

Towards a sustainable approach for sound absorption assessment of building materials: Validation of small-scale reverberation room measurement

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1 **Towards a sustainable approach for sound absorption assessment of building materials:**  
2 **validation of small-scale reverberation room measurements** <sup>a)</sup>  
3

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15 **Abstract**

16  
17 The research and development phase of sound absorptive building materials by designers,  
18 engineers, acoustic consultants and architects need tools for fast, inexpensive preliminary  
19 comparison tests on products or acoustic systems. The existing methods exhibit some drawbacks:  
20 the impedance tube (IT) is not suitable for 3D systems, while the full-scale reverberation room  
21 (FSRR) requires test samples of large dimensions. To overcome these limitations, this work aims to  
22 explore the capabilities of small-scale reverberation rooms (SSRR) of about 3 m<sup>3</sup> located at  
23 Politecnico di Torino in evaluating the random-incidence sound absorption coefficient. In order to  
24 define the range of application and reliability of the method, the considered factors are the sample  
25 area and its orientation on the room floor. Four different materials have been tested by applying IT,  
26 FSRR and SSRR. The absorption coefficients data obtained with SSRR are compatible with the  
27 FSRR benchmarking in the 400-5000 Hz frequency range for three porous materials, and in the  
28 range 1000-5000 Hz for the thin rigid material. Therefore, the SSRR can be considered as a reliable  
29 alternative for the sound absorption characterization in these ranges for this kind of materials,  
30 leading to several benefits. Among them, samples with reduced size can be evaluated with a  
31 cheaper equipment in a short time, increasing the overall economical sustainability of the  
32 measurement process; in turn, this can encourage designers and architects to perform acoustical  
33 measurements since the very early research and development phase, leading to an overall reduction  
34 of design costs and improved product quality.

35

36 *Keywords:* Acoustic measurements; Sound absorption coefficient; Measurement uncertainty;  
37 Building materials; Sustainability; Small-scale reverberation room.

38

## 1. Introduction

The design process of sound absorptive materials is complemented by a preliminary exploratory phase that requires an immediate feedback on the acoustic performance, i.e. the absorption coefficient. Therefore, adequate tools are needed to accelerate the research and development process, minimize costs, and reduce waste due to dismantled samples after their characterization. The absorption coefficient measurement procedure has been the focus of continuous research that have led to two main standardized methods, i.e. the impedance tube (IT) method defined in ISO 10534 [1] and the full-scale reverberation room (FSRR) method described in ISO 354 [2] and ASTM Standard C423 [3]. However, these methods present several disadvantages: IT does not allow to test 3D systems, while FSRR requires large samples. This paper aims to explore the capabilities of small-scale reverberation rooms (SSRR) in providing accurate estimations of the absorption coefficients with respect to the FSRR benchmarking and in overcoming the above-mentioned drawbacks of existing methods.

The main advantages of a SSRR are the possibility to test samples that are much smaller than 10-12 m<sup>2</sup> and the 6.69 m<sup>2</sup> recommended by the FSRR measurements ( $V > 200 \text{ m}^3$ ) according to ISO 354 [2] and ASTM Standard C423 [3], respectively, and to allow more acousticians, manufacturers and practitioners to build their test facility due to the more feasible construction compared to a FSRR. This, in turn, enables a dramatic reduction of economical and time efforts necessary to perform a FSRR measurement. Moreover, the SSRR can be used to improve the quality of acoustic simulations: novel materials at configurations not available in existing databases can be characterized much more easily [4].

Due to their cost effectiveness, SSRRs have been the focus of research in the automotive sector [5], which usually requires absorption data at medium-high frequencies due to the small size of the involved samples. The research has led to a SAE (Society of Automotive Engineers) standard [6] on the use of small rooms for absorption coefficients measurements. The common size of these rooms

64 is in the range of 3-10 m<sup>3</sup>, and a sample area of 0.4-1.5 m<sup>2</sup> is usually deployed [7]: this leads to  
65 nearly 90% reduction of the wasted material for laboratory measurements compared to the FSRR  
66 (12 m<sup>2</sup>). The sample arrangement in the SSRR requires a shorter set-up time: a single panel is  
67 usually sufficient, while in FSRR several panels need to be assembled to reach a 12 m<sup>2</sup> sample. In  
68 turn the transportation costs and the related environmental pollution benefit from the reduction in  
69 material volume. Moreover, the same samples could be reused to measure other important  
70 properties for building materials, e.g. the thermal conductivity [8], since the required sample  
71 dimensions are comparable to those used in small-scaled rooms.

