured in μm until the International System (IS) adopted the linear mass, tex (g/km), as the valid unit to obtain the fiber fineness.[3] Regarding the fiber dimension, dtex is commonly used the, that is, one 10th of a tex.

Later in the 20th century, the consumption of fibers around the world rapidly increased due to their use in new application areas and technological advancements.[4] It is commonly accepted that a microfiber is considered when the fineness is below 1.1 dtex,[5] equal to 1 denier. The denier is also a unit for measuring the linear mass density of fibers and it is defined as the mass in grams per 9000 m of the fiber. It is also commonly used in the textile industry to measure the

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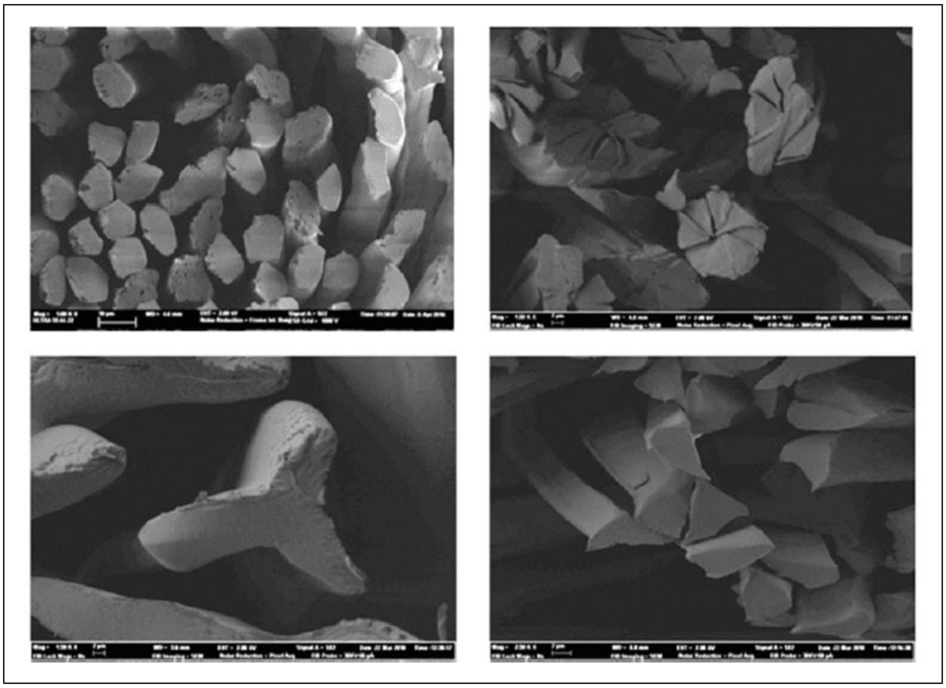

Figure 1. Electron microscopy images of the cross-section of different fibers.

fineness of fibers. The physical and mechanical properties of fibers have been widely studied in the last decade.[6–9]

Generally, fibers are used in the manufacture of textile fabrics, composites or thermal and acoustic isolation materials.[10–12] Several studies based on the acoustic properties of fibers have been reported due to their practical interest. The absorption properties of fibers may vary depending on the manufacturing method, the inhomogeneity of the fiber structure, the fiber macrostructure and the fiber configuration.[13] Aso and Kinoshita[14] studied several parameters influencing the sound absorption characteristics of the fiber assembly, such as length, fineness, thickness, fiber orientation, porosity and elasticity of the constituent fibers. The homogeneity of the total fiber surface area determines equal absorption values, regardless of the length or fineness of the fiber. Shoshani and Rosenhouse[15] determined that fiber content caused a small effect on the sound absorption coefficient at low frequencies, but a significant impact at high frequencies. Na et al.[16] examined how the structure and geometric shape of the microfiber affects the sound absorption compared to regular fibers. Microfibers absorb sound better than traditional fibers due to their higher surface area. Recently, Berardi and Iannace[17] studied the sound-absorbing characteristics of different natural fibers and they used theoretical models to predict the acoustic behavior of these fibers.

