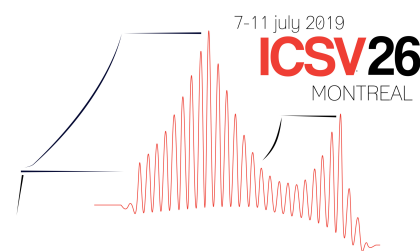


26<sup>th</sup> INTERNATIONAL CONGRESS ON SOUND AND VIBRATION  
7-11 July 2019, Montreal



## IMPEDANCE TUBE MEASUREMENTS ON THE DENORMS ROUND ROBIN TEST MATERIAL SAMPLES

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The DENORMS Round Robin Test aims to study and improve the techniques used to determine the sound absorption coefficient of materials. Within this framework, samples taken from the same batch have been tested in both reverberation room and impedance tube. The latter technique presents some challenges in that the results may strongly depend on the specimen preparation and set-up. The purpose of this paper is to present the results obtained in custom-made impedance tube for the RRT set of materials. The tests have been carried out using a four-microphone impedance tube, according to the method outlined in the ASTM E2611-09 standard. The results obtained for the different parameters provided by the test, in particular the sound absorption coefficient and the sound transmission loss, are taken into account and discussed.

Keywords: impedance tube, sound absorption, acoustic impedance, transfer matrix

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### 1. Introduction

The acoustic characterization of materials in industrial, transport and building sectors mainly relies on the evaluation of two properties: the attitude of the material to dissipate sound energy due to viscous phenomena, expressed through the sound absorption coefficient  $\alpha$ , and the sound insulation capability, represented by the sound transmission loss  $TL$  which is related to the sound transmission coefficient  $\tau$  through the formula  $TL = 10 \log_{10}(1/\tau)$ . These parameters can be obtained by different types of tests [1, 2]. The most popular methods to measure the sound absorption coefficient consist in testing the material in reverberation room or in standing wave tube, which provide information on the material behavior with diffuse or normal incidence, respectively. Measurements in reverberation room are often preferred because they provide closer results to the actual working conditions of the material because of the random incidence excitation. However, the tests in standing wave tube, also known as 2-microphone impedance tube, allow to obtain additional information about the characteristic acoustic impedance of the sample. A third method can be mentioned which is designed to perform in-situ tests on materials

Table 1: Some strengths and weaknesses of different methods to measure sound absorption coefficient.

Method	Strengths	Weaknesses
Reverberant room	Measurement of diffuse-incidence $\alpha$	At least 10 m <sup>2</sup> of material are required; no information about material acoustic impedance
Impedance tube	Small sample of material required; provides information on the material acoustic impedance	Measurement of normal-incidence $\alpha$
EN 1793	Measurement of in-situ $\alpha$	Complex equipment required; no information about material acoustic impedance

installed outdoors; this method is described in EN 1793 standard concerning road barriers. Each of the aforementioned methods has some strengths and weaknesses, summarized in Table 1.

As concerns the experimental determination of the sound transmission coefficient, two measurement procedures are standardized. The first procedure is based on the use of transmission suites, that is, two reverberation rooms between which a specimen of the material under test is mounted; the second procedure is based on the use of a double standing wave tube, also known as transmission tube. This 4-microphone impedance tube has similar pros and cons as 2-microphone impedance tube has for the measurement of the sound absorption coefficient, in that it can be used to estimate only the normal-incidence sound transmission loss, but it provides interesting information about the material, such as the propagation wavenumber and the characteristic impedance in the material. Moreover, testing a material in impedance tube allows to build the transfer matrix establishing the correlation between the state variables on the two surfaces of the sample:

$$\begin{bmatrix} p_0 \\ u_0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_d \\ u_d \end{bmatrix} \quad (1)$$

where  $p$  and  $u$  are the sound pressure and the particle velocity, 0 and  $d$  subscripts indicate, respectively, the front and back surfaces of the sample with respect to the direction of the incident sound wave, and  $T_{ij}$  are the elements of the transfer matrix. This information allows to apply the transfer matrix method to the optimization of complex layered materials, whose overall acoustic properties can be estimated once the transfer matrices of the single layers have been carefully characterized. The method can be of practical interest for example in the maritime field, where bulkheads often consist of rigid layers [3] covered by soft, sound insulating layers [4]. Finally, among the described equipment, only the four-microphone impedance tube allows to simultaneously measure both the sound absorption and the sound transmission coefficients, not to mention other parameters, such as acoustic impedance and speed of sound, that can be used to characterize the acoustic material [5].

