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Technical Notes

Evaluation of Two Alternative Procedures for Measuring Airflow Resistance of Sound Absorbing Materials

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It is well known that sound absorption and sound transmission properties of open porous materials are highly dependent on their airflow resistance values. Low values of airflow resistance indicate little resistance for air streaming through the porous material and high values are a sign that most of the pores inside the material are closed. The laboratory procedures for measuring airflow resistance have been standardized by several organizations, including ISO and ASTM for both alternate flow and continuous flow. However, practical implementation of these standardized methods could be both complex and expensive. In this work, two indirect alternative measurement procedures were compared against the alternate flow standardized technique. The techniques were tested using three families of eco-friendly sound absorbent materials: recycled polyurethane foams, coconut natural fibres, and recycled polyester fibres. It is found that the values of airflow resistance measured using both alternative methods are very similar. There is also a good correlation between the values obtained through alternative and standardized methods.

Keywords: material characterization, airflow resistance, sound absorbing materials, eco-friendly materials.

1. Introduction

Presently, there exists a wide range of sound absorbing materials. This is due not only to technological advances in the field, but also to the importance of reducing noise pollution for health and environmental concerns. For this reason, current research focuses on the application of sound absorbing materials in different environments, with the goal of improving acoustic comfort, as well as searching for alternative fabrication methods of sound absorbing materials. Furthermore, an enormous importance is given to the development of *eco-materials*. These eco-materials are an alternative to the conventional materials for actual and future applications (Nick *et al.*, 2002; Asdrubali, 2006).

The great majority of sound absorbing materials, independent of the composition, are of the porous and/or fibrous type. There are many studies about the absorption mechanisms of the acoustic energy in the interior of porous materials, differentiating the distinctive mechanisms in function of the type of pore of which the material is composed (Arenas, Crocker, 2010).

Various studies have proposed physical-mathematical models to interpret the acoustic behavior in porous sound absorbing materials. The majority of these models are based on describing the characteristic wave impedance and the propagation constant in function of the frequency, given the physical properties of the materials, such as the porosity, tortuosity, or airflow resistance (Alba *et al.*, 2011).

The airflow resistance is the resistance experienced by air as it passes through a material. This property is directly related to the capacity of the material to absorb sound energy. Thus, the value of this magnitude is used as an input variable in prediction models in the frequency domain, of which the majority is based on empirical expressions.

In the works published on the topic, airflow resistance values measured by the same producers of absorbent materials can be found. On the other hand, other authors present empirical formulas for the determination of the airflow resistance of fibrous materials using values such as the bulk density of the material and diameter of the fibres. Bies and Hansen (1980), presented a formula of this type for the case of fibres with a relatively uniform diameter and with small quantities of binder, such as rockwool and fibreglass. Subsequently, Garai and Pompoli (2005), modified this formula for the specific case of polyester fibres.

The airflow resistance in Rayls or in kNs/m can be obtained in the laboratory in a standardized form (ISO, 1991). The standardized testing procedure is based on the passing of airflow through the sample. This airflow should be unidirectional, controlled, and constant. Also, it is necessary to determine the differential pressure created across the sample under study. Another procedure is one where the airflow is alternated. In this case, it is necessary to determine the alternate component of the pressure in the volume that is occupied by the sample. Both methods are described in the ISO standard. The second procedure (method B) consists in a piston connected to a motor and coupled with a circular tube and a sample holder. This procedure not only requires complex equipment, but also it is necessary to work at a very low frequency, in some cases around 2 Hz, leading to performance problems in microphones that register the signal at such low frequencies. It is also difficult to achieve a controlled unidirectional laminar airflow. The recommended velocity of the airflow that passes through the material sample is between 0.5 mm/s and 4 mm/s.