Although many researchers have studied specifically the acoustic behavior of fibers, the influence of the specific characteristics of the fiber parameters on the sound absorption is not still well known. In this work, different fibers are organized in a cylindrical shape inside the sample holder of the impedance tube to assess the influence of the length, fineness and hollow section of the fibers on the sound absorption at normal incidence.

Experimental investigation

Materials

A total of six different polyacrylonitrile fibers, three acrylic and three polyester fibers, were analyzed. Table 1 shows the reference given to each fiber and the technical information, including the description, length (mm), fineness (dtex) and composition. Acrylic fiber is labeled as A and polyester fiber is referenced as P.

The difference between the acrylic fibers (A1, A2 and A3) lies largely in the fineness and the length of the fiber, while the main difference between the polyester fibers (P1, P2 and P3) is based on the presence and geometry of holes. The hollow polyester fibers (P1 and P2) are used in some applications, such as for improving the resistance of fabrics, due to the higher fiber surface/volume ratio.[18] Several researchers have

Table 1. Reference and technical information for the six fibers (acrylic and polyester)

Reference	Description	Length (mm)	Fineness (dtex)	Composition	Type of fiber
A1	Neochrome BR	63	3.3	Acrylic	Solid
A2	Neochrome MT	63	5.4	Acrylic	Solid
A3	Negro BR	37	5.4	Acrylic	Solid
P1	HCS	32	7.8	Polyester	Hollow (10 holes)
P2	HCSh	32	7.8	Polyester	Hollow (one hole)
P3	NHCS	32	7.8	Polyester	Solid

A: acrylic fiber; P: polyester fiber.

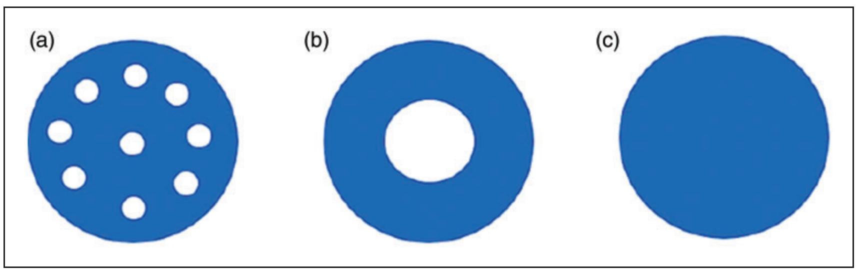

Figure 2. Cross-sections of polyester fibers: (a) P1; (b) P2; (c) P3.

focused on the analysis of the influence of hollow polyester fibers on the mechanical properties.[19,20] Here, we investigate the influence of the hollow section of the fibers in the acoustic behavior.

Figure 2 shows cross-sections of the three polyester fibers presented in Table 1. The P1 polyester fiber has 10 holes, P2 has a unique central hole and P3 has no holes.

Three microscope images of the polyester fibers are shown in Figure 3. In this study, fibers were examined with a suitable accelerating voltage of 10 kV and 2000× magnifications. Fibers were frozen to –19°C before being cut. Due to the fiber shear deformation, the cutting changes their circular shape to an irregular or oval shape, as shown in Figure 3.

Fiber preparation

In this work, different test specimens were prepared from the fibers shown in Table 1. The preparation of the fibers was divided into two parts. In the first part, the fibers were cut into smaller sizes to facilitate the handling process. In the second part, after the fibers were cut into smaller sizes, three samples with different fiber content (low, medium and high density) were made for each type of fiber. Specifically, there were nine acrylic fibers using a thickness (total length) from 3.8 to 6.5 cm, (see Table 2) and nine polyester fibers using a thickness from 4 to 7 cm (see Table 2). The thickness values selected for the fibers are typical of porous or fibrous materials, which are used as acoustic absorbent materials or part of acoustic solutions.