In the following, some preliminary results from impedance tube measurements performed on the material set chosen for the DENORMS Round Robin Test on the low-frequency sound absorption of materials [6] are presented. The samples have been tested in a custom-made 4-microphone impedance tube according to the procedure described in the ASTM E2611 [7].

## 2. Standard procedure

The ASTM E2611 standard procedure requires the use of a four-microphone impedance tube (Fig. 1). A loudspeaker is installed at one endpoint of the tube and generates a wide-band white noise test signal.

The sample to test is mounted in the central section of the tube, between two microphone pairs. The second endpoint of the tube can be equipped with either anechoic or reflecting termination, which allow to perform the tests with two different boundary conditions.

With reference to Fig. 1, the possibility to compare signals from four microphones allows to decompose the sound wave among the incident and reflected fractions on either side of the specimen.

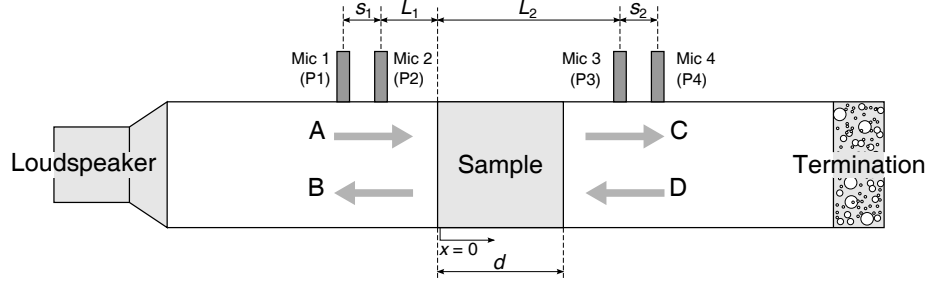


Figure 1: Schematic drawing of a four-microphone impedance tube.

Defining the wavenumber in air,  $k = 2\pi f/c$ , the four components  $A$ ,  $B$ ,  $C$  and  $D$  can be calculated with the following correlations, once the complex acoustic transfer functions  $H_{i,ref}$  between the  $i$ th microphone and the reference microphone are measured:

$$\begin{aligned} A &= 0.5 \cdot j \left( H_{1,ref} e^{-jkL_1} - H_{2,ref} e^{-jk(L_1+s_1)} \right) / \sin(k s_1) \\ B &= 0.5 \cdot j \left( H_{2,ref} e^{+jk(L_1+s_1)} - H_{1,ref} e^{+jkL_1} \right) / \sin(k s_1) \\ C &= 0.5 \cdot j \left( H_{3,ref} e^{+jk(L_2+s_2)} - H_{4,ref} e^{+jkL_2} \right) / \sin(k s_2) \\ D &= 0.5 \cdot j \left( H_{4,ref} e^{-jkL_2} - H_{3,ref} e^{-jk(L_2+s_2)} \right) / \sin(k s_2) \end{aligned} \quad (2)$$

where any of the four microphones available can be arbitrarily selected as the reference microphone.

For a given boundary condition, it is possible to determine the acoustic pressure and the particle velocity on each face of the specimen using the following equations:

$$\begin{aligned} p_0 &= A + B & p_d &= C e^{-jkd} + D e^{+jkd} \\ u_0 &= (A - B) / \rho c & u_d &= (C e^{-jkd} - D e^{+jkd}) / \rho c \end{aligned} \quad (3)$$

where  $\rho$  is the density of air and  $c$  is speed of sound in air. In general, the elements of the transfer matrix  $T$  introduced in Eq. 1 can be calculated from the acoustic pressures and particle velocities measured with two – anechoic  $a$  and reflecting  $b$  – terminations:

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} (p_{0a}u_{db} - p_{0b}u_{da}) / (p_{da}u_{db} - p_{db}u_{da}) & (p_{0b}p_{da} - p_{0a}p_{db}) / (p_{da}u_{db} - p_{db}u_{da}) \\ (u_{0a}u_{db} - u_{0b}u_{da}) / (p_{da}u_{db} - p_{db}u_{da}) & (p_{da}u_{0b} - p_{db}u_{0a}) / (p_{da}u_{db} - p_{db}u_{da}) \end{bmatrix} \quad (4)$$

In the case of a symmetric sample, the transfer matrix calculation can be simplified considering that  $T_{11} = T_{22}$  and  $T_{11}T_{22} - T_{12}T_{21} = 1$ , and measurements with a single boundary condition (usually obtained with the anechoic termination) suffice.

