Sound absorption of textile fabrics doped with microcapsules

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Abstract

The use of microcapsules is increasing in the textile industry and play an important role in the field of acoustical porous materials in order to adopt solutions for the control of noise. In this work, we present an experimental study of the acoustic effect of woven textile fabrics doped with microcapsules by using the padding technique. For this purpose, measurements with the fabric backed by an air-cavity or by a rigid wall in the impedance tube have been done. A comparative analysis of acoustic effect by using cotton fabrics with the same yarn density but different doping percentage is presented. We have investigated the influence of the sound damping effect of doping six different textile woven fabrics with the same concentration of microcapsules. The results show that the variation on the sound absorption coefficient of doped woven fabrics depends on the type of fabric, the concentration of microcapsules and the experimental setup.

Keywords: sound absorption; microcapsules; padding technique; woven fabrics;

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1. Introduction

The acoustic pollution generated by human activities has experienced a drastic increase in recent years affecting a large part of society and the environment, as specified by the World Health Organization (WHO) [1]. According to the Organization for Economic Co-operation and Development (OECD) [2] and the European Environment Agency (EEA) [3], the effect of noise pollution is one of the biggest environmental problems today because noise and vibrations have both physiological and psychological effects on human health [4]. Some examples of these problems, on humans, due to the high levels of noise are permanent hearing loss, sleep disturbance, less blood supply, decreased working capacity, fatigue, stress, cardiovascular disorders, tachycardia and pupil dilation. Public concern continues

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due to these adverse effects caused by noise pollution. In order to avoid these, and in accordance with the Action 5 of the EU Framework Program for Research and Innovation (HORIZON2020), new acoustic solutions to mitigate noise must be found from new economic and sustainable materials [5]. The new European program (HORIZON2030) will be in operation by the end of 2020 [6]. The Sustainable Development Goals (SDGs) of this program, in particular, the SDG12 reinforces the need to reduce, recycle and reuse waste in search of sustainable development.

Traditionally, materials difficult to recycle based on rockwool and fiberglass have been used to mitigate high noise levels [7]. Nowadays, research is oriented to new and innovative materials [8–12] that are respectful with the environment [13]. The use of wastes as acoustic and/or thermal insulating materials is a goal under study. Maderuelo-Sanz et al. showed in [9] a novel sound absorber made from end of life tyres useful to reduce noise pollution in building construction. Del Rey et al. [10] proposed to control noise using recycled polyurethane foam. These new materials have useful sound absorbing properties and they are a viable alternative to traditional materials for practical applications.

Another valid alternative to traditional solutions is the use of waste materials from manufacturing processes in the textile industry, in combination with natural fibers or other types of fibers. For that purpose, different techniques such as knitting, weaving or nonwoven are used [14, 15]. The acoustic properties of fabrics may vary depending on the method of preparation, their nature, fibers and pore treatment, yarn density and humidity conditions [16]. The acoustic properties of the textile materials also depend on the mechancial characteristics of the fabric and the manufacturing process. Bies et al. showed in [17] that the most important parameter to determine how a fabric acts as a sound absorbing material is the airflow resistance. Specific fabric features like the twisting of the weft yarn and the density of the fabric selection also have an influence in the porosity and the air permeability of the fabric as acoustic material [18]. The most used textile structure for acoustic applications is the nonwoven, but for lack of aesthetic appeal they are usually covered with woven fabrics in order to produce a pleasant appearance [19]. In general, these textile woven fabrics can be considered thin compared to the wavelength in the frequency range up to 3.15 kHz and can be acoustically characterized as a permeable membrane [20, 21]. Pieren et al. used in [21] thin fabrics that have a membrane-type acoustic response in their sound absorption models. The sound absorption properties for thin and lightweight fabrics is affected by sound-induced vibrations [22, 23]. Sakagami et al. presented in [22] a detailed analysis of the acoustic properties of a permeable membrane and they proposed theoretical methods to take the vibration effect of the membrane into account.

Numerous previous studies can be found in the literature about the acoustical properties of woven textile materials [24]. In 1990, Shoshani et al. showed in [25] that some intrinsic parameters analyzed of nonwoven fiberwebs and woven fabrics, like number of fiberweb layers, fiber contents and the opening angle between individual panels, have a small effect on the sound absorption coefficient at low frequencies ($f < 0.5$ kHz), but a significant impact at high frequencies (around $f = 4$ kHz). Due to the practical interest of using textile materials, new solutions have been investigated to increase the overall sound absorption of fabrics. In 2007, Na et al. [26] showed that microfiber fabrics have higher sound absorption than tradicional textile fabrics due to its great surface area, resulting in higher airflow resistance. In 2012, Soltani et al. demonstrated in [27] that plain weave fabrics absorb more sound than other weave types due to several reasons: these have a great number of yarn intersections, a short free float length, severe crimping of the yarns in the plain weave and higher yarn density. In the same year, Ekici et al. presented in [28] a new sound absorbent material made of tea-leaf fibers and luffa cylindrica with polyurethane foam and by increasing the tea-leaf-fibers, the sound absorption values for all frequency ranges improved. The motivation for the research of new sound absorbing materials is not only in the field of acoustic conditioning, but also in the field of acoustic insulation. In 2015, Reixach et al. investigated in [29] composite materials made of fibers from orange tree pruning reinforced polypropylene in order to obtain airborne insulation solutions. Recently, Naghmouchi et al. studied in [30] a new natural fiber-based composite material made with olive stone flour reinforced polypropylene as a solution for airborne isolation. The results showed that for frequencies below 0.63 kHz third octave, this new material shows similar soundproofing properties compared to gypsum boards.