Table 2 shows the physical properties of the acrylic and polyester fibers. Each test is performed with three samples with identical thickness using the same mounting conditions with the aim of reducing the dispersion error produced by the inhomogeneity of the fiber material.

Methods: sound absorption coefficient at normal incidence

The sound absorption properties of fibers were characterized by using the impedance tube method. The sound absorption coefficient at normal incidence is obtained with the two-microphone technique according to the standard ISO 10534-2,[21] which is based on the transfer-function method. This test method requires two microphones ($^1\!/_2$-inch free-field Brüel and Kjær – type 4190), a digital system (Pulse LabShop v.22.2.0.197), a PC for the signal treatment and a sound source (Beyma CP800Ti loudspeaker). In the impedance tube used in this work, the measurements cover the frequency range from 100 to 3150 Hz. These frequencies are established by the restrictions imposed by the distance between both microphones, the precision of the signal processing equipment and the inner diameter of the impedance tube. The impedance tube is a rigid methacrylate duct with a circular cross-section of 4 cm. The material under test is a fiber (acrylic or

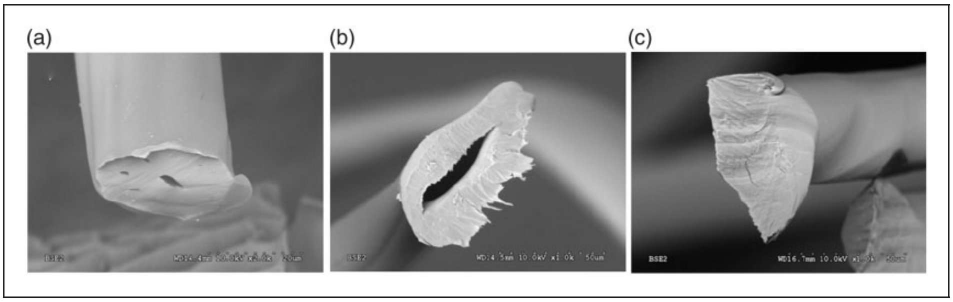

Figure 3. Cross-sections of polyester fibers: (a) P1; (b) P2; (c) P3. The area of the hole of the cross-section of the P2 fiber seems to be visually larger than the cross-sectional area of the 10 holes of the P1 fiber, but this optical effect is due to shear deformation of the fiber.

Table 2. Specifications of acrylic and polyester fibers

Type	Thickness (cm)	Physical density (kg/m^2)	Type	Thickness (cm)	Physical density (kg/m^2)
$A1_{1.3g}$	3.80 ± 0.20	0.94 ± 0.10	$P1_{1.3g}$	4.00 ± 0.15	0.94 ± 0.01
$A1_{3.2g}$	4.30 ± 0.25	2.31 ± 0.24	$P1_{3.2g}$	5.00 ± 0.20	2.31 ± 0.04
$A1_{6.4g}$	6.50 ± 0.80	4.62 ± 0.31	$P1_{6.4g}$	7.00 ± 0.50	4.62 ± 0.15
$A2_{1.3g}$	4.00 ± 0.15	0.94 ± 0.10	$P2_{1.3g}$	4.00 ± 0.20	0.94 ± 0.05
$A2_{3.2g}$	4.50 ± 0.20	2.31 ± 0.25	$P2_{3.2g}$	5.00 ± 0.30	2.31 ± 0.32
$A2_{6.4g}$	5.50 ± 0.50	4.62 ± 0.49	$P2_{6.4g}$	6.50 ± 0.50	4.62 ± 0.22
$A3_{1.3g}$	3.80 ± 0.30	0.94 ± 0.11	$P3_{1.3g}$	4.00 ± 0.30	0.94 ± 0.09
$A3_{3.2g}$	4.30 ± 0.20	2.31 ± 0.28	$P3_{3.2g}$	4.00 ± 0.40	2.31 ± 0.03
$A3_{6.4g}$	6.50 ± 0.50	4.62 ± 0.39	$P3_{6.4g}$	5.00 ± 0.45	4.62 ± 0.12

A: acrylic fiber; P: polyester fiber.