The absorption coefficient (hard-backed) can be computed as:

$$\alpha = 1 - \left| \frac{T_{11} - \rho c T_{21}}{T_{11} + \rho c T_{21}} \right|^2 \quad (5)$$

The sound transmission loss  $TL$  (anechoic-backed) is:

$$TL = 20 \log_{10} \left| \frac{T_{11} + (T_{12}/\rho c) + T_{21}\rho c + T_{22}}{2 e^{jkd}} \right| \quad (6)$$

The propagation wavenumber  $k'$  and characteristic impedance  $z$  can be expressed as:

$$k' = \frac{1}{d} \cos^{-1} T_{11} \quad Z = \sqrt{\frac{T_{12}}{T_{21}}} \quad (7)$$

When using the impedance tube to estimate the transmission loss, one must consider that only for materials whose shear modulus is negligible can the resulting  $TL$  be assumed to be independent of boundary conditions [8]. In case of rigid panels, the actual boundary conditions can be better taken into account through direct measurements and condensed in the acoustic impedance of the material,  $Z_p$ . The transfer matrix of the rigid panel can then be written as

$$T_p = \begin{bmatrix} 1 & Z_p \\ 0 & 1 \end{bmatrix} \quad (8)$$

$Z_p = j\omega\mu[1 - (1 + j\eta) \sin^2 \theta(f/f_c)^2]$ , where  $\mu$  is the mass per unit area of the panel and  $\eta$  is the loss factor.  $f_c$  is the critical frequency, defined, for a homogeneous plate having a given bending stiffness per unit width  $D_p$ , as  $f_c = c^2/(2\pi)\sqrt{\mu/D_p}$ .  $D_p$  can be obtained for example according to [9], when beam samples of the material are available, or with point mobility measurements [10]. The dependence of vibro-acoustic properties of layered structures on boundary conditions is discussed in [11].

In the next sections, Eqs. 1-6 are used to compute the main acoustic parameters of the samples tested in the custom-made impedance tube built by the Applied Acoustics Laboratory, the University of Brescia.

### 3. Experimental set-up

#### 3.1 The impedance tube

The custom-made impedance tube consists of two segments of length 1200 mm and internal diameter 45 mm. The corresponding cross-section allows to keep the plane-wave assumption valid up to about 3800 Hz. The source endpoint features a loudspeaker of 100 mm enclosed in a sealed volume, while the second endpoint can be connected to a rigid reflective termination or to an anechoic termination. The microphone ports for high-frequency measurements are spaced 45 mm apart; the ports for low-frequency measurements are spaced 500 mm. The sample can be placed in a separate segment of tube of the most appropriate length, which can subsequently be installed between the two measurement sections described above. The model of the tube is shown in Fig. 2.