Given the complexity of the standardized method, some alternative experimental procedures have been described by different authors. For example, Stinson and Daigle (1983) presented the fundamentals of an electronic system to measure the airflow resistance in an absorbent porous material using a variable capacitance pressure transducer. A procedure for measuring the airflow resistance was also proposed by Woodcock and Hodgson (1992) using the inversion of the Delany and Bazley (1970), expression of the characteristic impedance as a function of airflow resistivity. Another technique was proposed by Sebaa *et al.* (2005) who used the physical property that in low frequencies the resistivity to the flow has a significant influence on the sound waves reflected. The flow resistivity was estimated, solving an inverse scattering problem for the waves reflected by a homogeneous isotropic porous material with a rigid skeleton. Subsequently, an extension of this work was presented using an acoustic transmissivity method to determine flow resistivity (Fellah *et al.*, 2006).

Indirect methods for obtaining airflow resistance have also been developed based on measurements in an impedance tube and two side-mounted microphones (Picard *et al.*, 1998; Panneton, Olny, 2006). Doutres *et al.* (2010) evaluated the macroscopic non-acoustical properties measuring the acoustical properties using a three-microphone impedance tube in the frequency bands where the material behaves as an equivalent fluid. These methods (using either two or three microphone positions) yield good results, although minimization of errors has to be done through accurate calibration procedures.

In particular, the method described by Ingard and Dear (1985) is an indirect way for obtaining the value of the airflow resistance of sound absorbing materials at certain frequencies. This method is used in the area of acoustic characterization of materials as an alternative to the standardized method. The measuring device in this indirect model is based on an impedance tube, device which is more sensitive than the one described in the standardized model. This method was subsequently modified by Ren and Jacobsen (1993) who replaced the position of microphones and the rigid termination for a completely absorbent one. Also, introduction of the concept of dynamic flow impedance identified that the real part (flow resistance) represents the frictional retardation to flow and the imaginary part (flow reactance) is attributable to the effective mass density of the fluid. This study also analyzed the measurement errors and optimization of the arrangement given by Ingard and Dear.

McIntosh *et al.* (1990) analyzed the Ingard and Dear technique. They measured the complex flow impedance under low- and high-intensity levels and showed that finite sample lengths have an effect on the accuracy of the measurements. They demonstrated that a sample length much less than a wavelength is required for good finite amplitude flow impedance measurement. Iannace *et al.* (1999) compared airflow resistivity measurements using both the Ingard and Dear technique and steady-state airflow method. They confirmed that both methods give compatible results for thin layers of loose granular materials. Another variation of the method included the change of position of the two microphones at the front of the sample (Picard *et al.*, 1998). In this configuration, the method was applied to the particular case of stratified rockwool samples.

Another alternative way of measurement in order to estimate the airflow resistance value is a recently proposed method by Dragonetti *et al.* (2011). From a structural point of view, the developed by this method device is quite simple and does not present the low frequency limitation unlike the standardized method. The results of Dragonetti *et al.* were compared to the standardized method B (ISO, 1991) with good correlation.

Given that the method proposed by Dragonetti *et al.* (2011) is part of a recent study, it is useful to implement it to evaluate its performance in different types of materials including recycled porous ones. The main objective of this study is to compare the experimental airflow results obtained by the Dragonetti *et al.* method to those obtained by the method of Ingard and Dear (1985) and the standardized method. The two alternative methods are similar in the use a loudspeaker and two microphones. This study presents measurements of airflow resistance for three distinct families of eco-materials. The measuring devices that are described in these two references were reproduced by the authors.

2. Two simple alternative methods

2.1. Ingard and Dear method

In this method the airflow resistance is measured using a closed cylindrical tube with a perfectly rigid termination, a loudspeaker at the other end, and a pair of microphones. Figure 1 (top) shows the schematics of the measuring device. The sample of the absorbent material of thickness d is inserted in the middle of the tube. The distance between the posterior face of the sample material and the rigid termination is l. One of the microphones is located to measure the sound pressure directly in front of the absorbent material (p_1). The other microphone is located in front of the rigid termination that closes the tube (p_2). The loudspeaker emits a low frequency pure tone signal chosen to produce an odd number of quarter wavelengths throughout the distance $l+d$ from the rigid termination to the sample material. It should satisfy the condition $\lambda \gg 1.7D$, where D is the inner diameter of the tube and λ is the wavelength of sound. Also, $l + d = (2n - 1)\lambda/4$, whereas n is a whole number.