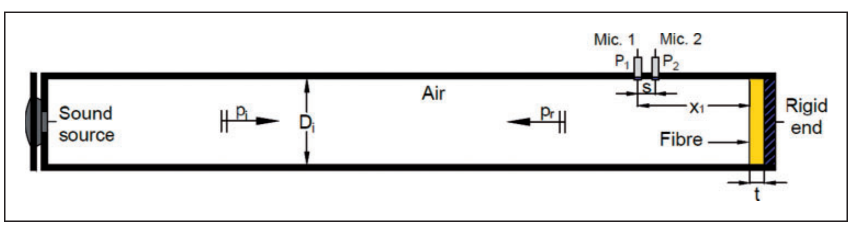

Figure 4. Scheme of the acoustic impedance tube used to measure the sound absorption coefficient at normal incidence of the fibers. Here, D_i is the inner diameter of the tube ($D_i = 4$ cm); t is the fiber thickness, x_1 is the distance between Mic. 1 and the fiber; p_i is the acoustic pressure of the incident wave; p_r is the acoustic pressure of the reflected wave; and s is the separation between both microphones ($s = 3.2$ cm).

polyester) and it is placed at the end of the impedance tube rigidly backed, as shown in Figure 4.

In the two-microphone technique,[21] complex acoustic pressure is registered in both microphones in order to calculate the complex acoustic transfer function (H_{12}), as

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{jk_0x_2} + re^{-jk_0x_2}}{e^{jk_0x_1} + re^{-jk_0x_1}} \quad (1)$$

where $k_0 = 2\pi f/c_0$ is the wave number, f being the frequency and c_0 the speed of sound in air (in our case, $c_0 = 340$ m/s), r is the complex acoustic pressure reflection coefficient and x_2 and x_1 are the distance between the fiber and the microphone placed farther from and closer to it, respectively.

The complex acoustic pressure reflection coefficient, r, for a plane wave at normal incidence can be obtained from Equation (1) as

$$r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1} \quad (2)$$

where $H_I = e^{jks}$ is the sound pressure transfer function of the incident wave, $H_R = e^{-jks}$ is the sound pressure transfer function of the reflected wave and s is the separation between both microphones (in our study, $s = 3.2$ cm).

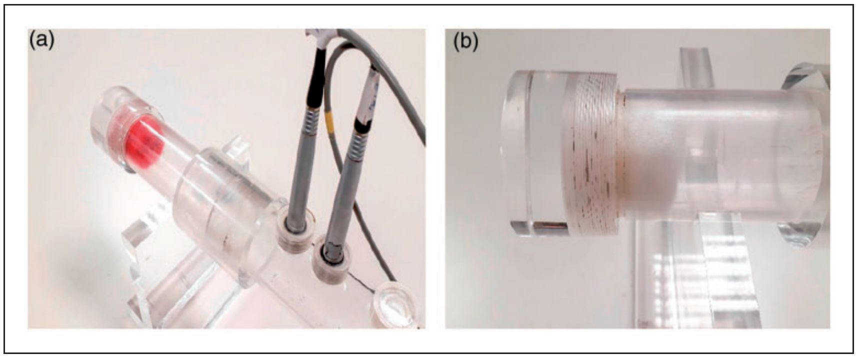

Figure 5. Detail of the end of the impedance tube used to measure the sound absorption coefficient at normal incidence, including samples of (a) A1 fiber and (b) P1 fiber.