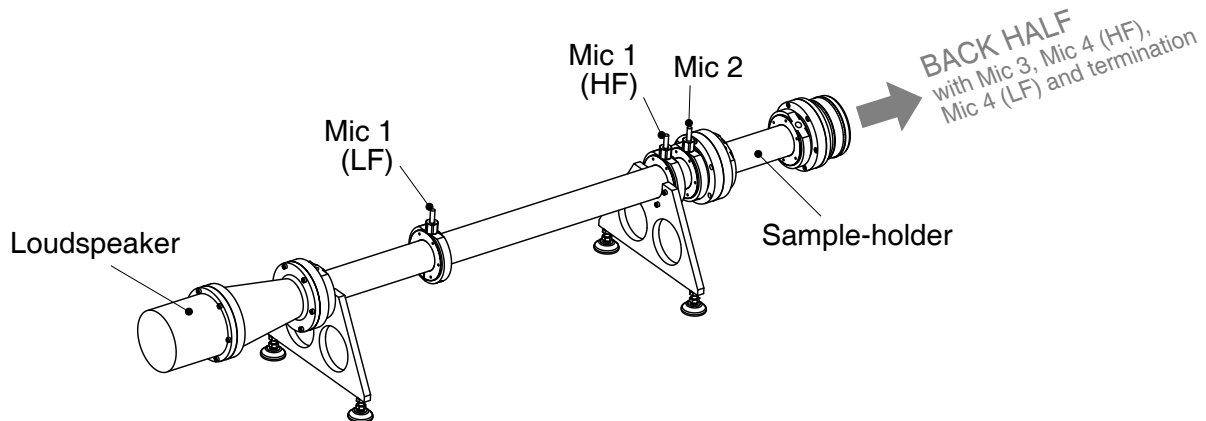


Figure 2: Portion of the tube including the loudspeaker. LF = low frequency; HF = high frequency.

Four BSWA Type MPA416 microphones housed in o-ring-equipped ports have been used. The diaphragm of the microphones is recessed with respect to the side wall of the tube. The transducers are connected to an OROS Type OR36 analyzer measuring the complex transfer functions between microphones. During the measurements, the coherence function is also monitored to check that the signal-to-noise ratio be high enough over all the frequency range of interest. The white noise employed as a test signal is generated by the analyzer itself.

### 3.2 Test specimens

The following samples have been tested (see Fig. 3):

1. Ecophon Modus S glasswool, 200 mm thickness
2. Ecophon Modus S glasswool, 200 mm thickness, with Fantoni 4Akustik milled panel
3. Ecophon Modus S glasswool, 200 mm thickness, with Fantoni 4For drilled panel

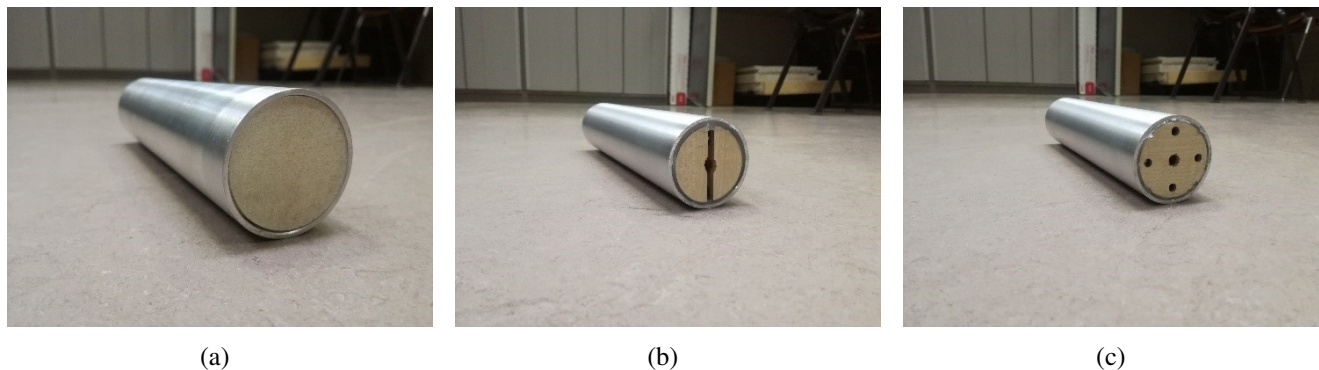


Figure 3: Tested samples: (a) glasswool; (b) glasswool + milled panel; (c) glasswool + drilled panel.

The glasswool samples have been cut by means of a manual hole saw with internal diameter slightly smaller than the sample holder, in order to prevent the direct contact between the stiffer glass tissue protecting the wool and the inner surface of the metal sample holder. Since the original glasswool panel is 100 mm-thick, the 200 mm-thick sample has been created by putting two 100 mm samples together, with the protecting glass tissue layers facing outward. The samples have been united by means of very thin needles inserted throughout the material; this expedient turned out to be necessary to keep the parts integral with each other and to avoid possible problems of structural resonances. In case of glasswool/rigid panel samples, the gap between the external edge of the panel layer and the metal tube has been accurately sealed with petroleum jelly so to prevent sound and air from leaking through it and negatively influence the measurement. The sample holder has been additionally sealed towards the outside by means of o-rings and petroleum jelly.

### 3.3 Data acquisition and post-processing

The measurements on the specimens described in the previous section have been carried out at the Applied Acoustics Laboratory, the University of Brescia. The temperature and the atmospheric pressure have been noted before the tests, so to enable the necessary corrections during the post-processing of the data. The microphones have been calibrated in advance through pistonphone Brüel & Kjær Type 4228 equipped with 1/4" adapter.