Assuming that the losses in the tube are negligible, that the microphones are calibrated to have the same sensibility, and that the flow reactance is small at low frequencies, the airflow resistance σ is determined by the equation

$$\sigma = \rho c 10^{\left(L_{p_1} - L_{p_2}\right)/20}, \tag{1}$$

where ρ is the average air density, c is the speed of the sound in the tube, and L_{p_1} and L_{p_2} are the pressure levels that correspond to the pressure measurements p_1 and p_2, respectively.

However, the measurement process is facilitated with the use of a dual channel FFT analyzer and a sound source generating a broadband stationary random noise inside the tube. In this case, the airflow resistance is calculated as a function of frequency using the absolute value of the imaginary part of the transfer function between the microphone signals, i.e. (Ingard, Dear, 1985)

$$\sigma = \rho c \left| \operatorname{Im}\left(\frac{p_1}{p_2} \right) \right|. \tag{2}$$

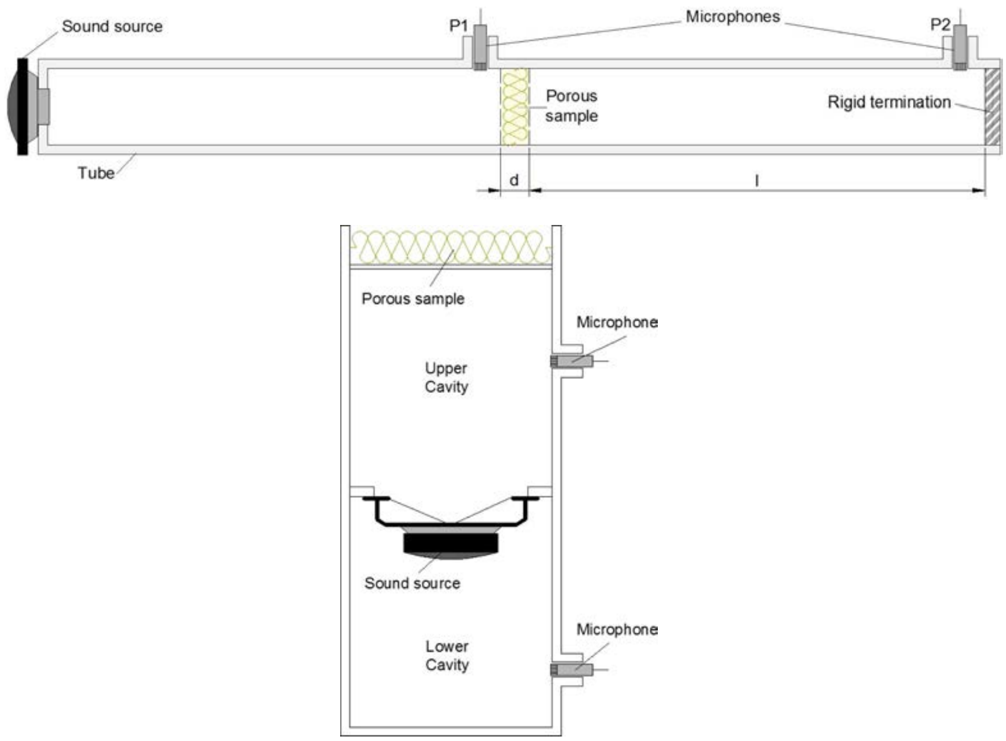


Fig. 1. Schematic diagram of the two measuring devices; top: Ingard and Dear (1985) and bottom: Dragonetti *et al.* (2011).

Thus, it is possible to read the numerical value of the airflow resistance at frequencies where the length is an odd number of quarter wavelengths, i.e. looking for the minima of this function. Then, by extrapolating towards a zero frequency value, the "DC" airflow resistance is estimated (McIntosh *et al.*, 1990).