New advances in acoustic textiles have increased their use exponentially in numerous areas of application, particularly in new technological advances [31]. Textile fabrics are used in public spaces, such as theaters, museums, opera houses and other cultural spaces in order to improve the indoor sound quality by using curtains and carpets [32–34]. The evolution of textile engineering last years has brought new mechanisms and solutions to confer new properties to textile fabrics as for example Chevillotte who studied in [35] the way of controlling sound absorption of a porous media by adding an upstream resistive layer of glass screen. The results revealed an improvement of sound absorption at low frequencies and lately, Segura-Alcaraz et al. investigated in [36] the best combination fabric-nonwoven and results showed a good interaction between both of them obtaining thermal effects of the nonwoven and resonant effects of the fabric that cause a variation in the sound absorption coefficient. At higher density of yarns in the fabric, the sound absorption increases and the resonance peak shifts to low frequencies.

In the textile engineering, Nelson, G. considered the use of microcapsules (MCCs) applied on textile fabrics for the first time [37]. MCCs are micrometric particles composed of one or more active ingredients [38–40]. They are formed by a membrane (outer layer) that encompasses the active compound in the nucleus [41]. Microencapsulation is used to alter the physical properties of the volatile substance used in order to make it more manageable and to protect it from multiple external factors such as sunlight, evaporation, humidity, alkalinity, unwanted rubbing action or the combination between them [42]. The most known industrial methods for adhering microcapsules to textile fabrics are bath exhaustion, padding, spraying and coating. MCCs adhere to textile structures using a binding agent. The acoustic effect of MCCs adhered to fabrics has been shown in a previous work [43]. Few recent studies have been consacrated last decades to the use of microparticles for acoustical purposes [44–48]. However, the physical mechanism involved in the sound absorption related to the adhesion of MCCs is not still well known. One of the reasons is that sound absorption depends on many factors of different nature like the size of MCCs, the hosting material or the doping technique. Zhou et al. presented a polyurethane foam (PU) composed of polymer microparticles of size from 0.1 μm to 1 mm [49]. They show that the size of polymer microparticles have an influence on the absorption peak frequency. Indeed, at low frequencies, the sound absorption coefficient of PU foam with microparticles is higher than traditional PU foams, with the same thickness. The same authors studied the acoustic properties of hollow polymeric multiporous microspheres with different porous structure [50]. The results revealed a high sound absorption at high frequencies in comparison with granular materials of the same thickness when the density value of the microspheres is increased and the porosity is increased. Also Cheng et al. [51] observed a big absorption at high frequencies in a foamed cellulose-polymer material formed from microspheres. Few works can be found in literature accounting for the effect of MCCs in textile fabrics as acoustic materials. Zhi et al. [52] studied the sound absorption of a synthetic foam reinforced with spacer fabric. Authors analyze the effect on sound absorption of adding microspheres to it, showing that a great influence on the propagation of sound waves. When the microspheres content decreases, the first resonance frequency shifts to the higher frequency range and it has little influence on the value of peak sound absorption coefficient.

In this work, the effect of doping different textile fabrics with microcapsules on the sound absorption coefficient is analyzed. Depending on the type of fabric and the MCCs concentration, the damping effect on the sound absorption of doped textil materials is shown. A comparative analysis between a cotton fabric (CO) with different MCCs concentration and the same non-doped fabric is presented. Experimental results are shown in both, back-end and air-cavity impedance measurements. The influence of the type of fabric is analyzed by doping different textile fabrics with the same technique described above and with the same MCCs concentration.

2. Experimental

2.1. Materials

Different types of fabrics were tested. The first one referenced as T1 is comprised of polyester yarns and a weft yarn of blue chenille with a ratio one chenille two polyester, which creates the bubble effect and increases the thickness. Textile fabrics labeled as T2, T3 and T5 were also comprised of polyester yarns but without chenille, their colour effect was obtained by printing on the fabric surface, even the flat colours. In particular, T3 is printed with simple designs employing one or more colours and it has a rough texture and both T2 and T5 are made with a soft face on one side and with a slight texture on the other. The difference between the two woven fabrics are in dyeing and grammage. The next one referenced as T4, was also made of 100% polyester fibers, without chenille yarns nor printing colour designs were created by jacquard weaving and the last one referenced as T6 is comprised of polyester yarns and a yarn of pink chenille gives the fabric the thickness.

Reference CO corresponds to fabric made of 100% cotton fibers, which was chemically bleached. The cotton sample was a twill weaved fabric and no chenille was included.

The surface mass density of the textile fabrics under study is presented in Table 1 and in Table 2.