For each tested specimen, two data-sets relative to the anechoic and reflecting terminations are available. Following the standard procedure, 4 measurements have been performed permuting the position of the microphones in the ports. In particular, microphone 1 has been taken as a reference and microphones

1 to 4 have been mounted to ports P1 to P4 according to the following sequences: [1-2-3-4], [2-1-3-4], [3-2-1-4] and [4-2-3-1]. For each data-set, the first measurement provides the complex transfer functions  $H_{2,1}$ ,  $H_{3,1}$  and  $H_{4,1}$ . The subsequent measurements allowed to determine corrected transfer functions necessary to account for discrepancies arising from mismatches due to microphones amplitude and phase responses. The measured transfer functions have been saved and post-processed by means of a self-built code based on the ASTM E2611 standard procedure. The script implements the theory in Section 2 and outputs the sound absorption coefficient, the sound transmission loss, the propagation wavenumber and the speed of sound in the material and the characteristic acoustic impedance of the specimen. In the following section, some preliminary results of the measurements performed on the materials selected for the DENORMS RRT tests are presented.

### 4. Results

Figure 4 shows the sound absorption coefficient and the sound transmission loss measured on a 200 mm specimen of the Ecophon Modus S glasswool with protecting tissue layer facing outward. Figure 5 shows the sound absorption coefficient and the sound transmission loss measured on a 200 mm specimen of the Ecophon Modus S glasswool with protecting tissue layer, faced by Fantoni 4For drilled panel. Figure 6 show the sound absorption coefficient and the sound transmission loss measured on a 200 mm specimen of the Ecophon Modus S glasswool with protecting tissue layer, faced by Fantoni 4Akustik milled panel.

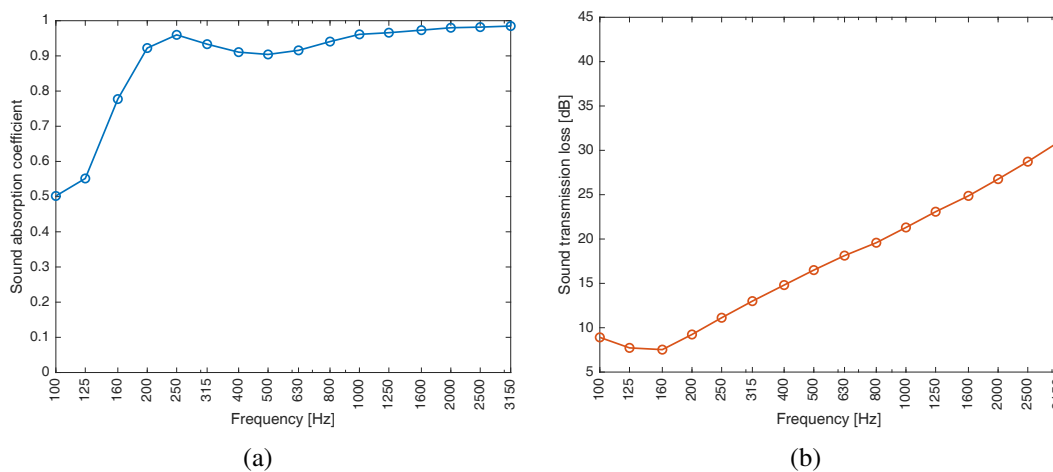


Figure 4: Sound absorption coefficient (a) and transmission loss (b) of 200 mm Ecophon Modus S glasswool specimen.

It can be observed that the sound absorption performances are greatly influenced by the presence of the Fantoni panels. In particular, in the specimen featuring the drilled panel, the sound absorption coefficient reaches the maximum value at a frequency slightly below 250 Hz and stabilizes on this good value from that frequency on. On the other hand, in the specimen featuring the milled panel, the maximum sound absorption performance is achieved at about 160 Hz, but it progressively worsen until it reaches about 40% of the maximum value at about 300 Hz.