2.2. Dragonetti et al. method

The study by Dragonetti *et al.* (2011) includes a detailed description of an analogy between the prototype designed and an equivalent electrical circuit which permits the mathematical analysis of the behavior of the sound pressure in both cavities of the measuring device. Figure 1 (bottom) shows the schematic of the measuring device. In particular, in the case of low frequencies, the airflow resistance value can be obtained easily from the transfer function (H) between the microphones situated in both cavities of the device, which is given by

$$\sigma = \frac{\mathrm{Im}(H)}{-\omega C_{dw} d}, \tag{3}$$

where ω is the circular frequency, d is the sample thickness, $\mathrm{Im}(H)$ is the imaginary part of the transfer function H between the sound pressure measured in the upper and lower cavity given by

$$H = \frac{p_{up}}{p_{dw}}, \tag{4}$$

C_{dw} is the acoustic compliance of the lower cavity given by

$$C_{dw} = \frac{V_{dw}}{\gamma P_0 S}, \tag{5}$$

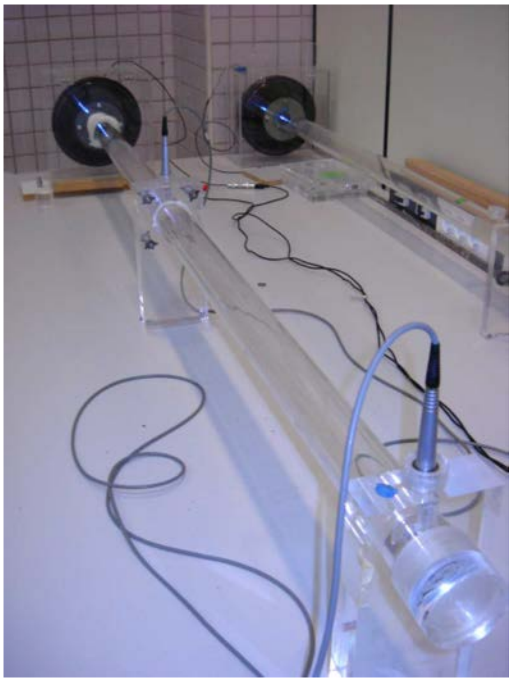
S is the cross sectional area of the porous sample, P_0 is the atmospheric pressure, γ is the specific heat ratio (approximately 1.41 for air), and V_{dw} is the compressible air volume in the lower cavity.

As it can be seen, once calibrated, the device in Fig. 1 provides a simple way to determine the value of airflow resistivity. The appropriate seals of each part of the device are essential to avoid air leaks, which helps to obtain consistent results. In this case, the calibration process is very important due to the effective volumes of both cavities. This calibration process is detailed in the study by Dragonetti *et al.* (2011).

3. Constructed measuring devices

3.1. Ingard and Dear device

The measuring device described by Ingard and Dear (1985) was designed and built by the authors of this study (Ramis *et al.*, 2010). The apparatus consists of a cylindrical, polymethylmethacrylate (PMMA) tube with a 40 mm diameter, wall thickness of 5 mm, and 169 cm in length. One end of the tube is equipped with a high frequency compression driver (Beyma CP800TI) with a throat diameter of 49 mm, which permits emission without considerable distortion at 100 Hz. The other end is closed with a rigid, highly sound-reflective termination. The distance between the first microphone and the rigid termination was 0.845 m. This value was chosen to be one quarter wavelength at 100 Hz, approximately. The two microphones used are of 1/2 inch, and mounted flush into the tube wall. Figure 2 (top) shows a photograph of the constructed device.