2.2. Preparation and characterization of the doped fabrics

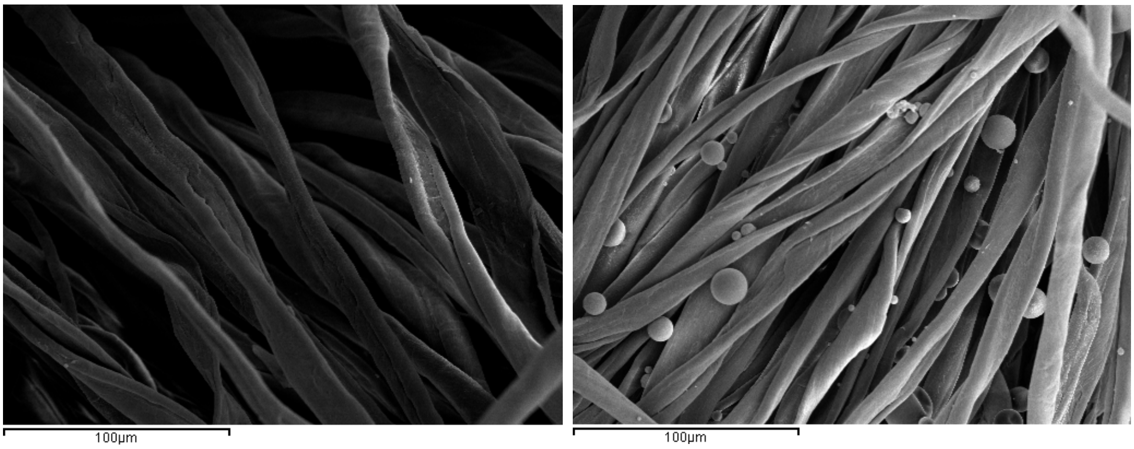
During the microencapsulation process, the shape, size, durability, permeability and wall properties of the MCCs are considered. One of the most important characteristics that determines the purpose of microcapsules is permeability. Often, a solid and insoluble waterproof membrane shell (natural polymer) is used to isolate the active principle in liquid form and in order to protect it from environmental factors, thus converting a liquid substance into a solid state.

Padding is an impregnation technique to adhere MCCs onto the textile fabrics surface. It consists of a rapid immersion process of the textile sample and two squeezing rolls press the liquid from both sides in the treatment bath, to force the liquid to pass through the fibers. The padding process was made with a horizontal foulard (2608 TEPA). The squeeze roll speed and pressure were regulated in order to achieve 80% wet pick-up (percentage of bath absorbed by the textile fabric) [53].

The doping process of the different textile fabrics was carried out by using microcapsules containing Lavender essential oil fragrance, which were supplied by InnovaTec S&C S.L. and its size varies from 1 μm to 8 μm in order to avoid agents which can interfer. No binder was added.

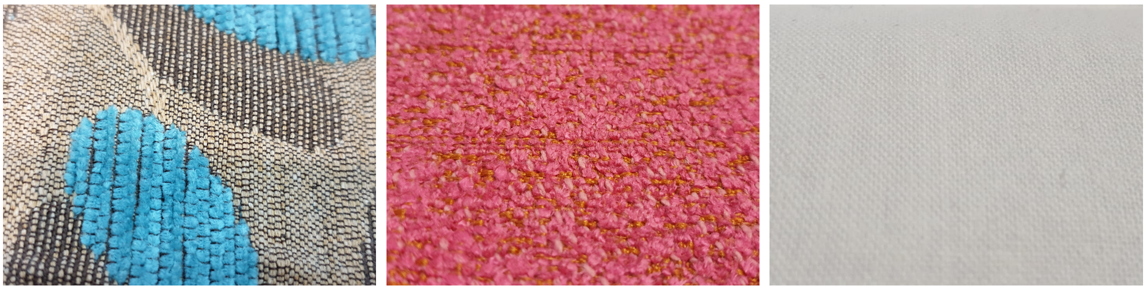
In this work, one of the baths was comprised of MCCs in distilled water with 100 g/L MCCs concentration for all fabric samples and other bath, different cotton samples were prepared with different MCCs concentration: 25 g/L, 50 g/L and 100 g/L. To complete the adhesion process between fibers and MCCs, the CO samples were dried in a horizontal infrared dryer during 180 s at a temperature of 105° C. The rest of the fabrics were treated with 100 g/L MCCs concentration.

MCCs, due to its micrometric size, are imperceptible to the human eye. Field Emission Scanning Electron Microscope (FESEM) mod. ZEISS ULTRA55 was used to observe the surface of the fabrics with high resolution. With this technique, it is possible to visualize the shape of the membrane of each microcapsule (smooth or rough), their structure, their size and their location [54, 55]. In this study, CO samples were examined with suitable accelerating voltage of 2 kV and 2000X magnifications (see Fig.1a and Fig.1b). In order to make them conductive, and observe them by SEM, previously the samples were fixed on a standard sample holder and the sputter-coated with a thin



(a) Undoped CO **(b)** CO doped 25 g/L

Figure 1. FESEM micrographs of cotton fabrics. (a) Sample surface of undoped CO before impregnation treatment; (b) CO doped with 25 g/L concentration of microcapsules.



(a) T1 **(b)** T6 **(c)** CO 100 g/L

Figure 2. Some of the textile fabrics analyzed. (a) Undoped T1 (1.8 mm thickness); (b) Undoped T6 (1.4 mm thickness); (c) CO doped with 100 g/L concentration of microcapsules (0.2 mm thickness).

film of gold/platinum metal under vacuum conditions. This process was done in a Sputter Coater BAL-TEC mod. SCD005.