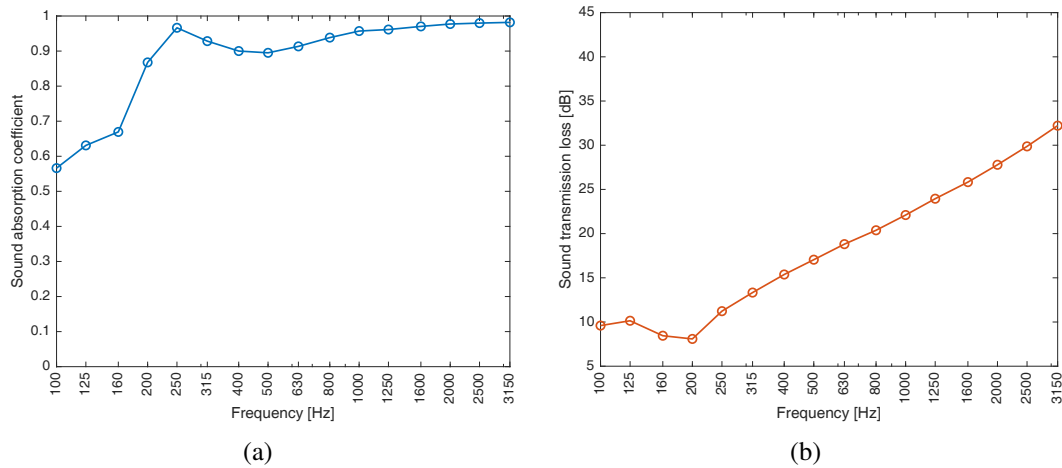


Figure 5: Sound absorption coefficient (a) and transmission loss (b) of 200 mm Ecophon Modus S glass-wool faced by Fantoni 4For drilled specimen.

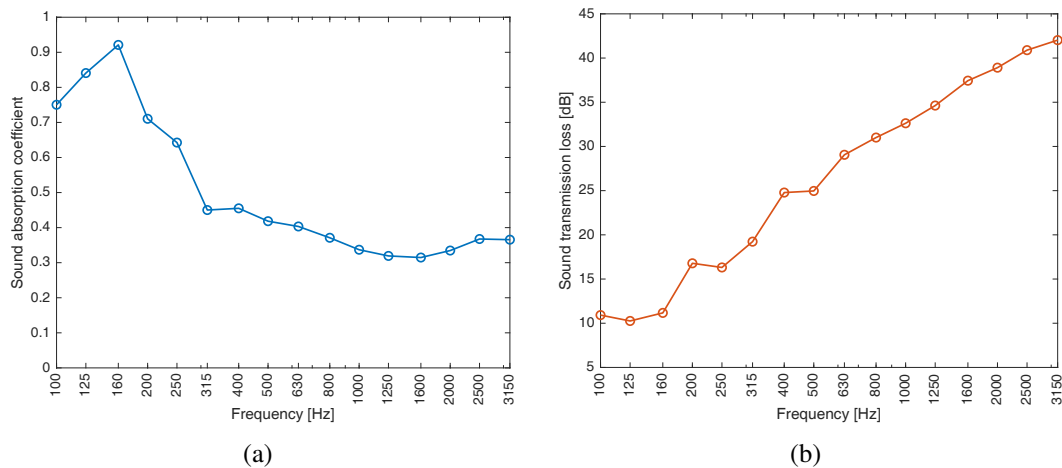


Figure 6: Sound absorption coefficient (a) and transmission loss (b) of 200 mm Ecophon Modus S glass-wool faced by Fantoni 4Akustik milled specimen.

## 5. Conclusions

The four-microphone impedance tube allows a fast and reliable characterization of the acoustic properties of materials. When estimating the transmission loss, particular attention has to be paid in cutting the samples and in preparing them, since this parameter may strongly depend on the boundary conditions represented by the interference between the specimen and the test equipment.

The transfer matrix method can also be used to characterize the single layers composing a complex stratigraphy and predict the overall acoustic behavior. Moreover, when the material under test can be considered an equivalent fluid, the acoustic measurements in the impedance tube can potentially be used also to derive the physical characteristics of the material. This approach, some examples of which can already be found in the literature, allows to feed the physical parameters of porous media as input to a FE model of a reverberation room [12] to simulate the low frequency damping due to the presence of a porous material.

## Acknowledgements

This article is based upon work from COST Action DENORMS CA15125, supported by COST (European Cooperation in Science and Technology). The authors would like to thank Saint-Gobain ECOFON AB and Fantoni S.p.A. for providing the materials to test.

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