Once the complex reflection coefficient has been calculated, the normal incidence sound absorption coefficient is obtained from its definition in a reflection configuration as

$$\alpha = 1 - |r|^2 \tag{3}$$

The sound absorption coefficient as a function of frequency is the relevant magnitude to characterize the ability to absorb acoustic energy of the material under test, but often an average value in octave frequency bands of the absorption coefficient is expressed. Figure 5 shows detail of the end of the impedance tube with the two microphones. Fibers are not arranged like woven or nonwoven textiles, but they are organized in a cylindrical shape inside the sample holder of the impedance tube for sound absorption tests at normal incidence.

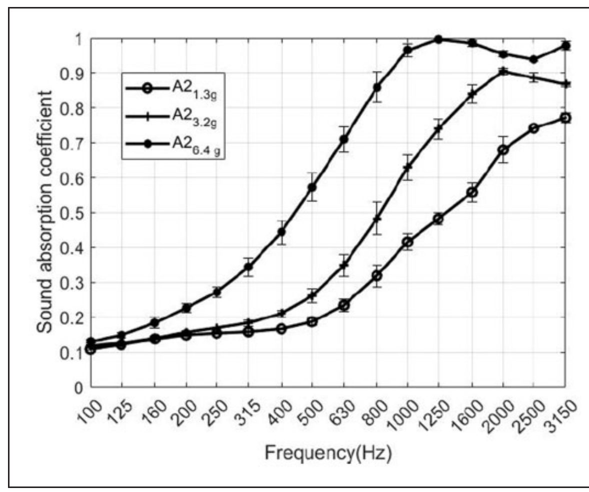

Figure 6. Sound absorption coefficient at normal incidence of A2 acrylic fiber with different fiber contents.

Results and discussion

In this section, the experimental results are presented and analyzed. In the first study, the influence of the fiber fineness on the sound absorption is presented using different acrylic fibers with the same length. Next, the effect of the fiber length on the sound absorption coefficient using acrylic fibers is analyzed. Subsequently, the results of three polyester fibers with different transverse sections (solid/hollow) are presented to investigate its influence on the acoustic behavior. Finally, the average sound absorption coefficient in the working frequency range of fibers (acrylic and polyester) is presented to show their overall acoustic behavior.

Fiber fineness

The results of fibers with the same length (63 mm) and composition (polyacrylonitrile) are presented and compared. The significant parameter of these fibers is the fiber fineness: A1 fibers have a fineness of 3.3 dtex whereas A2 fibers have a fineness of 5.4 dtex.

In Figure 6, the sound absorption coefficient at normal incidence measured in the impedance tube of three A2 acrylic fibers with different fiber content (low, medium and high density) is shown. It can be seen that the maximum absorption gradually increases and shifts towards low frequencies as the fiber content increases. A2 fibers have been taken as reference for the study as they have the same fiber length (63 mm) as A1 fibers and they have the same fineness (5.4 dtex) as A3 fibers. Figure 7 shows the sound absorption coefficient difference of both A1 and A3 fibers with respect to the reference A2 fibers for each fiber content. Note that the ordinates axis is not restricted to positive values, as differences of sound absorption coefficients are plotted. Figure 7(a) shows the clear influence of the fiber fineness on the sound absorption coefficient: A1 fibers present lower values of the sound absorption coefficient at normal incidence than A2 fibers, as all experimental points of the difference are positive values.