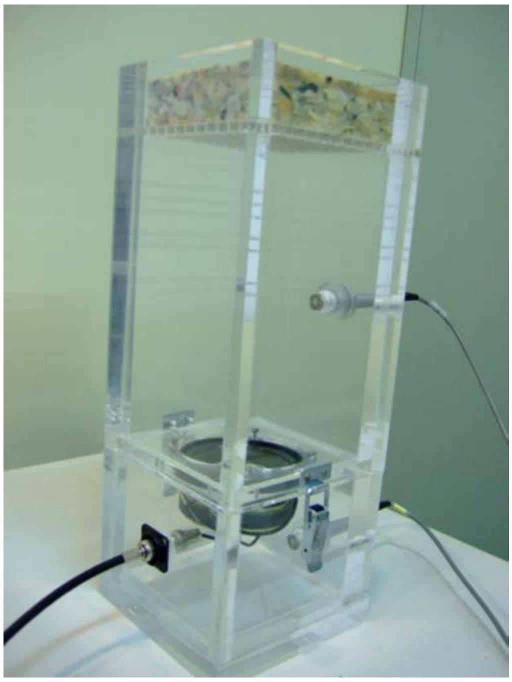


Fig. 2. Photographs of the constructed measuring devices; top: Ingard and Dear (1985); bottom: Dragonetti *et al.* (2011).

3.2. Device of Dragonetti et al.

The device is designed and built with the goal of characterizing new sound-absorbing eco-materials, corresponding to the one described in the reference (Dragonetti *et al.*, 2011) and is shown in Fig. 2 (bottom).

The device described in the reference, as well as the device designed for this study are constructed with polymethylmethacrylate (PMMA) with a 20 mm thickness. In both cases, the volume of the upper and lower cavities is 2.30 and 0.99 litres, respectively. The upper part of the device is composed by a perforated grate where the study sample is held. The design considers circular perforations of 8.5 mm in diameter, with separations of 10.4 mm on both the horizontal and vertical axis. With this, the perforated area of the sample holder is 64.7%. It is necessary, in line with the reference prototype, to have at least 50% of the surface perforated, with a diameter of perforation of at least 3 mm. Noteworthy is that the method proposed by Dragonetti *et al.* (2011) is based on the adaptation of the standard (ISO, 1991), particularly the method B that is based on alternate airflow.

The microphones in both cases are 1/2 inch and the diameter of the speaker used (Fonestar UT-354) is 3 inches wide. This speaker has a good response in the range of frequencies used in this study.

4. Eco-materials studied

Three distinct eco-materials families were studied: recycled polyurethane foams, materials elaborated from coconut fibres, and recycled polyester fibres. While fabricating each of the materials, the use of toxic resins was avoided. The binding agent used, as in the case of polyester, was the thermofusion of the fibres. The three types of eco-materials have been studied as sound absorbing materials in earlier works (del Rey *et al.* 2011a; 2011b; 2012). The recycled foam has an average pore diameter of 150 μm. The coconut and polyester fibre materials have a mean value of the fibre diameter 250 μm and 36 μm, respectively.

In Fig. 3, microscopic images are shown from these three families of materials. The distribution of pores in the interior of each type of material can be appreciated, although the images are not of the same scale. It can be easily seen that the recycled foam corresponds to a cellular type porous material, and that the vegetable fibres of the coconut and the recycled polyester (PET) are porous materials of the fibrous type (Arenas, Crocker, 2010).

5. Results

Tests of eco-materials were carried out with alternative methods to those described in the ISO standard. Also, the same materials were tested in concordance with the ISO standard (1991) in an external laboratory in Portugal. The tests were conducted based on the method B of alternated airflow. For all the methods three samples of each eco-material were tested and the average of these three measurements was calculated.

In the case of the Ingard and Dear method, the transfer function is measured between the two microphone positions on the constructed prototype. The airflow resistance value is obtained by looking for the minima of the modulus of the imaginary part of this function and extrapolating towards a zero frequency value. To subsequently obtain the flow resistivity, the value is multiplied by the air impedance and divided by the thickness of the sample. Measurements considered sound pressure levels of 126 dB at the rigid termination, corresponding to velocity amplitudes of approximately 0.144 m/s on the front side of the material