2.3. Methods

The textile samples are characterized acoustically either experimentally by using the same parameters as Chen et al. in [56] or by elaborating predictive models [57, 58]. In the Materials Laboratory of the Higher Polytechnic School of Gandia, measurements of textile fabrics (see Fig.2) have been carried out in order to characterize them acoustically by using two classical techniques: 1) the Standard ISO 10534-2:1998 [59] in order to calculate the normal incidence sound absorption coefficient (α) and 2) the Ingard&Dear method (1985) [60] in order to obtain the specific airflow resistance (R_s).

2.3.1. Sound absorption coefficient

The sound absorption coefficient (α_n) of the samples is measured according to the transfer function method described in the Standard ISO $10534-2:1998$ [59]. This test method requires an impedance tube, a digital signal analysis system

(Pulse LabShop v.22.2.0.197) and two microphones. Measurements are performed by using a sound source mounted in an isolated box (Beyma CP800Ti loudspeaker) placed to one end of the acoustic impedance tube and the textile fabric samples under study at the other end (see Fig.3). The sound source generates plane waves inside the impedance tube hitting the material perpendicularly. Free-field Brüel and Kjær pressure microphones (type 4190 1/2-inch) are mounted on the wall, in fixed positions close to the sample. The acoustic pressure is recorded in order to calculate the normal incidence sound absorption coefficients. The impedance tube is a rigid, methacrylate, smooth, transparent and airtight duct with circular cross section, which meets the specifications described in the standard [59].

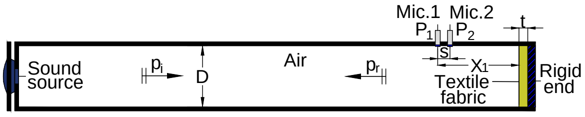


Figure 3. Scheme of the impedance tube used to measure the normal incidence sound absorption coefficient. D is the tube inner diameter (D = 4 cm), t is the thickness of the textile fabric, p_i is the sound pressure of the incident wave and p_r is the sound pressure of the reflected wave.

The working frequency range is from 0.1 kHz to 3.15 kHz due to restrictions impose by the distance between microphones, by the precision of the signal processing equipment and by the tube inner diameter [59]. Three test specimens from each configuration were prepared for the experiment in order to provide an acceptable uncertainty of measurements based on the material variability, cutting variability and other experimental factors.

The sound pressure transfer function (H_{12}) [59] is determined with the application of the two-microphone method in order to calculate the complex reflection coefficients (r) given by Eq.1 as follows:

$$r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1}, \qquad (1)$$

where $H_I = e^{jks}$ is the sound pressure transfer function for the incident waves, s is the distance between both microphones (s = 3.2 cm), $H_R = e^{-jks}$ is the sound pressure transfer function for the reflected waves, k_0 is the wave number, $j = \sqrt{-1}$ and x_1 is the distance between the corresponding microphone and the measured textile fabric.

The microphone spacing (s) introduces small inter-channel differences of the phase information contained in the data recorded. For this reason, the two-channels are exchanged for each measurement.

Finally, the absorption coefficients are calculated from Eq.1 as

$$\alpha_n = 1 - |r|^2. \qquad (2)$$

This testing method described in this section is valid for both configurations, the sample at the end of the impedance tube and backed by an air-cavity. In this last configuration, there is a theoretical model to predict the sound absorption at normal incidence of thin textile fabrics [57, 58]. In order to acoustically characterize the textile fabric, the model requires as input parameters its specific airflow resistance R_s (Pa · s/m) and its surface mass density m (kg/m^2). The normal incidence sound absorption coefficient can be calculated by using the surface impedance of the absorbent structure Z_{in}, which is described by impedance of fabric Z_s in series with the surface impedance of the air-cavity Z_c as follows:

$$Z_{in} = Z_s + Z_c = \frac{R_s(\omega m)^2}{R_s^2 + (\omega m)^2} + j\frac{R_s^2(\omega m)}{R_s^2 + (\omega m)^2} - jZ_0 \cot(k_0 D), \tag{3}$$

where Z_s is the impedance of the fabric and Z_c is the impedance of the backing air gap (cavity) being D the air gap depth, $Z_0 = \rho \cdot c$ is the air characteristic impedance, ρ is the air density (kg/m^3), c is the speed of sound in air (m/s), ω is the angular frequency and k_0 is the wave number.

From Eq.3, Z_{in} is used to calculate the normal incidence sound absorption coefficient by

$$\alpha_n = 1 - \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right|^2. \tag{4}$$

In this model, the fabric is assumed to be acoustically thin, which means the thickness is much smaller than the wavelength of sound. In our work, this condition is fullfilled for all the fabrics in the frequecy range up to 3.15 kHz. It is also considered that sound absorption occurs mainly inside the fabric and dissipative effects inside the air-cavity are neglected.

2.3.2. Airflow resistivity

Airflow resistivity (σ) is also measured in order to evaluate the difficulty of an air stream to flow through the fabric per unit thickness. The experimental setup is based on the indirect method proposed by Ingard&Dear that allows to obtain the value of the specific airflow resistance under certain limitations [60].