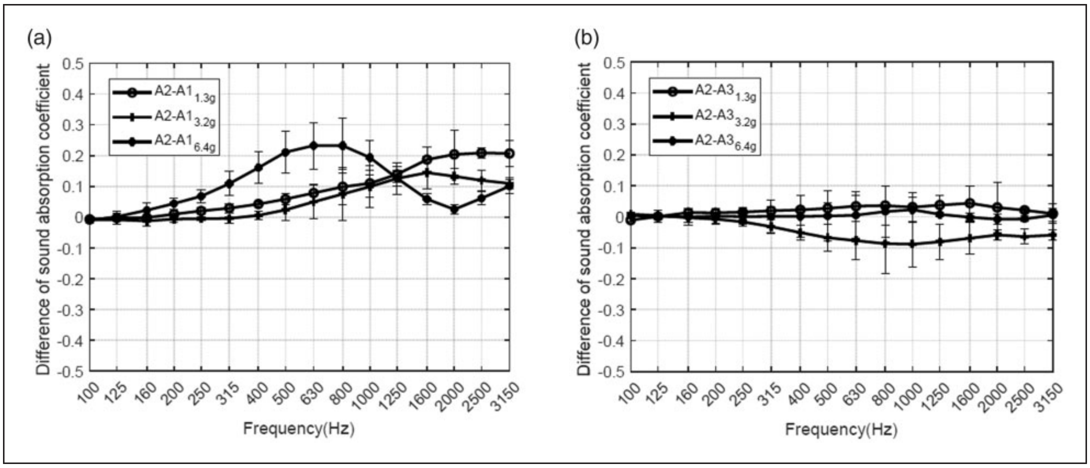

Figure 7. Difference of sound absorption coefficient at normal incidence of acrylic fibers with different fiber contents to observe the influence of (a) fiber fineness and (b) fiber length.

Consequently, from these results, it can be inferred that the increase in the fineness of acrylic fibers increases the sound absorption coefficient in the whole working frequency range. This effect can be observed disregarding the different fiber content of the acrylic fiber analyzed (low, medium and high density). However, the difference is higher at lower frequencies for denser fibers. We can assert that fiber fineness is an important parameter to enhance the sound absorption in the mid frequency region (above 400 Hz).

Fiber length

In this section, acrylic fibers with the same composition (polyacrylonitrile) and fineness (5.4 dtex), but with different lengths are presented and analyzed. As in the previous section, A2 acrylic fibers are taken as the reference. In Figure 7(b), the difference of the sound absorption coefficient at normal incidence of A3 acrylic fibers with respect to A2 fibers is presented. In this case, the significant parameter to be analyzed is the fiber length, as A2 fibers are 63 mm long and A3 fibers are 37 mm long. By comparing Figures 7(a) and (b), it can be noted that the fiber length has less influence on the sound absorption than fineness. In fact, the differences in Figure 7(b) are smaller than 0.1 for all frequencies. Moreover, the sound absorption coefficient differences have positive and negative values for different fiber contents, showing that there is not a clear tendency. The maximum difference between both fibers is observed for a medium fiber content (3.2 g), but no clear conclusions can be drawn with regard to the influence of the fiber length on the sound absorption coefficient. Thus, these results do not permit one to assume that the length of acrylic fibers has a significant effect on the sound absorption.

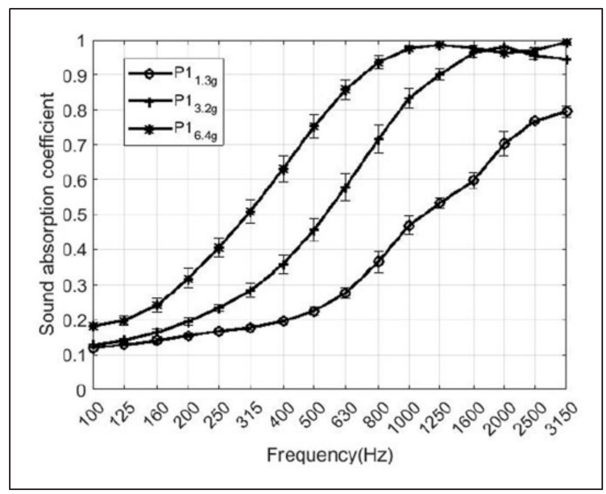

Figure 8. Sound absorption coefficient at normal incidence of P1 polyester fiber with different fiber contents.

Hollow cross-section

We are here interested in evaluating the effect of the cross-section of the fibers on the sound absorption. For this purpose, fibers presenting two different hollow patterns and solid (not hollowed) fibers are analyzed and compared. P1 polyester fibers with 10 holes in the cross-section have been chosen as the reference. Figure 8 shows the sound absorption coefficient at normal incidence of these fibers with different fiber contents. The maximum absorption gradually increases and shifts towards low frequencies when the fiber content is increased, that is, the same tendency as the fineness fiber with frequency.