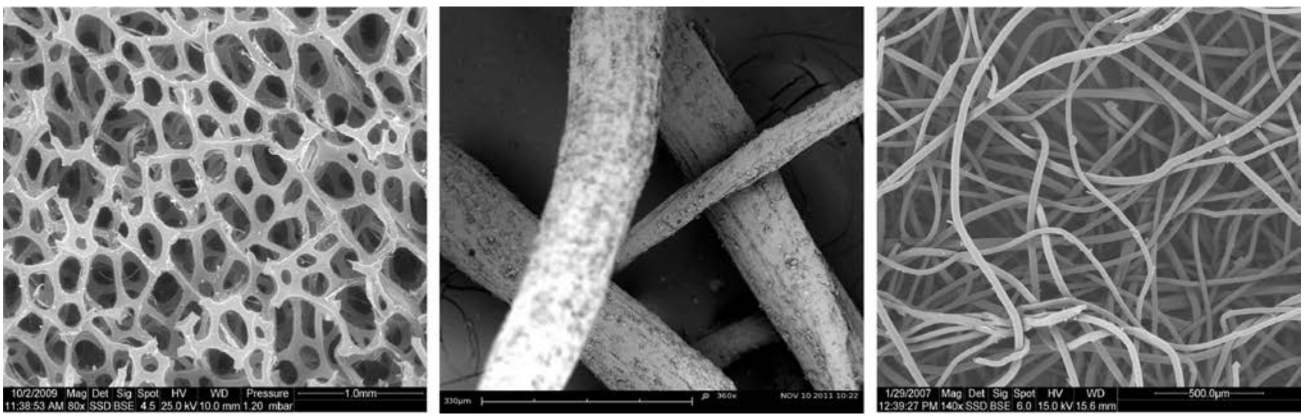


Fig. 3. Microscopic detail of the composition of each of the eco-materials studied (images are not of the same scale); left: Recycled foam; middle: Coconut fibres; right: Recycled polyester fibres.

sample at 100 Hz. Figure 4 shows an example of the values measured for a polyester fibre with a density of 10 kg/m^3 and thickness 4 cm (denoted as I400-40). As expected, minima are observed at 100, 300, 500, 700, and 900 Hz, approximately.

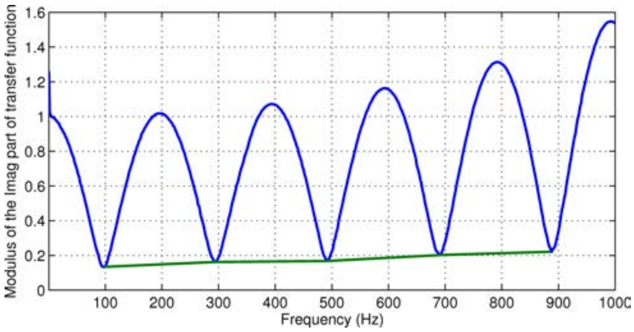


Fig. 4. Example of the values measured for a polyester fibre sample using the Ingard and Dear method.

Figure 5 shows the results measured from the imaginary part of the transfer function H as a function of frequency for the three families of eco-materials studied in concordance with the method of Dragonetti *et al.* To ensure a constant velocity for each frequency, the sound pressure level inside the lower cavity was 111 dB, corresponding to an approximately airflow velocity amplitude of 0.5 mm/s at the lowest frequency considered in this study. The plots in Fig. 5 give information about the limit on frequencies of Eqs. (3) and (5). The valid frequency limit is that in which the values can be approximated to a straight line. This frequency limit depends on intrinsic parameters of the porous material, such as the tortuosity and porosity values (Dragonetti *et al.*, 2011). In the samples studied in this test and for the frequency ranges considered, this dependence is shown clearly in Fig. 5 (bottom).