The rigid methacrylate tube has a circular cross section with an internal diameter of 4 cm, the total length of the tube is 169 cm and the distance between the first microphone and the rigid end is 84.5 cm. The sample thickness, t, is placed in the middle of the impedance tube. L is the distance between the back face of the fabric sample and the rigid end. Two microphones are used to measure the difference in sound pressure between fabric material. One of them (Mic. 1) is placed in front of the sample to directly measure the sound pressure (p_1); the other (Mic. 2) is located next to the highly sound-reflective end (p_2) as can be seen in Fig.4:

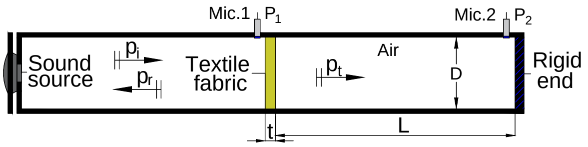


Figure 4. Schematic diagram of the impedance tube used to measure specific airflow resistance by Ingard&Dear method. P_t is the acoustic pressure of the transmitted wave.

According to Ingard&Dear method [60], the normalized airflow impedance for frequencies that satisfy the following condition: $\mathrm{L} + \mathrm{t} = (2n-1)\lambda/4$, where n is an integer number, is expressed as follows:

$$\frac{\mathrm{Z}}{\rho_0 \mathrm{c}_0} = \theta + \mathrm{i}\chi = \mathrm{i}\frac{1}{\mathrm{H}_{12}}(-1)^{\mathrm{n}-1}. \tag{5}$$

From Eq.5, it is possible to obtain the real (θ) and imaginary (χ) part of the characteristic impedance Z as

$$\theta = \left|\mathrm{Im}\left(\frac{1}{\mathrm{H}_{12}}\right)\right|, \tag{6}$$

$$\chi = \mathrm{Re}\left(\frac{1}{\mathrm{H}_{12}}\right)(-1)^{\mathrm{n}-1}, \tag{7}$$

where θ is the airflow resistance and χ is the airflow reactance.

At low frequencies, the airflow reactance is small compared to the airflow resistance doing the following simplification:

$$\theta \approx \left|\frac{1}{\mathrm{H}_{12}}\right|. \tag{8}$$

The average values of the airflow resistivity are obtained by using the absolute value of the imaginary part of the transfer function between the microphone signals as follows:

$$\sigma \approx \left(\frac{\rho_0 \mathrm{c}_0}{\mathrm{t}}\right)\left|\mathrm{Im}\left(\frac{1}{\mathrm{H}_{12}}\right)\right|, \quad \left[\frac{\mathrm{Pa}\cdot\mathrm{s}}{\mathrm{m}^2}\right]. \tag{9}$$

3. Results and discussion

The doping process is determined by several factors like the type of doping, the concentration of MCCs, the size of MCCs and the type of fabric. Due to the complexity of the problem and the high number of variables involved in the analysis, the following hypotheses have been assumed:

- The padding technique has been used to dop the samples with MCCs of size from 1 μm to 8 μm. The MCCs size distribution is identical in all dopages [61].
- The measurement process and the number of MCCs adhered to fabrics do not change during the experiments. Washing [62], but also rubbing and vibration [63, 64] of samples can reduce its MCCs concentration. In consequence, care has been taken in handling of doped samples so that they retain their acoustic properties during the measurement process.

3.1. Homogeneity of doping

In the process of doping the woven fabric, all the material is submitted to rapid immersion and it is squeezed. The quality of the treatment must ensure that the sample is homogeneously doped. This implies that the proportion and size of MCCs adhered to the doped material must be spatially distributed. It has been checked here the homogeneity of doping samples by analyzing the acoustic characteristics of different samples of the same cotton fabric. Cotton fabrics have been widely used in the textile industry for its biodegradable natural fiber, permeability, softness, comfort and high wettability [65]. CO fabric samples were obtained with a chemically and optically bleached. It is a twill weaved fabric with 115 g/m^2. Samples have been doped with the padding technique in a bath of distilled water solutions with a 25 g/L MCCs concentration. After doping and drying, sample have been cut in circular shape for the impedance tube characterization.

In Fig.5, the sound absorption coefficient against frequency is shown for three samples of the same cotton material doped with the same technique and concentration of MCCs (25 g/L). Samples are measured in the impedance tube by the air-cavity method. It can be seen that in all cases, the differences in the sound absorption coefficient are smaller than 10% and always below the margin of error of the experimental method. These results ensure the homogeneity of the doping process.

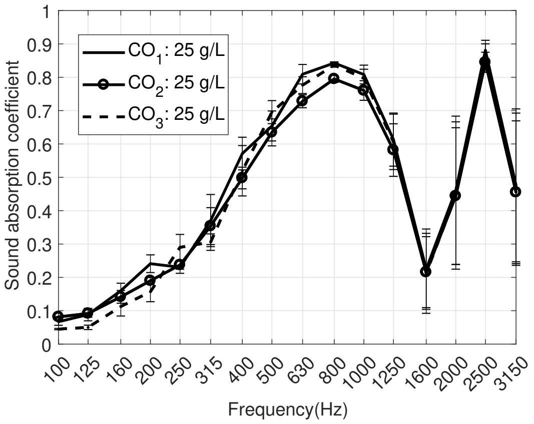


Figure 5. Normal incidence sound absorption coefficient of three cotton samples measured in the impedance tube with an air-cavity of 10 cm. Samples are cut from the same textile fabric doped with the same technique and same concentration of MCCs (25 g/L) to test the repeatability and the homogeinity of the doping process.