In Figure 9(a), P1 (10 holes) and P2 (unique central hole) hollow fibers are compared. No significant differences are observed between the sound absorption

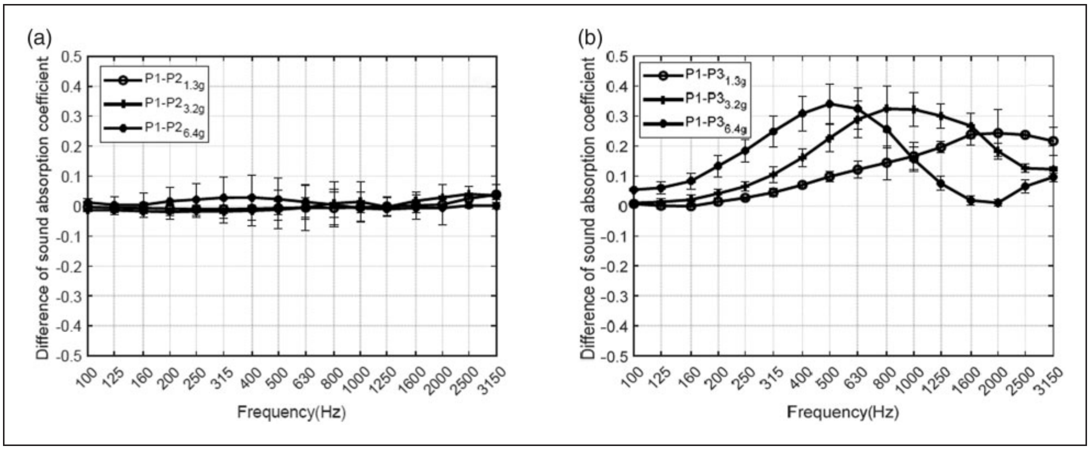

Figure 9. Difference of sound absorption coefficient at normal incidence of polyester fibers with different fiber contents to observe the influence of the hollow cross-section: (a) hollow fiber (P1/10 holes) is compared to hollow fiber (P2/1 hole); (b) hollow fiber (P1/10 holes) is compared to solid fiber (P3/no holes).

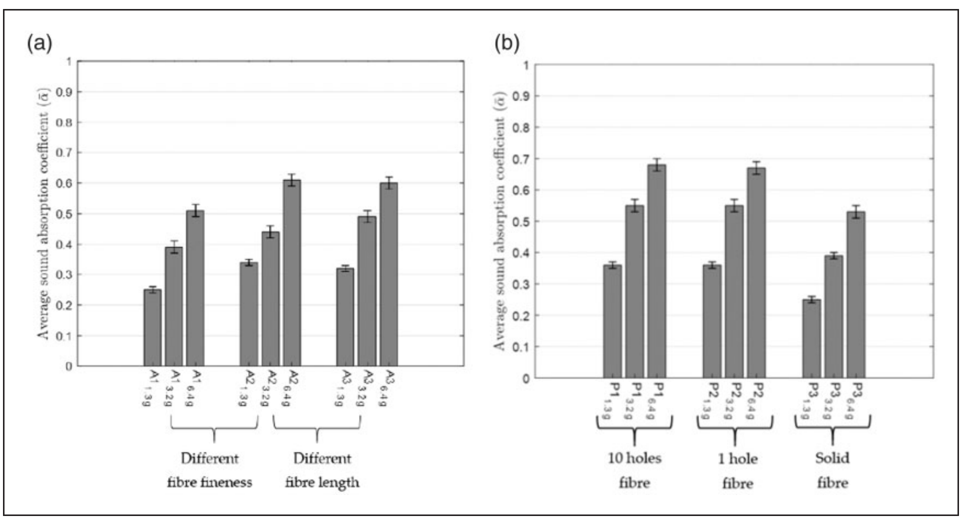

Figure 10. Average sound absorption coefficients of (a) acrylic and (b) polyester fibers. The dispersion percentage is presented in order to study the variability of the data, and it is expressed as error bars for each fiber.