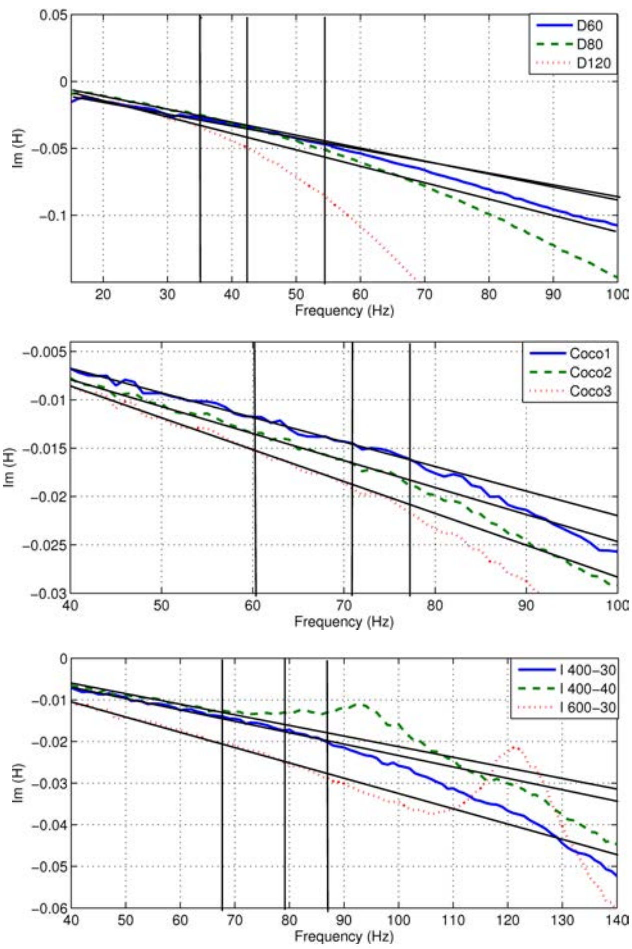


Fig. 5. Results of Im(H) as a function of frequency for three types of porous eco-materials; top: recycled foam, middle: coconut fibres, bottom: recycled polyester fibre. The vertical lines indicate the relevant upper frequency limits.

Figure 6 shows the average values of the airflow resistivity (airflow resistance divided by the sample thickness) in function of the frequency for each of the eco-material samples.

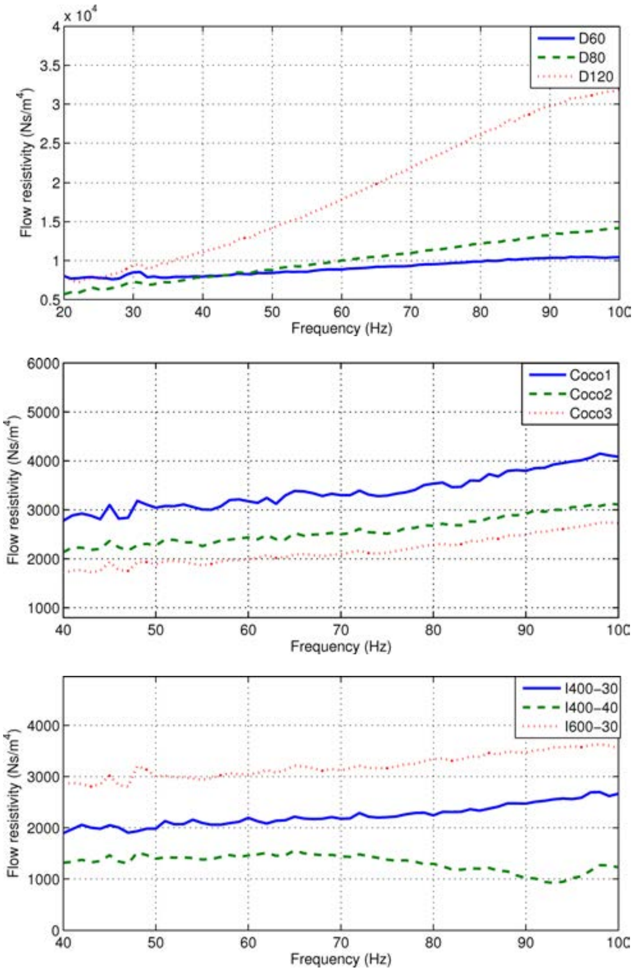


Fig. 6. Flow resistivity as a function of frequency for three types of porous eco-materials; top: recycled foam, middle: coconut fibres, bottom: recycled polyester fibre.

Table 1 presents the values obtained from all tested samples with both alternative indirect methods and the results according to the standard. Density, thick-

Table 1. Results of the airflow resistivity measured by different methodologies for the eco-material samples. The values in parenthesis indicate the standard deviation.