3.2. Microcapsules concentration on fabrics

A quantitative study of the concentration of MCCs in doped fabrics is performed here. The lower and upper limits of the concentration values are chosen by the following criteria, respectively: 1) a minimum concentration is required to produce a significant effect on the acoustic behavior of the material and 2) the acoustic effect produced by doping MCCs is expected to saturate. In this way, doping samples with very high values of MCCs concentration do not change their acoustic behaviour. These two values (minimum and maximum) may depend on the type of fabric. However, for simplicity it is proposed here to analyze the effect of concentration with a single cotton sample as a reference and general guide for the rest of textile fabrics.

Four samples of CO with a thickness less than 1 mm have been considered for the study. One of the samples has not been treated (undoped CO). The other three have been doped with the padding technique in a bath of distilled water solutions with the different MCCs concentrations each: 25 g/L, 50 g/L and 100 g/L. Figure 6 shows the sound absorption coefficient of the undoped and doped CO samples by using the air-cavity technique. In all cases, the maximum peak frequency is at 0.8 kHz. The undoped and all doped samples resonate at the same frequency. Thus, MCCs do not change the resonance properties of the material. The sound absorption coefficient is above α =0.5 near the first resonance, from 0.5 kHz to 1 kHz. In this frequency range, an increase of sound absorption is observed for all doped samples. The maximum difference in the sound absorption coefficient between doped and undoped samples is reached at the resonance. A similar behaviour is observed at the second resonance in 2.5 kHz. In CO fabric it is observed that a value of 25 g/L concentration of MCCs is enough to observe a noticeable acoustic effect. Doping CO fabrics changes the acoustic properties of the material. However, concentration of

MCCs in CO fabrics leads to apparently no important differences in their sound absorption performance above 25 g/L. In fact, varying the mechanical and acoustical properties of a material by doping it, induces changes in sound damping, but the effect saturates with concentration of MCCs.

Table 1 shows the surface mass density and airflow resistivity of the same CO fabric doped with different concentrations of MCCs. Differences measured for both variables due to doping of fabrics are smaller than 10%. Moreover, the concentration of MCCs has not a direct correlation with the resistivity neither the mass of the textile sample. Thus, variation of the sound absorption coefficient by doping CO fabrics is not due to the surface mass density (as the weight of MCCs is very small compared to the fabric) nor with the change of airflow resistivity (MCCs do not change the resistivity of fibers). As a consequence, other variables and mechanisms must be explored to explain the mechanical and acoustical effect of MCCs in doped fabrics.

3.3. Influence of textile woven fabrics

Textile woven fabrics are produced by interlacing warp and weft yarns. The warp consists of a multitude of separate parallel yarns. The weft consists of a multitude of separate parallel yarns at right angle to the warp ones. In the doping process, the adhesion of MCCs to the textile fabric depends on the type of yarn and its interweaving. Doping has been proven in section 3.2 to modify slightly the acoustic performances of CO fabrics. It is proposed to consider here the sound damping effect of doping different types of textile fabrics. A set of six different fabrics have been doped by the padding technique in a bath of distilled water with 100 g/L concentration. Table 2 shows the surface mass density and the thickness of the different textile fabrics analyzed. The airflow resistivity values of doped and undoped fabrics are presented with their standard deviation for the validity frequency range of the impedance tube. In general, less dense fabrics exhibit higher airflow resistivity. Same as for CO fabric, it can be seen that doping do not significantly varies the airflow resisitivy of textile fabric.

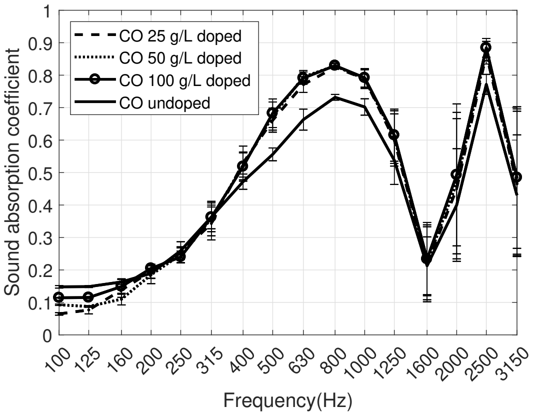


Figure 6. Normal incidence sound absorption coefficient of the cotton textile fabrics with different MCCs concentration of doping with a 10 cm thick air-cavity.

Figure 7 shows the results obtained for the sound absorption coefficient of the T4 sample at the end of the impedance tube. Although differences due to doping are small, it can be observed that the sound absorption of doped textile fabrics is slightly higher in medium and high frequencies. In general, the damping effect increases slightly but gradually with frequency. No significant differences due to doping

Fabric type	**Surface mass density** $(\mathrm{Kg}\cdot 10^{-3}/\mathrm{m}^2)$	σ $(\mathrm{kPa}\cdot\mathrm{s}\cdot\mathrm{m}^{-2})$
CO Undoped	183	1363−1370
CO 25 g/L	191	1344−1380
CO 50 g/L	199	1350−1383
CO 100 g/L	187	1342−1360

Table 1. Values of the surface mass density and airflow resistivity of undoped and doped cotton samples with a 0.3 mm thickness.