values of both hollow fibers that present different hole distributions. Note that the hollowed area is the same in both fibers (0.1 mm^2). Thus, these results show that the specific distribution of the hollowed surface of the cross-section of the fiber or the number of holes do not affect the sound absorption. However, the presence of holes is important, as shown in Figure 9(b), where hollowed fibers (P1/10 holes) are compared to solid fibers (P3/no holes).

In Figure 9(b), it can be seen that the differences in the sound absorption coefficient between hollow/solid fibers are greater than 0.3 for certain frequencies. Hollowed fibers present a higher sound absorption coefficient than solid fibers in the entire working frequency range for all fiber contents. This effect is more important for higher frequencies in fibers with less fiber content. Thus, it can be concluded that using hollowed fibers instead of solid fibers can have a significant effect on the acoustic behavior, but the specific distribution of the holes in the cross-section of the fiber is not relevant.

Average sound absorption coefficient

The average sound absorption coefficient ($\bar{\alpha}$) has been computed for all fibers. It is defined as the average of the absorption coefficients in frequency bands and it is obtained as $\frac{1}{n}\sum_{i=1}^{n}\alpha_i$, where $n = 16$ is the number of the one-third octave bands. Figures 10(a) and (b) show the average sound absorption coefficients between 100 and 3150 Hz for acrylic and polyester fibers, respectively. It is observed that the $\bar{\alpha}$ values of both fibers (acrylic and polyester) lie in the range of 0.25–0.68. In all cases, fibers with higher fiber content present a higher average sound absorption coefficient. In general, acrylic fibers show lower sound absorption coefficient values in comparison to hollowed polyester fibers.

Conclusions

In this work, the influence of the macrostructural parameters, such as fineness, length and cross-section (solid or hollow), on the average sound absorption coefficient at normal incidence has been analyzed. The fineness of the fibers has a significant influence on the acoustic behavior of the fibers under test. The effect of fineness can be observed for fibers with the same length and composition, where the use of different fiber contents is not influential. It has been possible to demonstrate that, for the fibers evaluated, the higher the fineness of the fiber, the better the acoustic properties are obtained throughout the working frequency range.

The length of the fibers does not show changes in sound absorption. The results were analyzed for fibers with the same composition and fineness, but no significant influence of length was observed on the sound absorption. This may be due to the fact that the acoustic effect caused by the length of the fibers saturates for a certain length; therefore, in this case, in order to observe an effect on the sound absorption, a greater spectrum of dimensions in length would have to be used, considering shorter fiber lengths.

In the hollow cross-section of the fiber, there are no significant differences between fibers that have 10 holes and fibers that only have a single central hole in their internal structure. This may be because the cross-sectional hole area of the fibers is similar. However, if both hollow fibers are compared with solid fibers, that is, without holes, differences in sound absorption can be observed. The results obtained differ from those presented by Campeau et al.[22] On the one hand, this could be due to the fact that fibers of different origin have been used and, in our case, the fibers were organized in a cylindrical way in the sample holder of the impedance tube; on the other hand, in Campeau et al.[22] the fibers of the nonwovens were randomly arranged in parallel planes. Hollow fibers have greater sound absorption than solid fibers throughout the frequency range and for all fiber contents (low, medium and high density). Therefore, it is shown that, with a lower quantity of hollow fibers, the material exhibits an acoustic behavior similar to that of solid fibers.

It can be concluded that the fiber parameters are really important from the acoustic point of view, because a certain value of sound absorption can be obtained. Therefore, this is a significant aspect for textile-based solutions.

Declaration of conflicting interests

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