Material	Density [kg/m^3]	Thickness [cm]	Airflow resistivity [kNs/m^2]		
			Dragonetti *et al.*	Ingard and Dear	ISO 9053:1991 Method B
Recycled foam D60	61	3.2	9.2 (1.8)	9.0 (1.1)	6.1 (0.1)
Recycled foam D80	86	3.1	10.9 (4.4)	14.6 (0.7)	13.2 (0.1)
Recycled foam D120	135	3.1	21.0 (5.0)	13.5 (0.5)	35.6 (0.8)
Coconut fibres Coco1	128	1.9	3.1 (0.4)	2.8 (0.5)	2.6 (0.1)
Coconut fibres Coco2	100	2.9	2.3 (0.2)	1.9 (0.1)	1.9 (0.1)
Coconut fibres Coco3	83	4.2	1.8 (0.2)	1.5 (0.2)	1.2 (0.1)
Recycled polyester fibre I400-30	14	3.0	2.2 (0.4)	1.7 (0.1)	1.5 (0.7)
Recycled polyester fibre I400-40	10	4.0	1.4 (0.2)	1.3 (0.1)	1.1 (0.2)
Recycled polyester fibre I600-30	20	3.3	2.7 (0.2)	2.3 (0.5)	2.4 (0.3)

ness, average values of the airflow resistivity, and standard deviation are shown.

Analyzing the experimental results, it is important to note several findings in particular. In the case of the polyester fibre samples, which are lighter and homogenous in composition, both indirect methods offer similar values and very low levels of error. Also, these values are similar to the ones obtained with the ISO standard. It is important to emphasize that the testing with this type of light materials is more comfortable with these indirect techniques than with the standard one. With the indirect techniques, it was easier to cut and adapt the sample correctly. However, in the case of the standard, it is necessary to increase the precautions. As a result, for these types of samples the use of the two alternative indirect methods seems very adequate.

For the coconut fibre samples, there is also a good coincidence between the results of the tested methods and the standardized method. The density of the coconut is greater than that of the polyester, the distribution of the fibres is less homogeneous, and there are more differences between the diameters of the fibres. The errors in this case are not only due to the method but also to the composition of the materials, which increases the dispersion of the results. For these types of materials, both proposed methods appear adequate.

With respect to the recycled foams, larger divergences are observed. In the first place, the data of the indirect methods are similar to D60 but it is not the case for higher densities. These materials present high heterogeneity in their composition. It is assumed that these foams contain pieces of recycled foam of different types, which means that each sample can have quite a different composition. It is only possible to control the density and thickness, as factors that the samples share. In this sense, if the indirect methods are valid they can offer an estimation of airflow resistivity which can change due to the inhomogeneous composition.

It is important to highlight the value of the sample D120. In the case of the Dragonetti *et al.* method, the error increased upon the increasing density of the samples. In the case of the Ingard and Dear method, the errors increased due to the construction of the tube where indirect transmissions appear to reduce the difference between the pressure levels, thus reducing the value of airflow resistivity.

6. Conclusions

This study presented the results of airflow resistance for three families of eco-materials, measured by two alternative methods to the ISO standard. It is possible to observe the dependency of frequency range on the thickness of the samples and nature of the material measured. In general, it was possible to observe that both alternative methods give similar values. In the case of the coconut fibres, the values measured using the Ingard and Dear method are closer to the values measured with the ISO standard, while the values obtained by the Dragonetti *et al.* method slightly overestimate the values of airflow resistivity. This also occurs in the case of the recycled polyester fibres.

In the case of the materials of recycled foams, larger differences are noted, which is explained by the inhomogeneity of this type of recycled material. It appears reasonable that the test of eco-materials with the ISO standard does not guarantee a reliable measured value of airflow resistivity. In this sense, the indirect techniques of Dragonetti *et al.* and of Ingard and Dear appear useful, facilitating in many situations the testing procedure. In other cases it can serve as a control measurement for estimating the range in which this parameter can move. In every case, it can be concluded that the alternative methods are a viable option to the more complex, standardized procedures.

Acknowledgments

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