Fabric type	**Thickness (cm)**	**Surface mass density** $(\mathrm{Kg}\cdot 10^{-3}/\mathrm{m}^2)$	**Undoped** σ $(\mathrm{kPa}\cdot\mathrm{s}\cdot\mathrm{m}^{-2})$	**Doped** σ $(\mathrm{kPa}\cdot\mathrm{s}\cdot\mathrm{m}^{-2})$
T1	0.18	398	204−250	230−232
T2	0.05	159	786−842	815−819
T3	0.08	358	506−516	509−510
T4	0.07	245	571−579	577−581
T5	0.05	199	809−823	820−839
T6	0.14	478	270−274	286−292

Table 2. Thickness, surface mass density and undoped and doped airflow resistivity values of the textile fabrics.

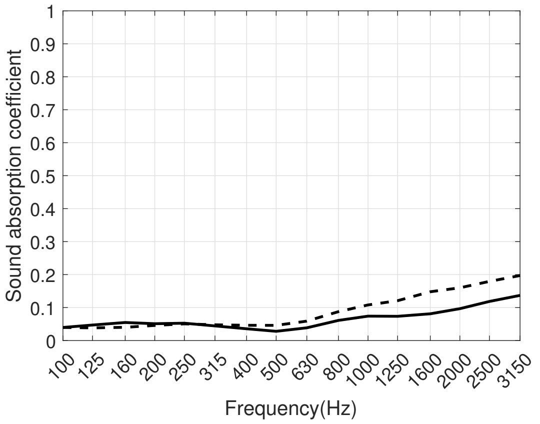
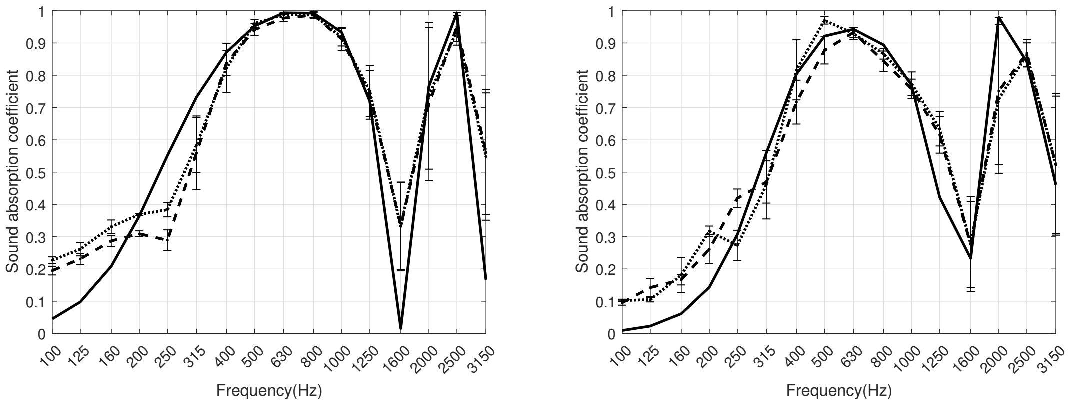


Figure 7. Measurement of the sound absorption coefficient of the T4 textile fabric at the end of the impedance tube. The doped fabric are compared (dashed line) to undoped fabric (solid line).

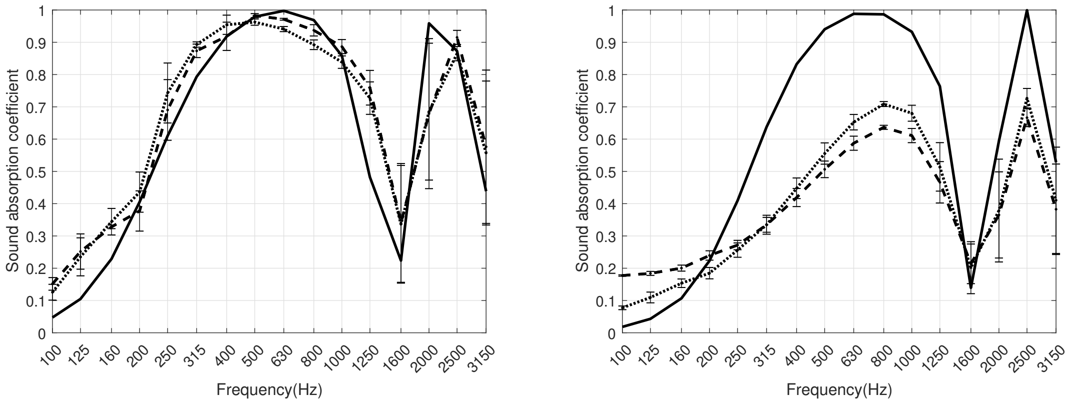
are observed at low frequencies below 0.3 kHz. Experimental measurements in this setup show that doping the samples does not change or slightly increases the absorption coefficient of fabrics, but in no case analyzed the absorption is reduced.

In order to enhance the damping effects of the samples, the normal incidence absorption coefficient is measured in the impedance tube in resonant conditions, that is, with an air-cavity of 10 cm. In this measurement configuration, sound damping is enhanced at the resonance and differences in the sound absorption coefficient of samples are increased. Figure 8 shows the results for all the textile fabrics.

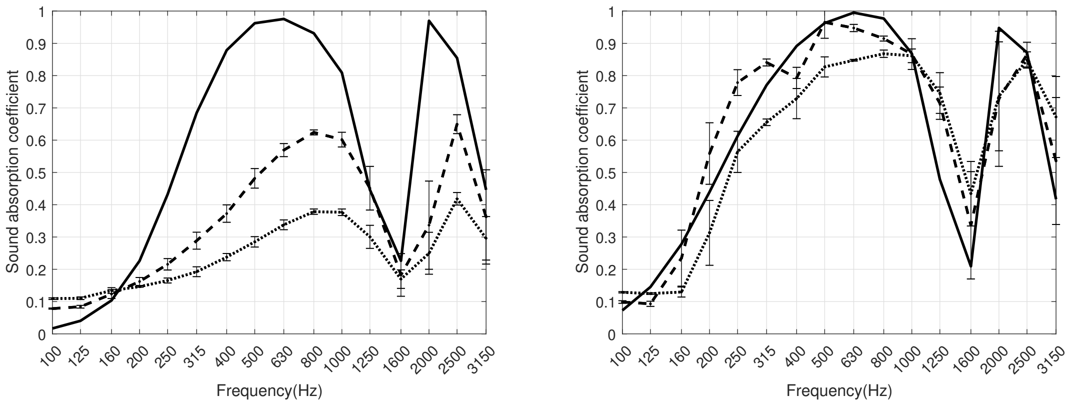
Depending on the effect of doping on the overall sound absorption at the resonance, fabrics can be grouped into three categories: 1) Fabrics that enhance the sound absorption by doping (T5 and T6), 2) Fabrics showing no acoustic effect by dopping (T1 and T3) and 3) Fabrics that decrease the sound absorption by doping (T2 and T4). It is remarkable that there is not a clear relation between the results



(a) T1 **(b)** T2



(c) T3 **(d)** T4



(e) T5 **(f)** T6

Figure 8. Sound absorption coefficient measured in impedance tube of doped (dotted line) and undoped (dashed line) textile fabrics by using an air-cavity of 10 cm. Experimental results have been compared with theoretical estimation of Pieren's model (solid line). Differences in the model between doped and undoped fabrics are negligeable. Both are represented with the same curve.

in both configurations: with rigid end and air-cavity. As a general rule, fabrics that are acoustically sensitive to doping have a higher damping at frequencies with higher sound absorption coefficient. In fact, at resonances the damping effect is the highest. The acoustic behavior of fabrics after doping is diverse (increase, decrease or no change in absorption) and depends on the type of fabric that is considered.

Pieren's model [57] from Eq.6 and Eq.7 has been represented using the experimental values obtained for the specific airflow resistance, R_s, and the surface mass density, m. The prediction model is a good approximation for fabrics with high absorption coefficient (T1, T2, T3 and T6), but it fails for less absorbent fabrics (T4 and T5) where losses in the air-cavity are comparable to those in the fabric, so a hypothesis of the model is not fulfilled. The difference between the experimental and predicted sound absorption values of these fabrics may be due to the fact that T4 has a different dye on both sides while T5 contains more irregularities because it has a fantasy thread that generates thickness changes. The small variations in the airflow resistivity and the surface mass density measured in doping fabrics do not explain the change measured in the absorption coefficient from the Pieren's model. Therefore, new theoretical models are necessary to understand the physical mechanisms underlying the effect of micoparticles adhered to the yards of textile fabrics and check the airflow resistance measurement technique for textile fabrics.

4. Conclusions

In this manuscript, the sound absorption coefficient has been measured from 0.1 kHz to 3.15 kHz in order to determine the influence of the microcapsules adhered to the different woven fabrics.

A comparative analysis of cotton samples by using different doping percentage but with the same yarn density is presented. In this case, MCCs do not change the position of first resonance, but an increase in the sound absorption coefficient is observed in all doped samples.

The acoustic effect of MCCs adhered to six different fabrics is analyzed by measuring the normal incidence sound absorption coefficient in an impedance tube. Doping has a different acoustic effect (increases, decreases or does not change) depending on the concentration of MCCs, the type of doped fabrics and the experimental setup (sample at the end or with an air-cavity).

Pieren's model predicts the sound absorption coefficient of textile fabrics by using its specific airflow resistance and its surface mass density. But, this model fails in fabrics where losses into the air-cavity are comparable to those in the fabric. It can be observed that Pieren's model does not correctly describe the effect of the microcapsules adhered to the textile fabrics. In other words, with the presence of microcapsules in the woven fabrics, the description of the acoustic behavior is very complex due to the high number of variables involved in the analysis.

Results have been analyzed under the

hypotheses of homogeneity of doping, the same number of MCCs adhered to fabrics and assuming that the MCCs size distribution is identical in all dopages.

This work is a first step to create new acoustic functional materials based on the increase and control of the acoustic damping with the use of MCCs and the results of this study evidence that it is possible to control the sound absorption by doping textile fabrics with different concentration of microcapsules.

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