72 Further SSRRs are reported in Rey et al. [9] with a volume of 1.12 m<sup>3</sup> and test sample area of 0.3  
73 m<sup>2</sup>, and Pacheco et al. [10] with a volume of 0.96 m<sup>3</sup> and test sample area of 0.3 m<sup>2</sup>. These scaled  
74 rooms have been useful also for testing more complicated structures, e.g. 3D rigid polyester  
75 systems, which is difficult to test in an impedance tube [11]. The continuous research on SSRRs has  
76 led to the Alpha Cabin, built by the Swiss company Rieter, with a volume of 6.5 m<sup>3</sup>. The design and  
77 size of the Alpha Cabin is 1:3 scale of the large reverberation room located in the Swiss Federal  
78 Laboratory of Material Testing and Research Institute (EMPA). It is largely used in the automotive  
79 industry allowing to measure 1.2 m<sup>2</sup> of flat samples or 3D moulded finished parts providing  
80 accurate measurements in the frequency range of 400-5000 Hz [11].

81 A few studies have also compared small-scale reverberation room measurements with those  
82 performed in a full-scale reverberation room [9, 11-13]. A good match of the results has been  
83 shown in the range of frequencies above 400 Hz, where the SSRR is expected to fulfil the perfect  
84 diffusion conditions, i.e. where the degree of diffusion is close to 1. However, these studies also  
85 highlight larger discrepancies at low frequencies due to the reduced size of the room. This is a  
86 critical aspect since the resulting smaller sample area with equal height produces a larger edge  
87 effect [14, 15]. The impact of these effects is particularly high at low frequencies if highly  
88 absorbing materials with high thicknesses are tested.

89 Therefore, two main concerns appear when dealing with small reverberation rooms. The first is  
90 related to the lack of a degree of diffusivity of the sound field required to make the measurement  
91 conditions largely independent of the room properties [16]. To mitigate this issue, usually different  
92 types of diffusers are introduced [2, 17,18]; nevertheless, the efficiency of the diffusers is shown to  
93 be reduced when the frequency decreases [19]. In addition, according to Scrosati et al. [20], the  
94 diffusers change the mean free path in the reverberation room, thus ISO 354 formula for the  
95 calculation of the equivalent absorption area is no longer valid since it does not take into account  
96 the actual mean free path and consequently the changed volume of the room. However, low  
97 diffusivity of reverberation rooms is still one of the main concerns of the ISO 354 measurements  
98 related to the low reproducibility values among laboratories. This is much evident at low  
99 frequencies [21], but appear even above the Schroeder frequency, where the sound field should  
100 reach a higher degree of diffusivity [22, 23]. One of the causes is due to the fact that the sound field  
101 is diffuse in the empty room, while in the room with a highly absorbing sample the sound field  
102 cannot be considered perfectly diffuse [20]. For this reason, the diffuse field conditions differences  
103 among laboratories has been questioned lately aiming at new requirements to be defined in terms of  
104 diffusivity for qualified laboratories [24]. Several studies have shown that large discrepancies might  
105 occur among different full-scale laboratories even though they fulfil the ISO qualification  
106 requirements [25]. As for FSRR, the low frequencies range in SSRR is the most critical one, where  
107 the early decay is dependent on strong, distinct reflections and need to be treated with specific  
108 methods [26, 27].

109 The second drawback of SSRR measurements is related to the diffraction due to the finite size of  
110 the tested material, especially at the low frequencies, which is known as the edge effect [14, 28, 29],  
111 and restricts the reliability frequency range at medium-high frequencies. Further investigation is  
112 needed to clarify the trade-off between reduced sample size and the appropriate room and sample  
113 conditions to obtain reliable results for building materials.

114 To shed light in this direction, this study examines a broad measurement campaign in a small-scale  
115 reverberation room in the laboratories of the Department of Energy (DENERG) of Politecnico di  
116 Torino, with the aim to evaluate the reliability of the sound absorption coefficient measurements.  
117 Four different materials at three different sizes and orientations on the room floor have been tested.  
118 The work assesses the compatibility of the SSRR measurements towards measurements made on  
119 the same materials in a full-scale reverberation room (ISO 354) [2] at INRiM (Istituto Nazionale di  
120 Ricerca Metrologica). Moreover, the same materials have been additionally characterized with the  
121 impedance tube method (ISO 10534-2) [1] in order to present an easier and direct comparison  
122 towards another standardized method. Finally, the single sound absorption indices  $\alpha_w$  (weighted  
123 sound absorption coefficient), NRC (Noise Reduction Coefficient), and SAA (Sound Absorption  
124 Average), which are used to assess the quality of the absorption and to select products by designers  
125 and architects, are derived from the three measurement methods.

## 126 **2. Methods**

127 The research has been organized through the following steps:

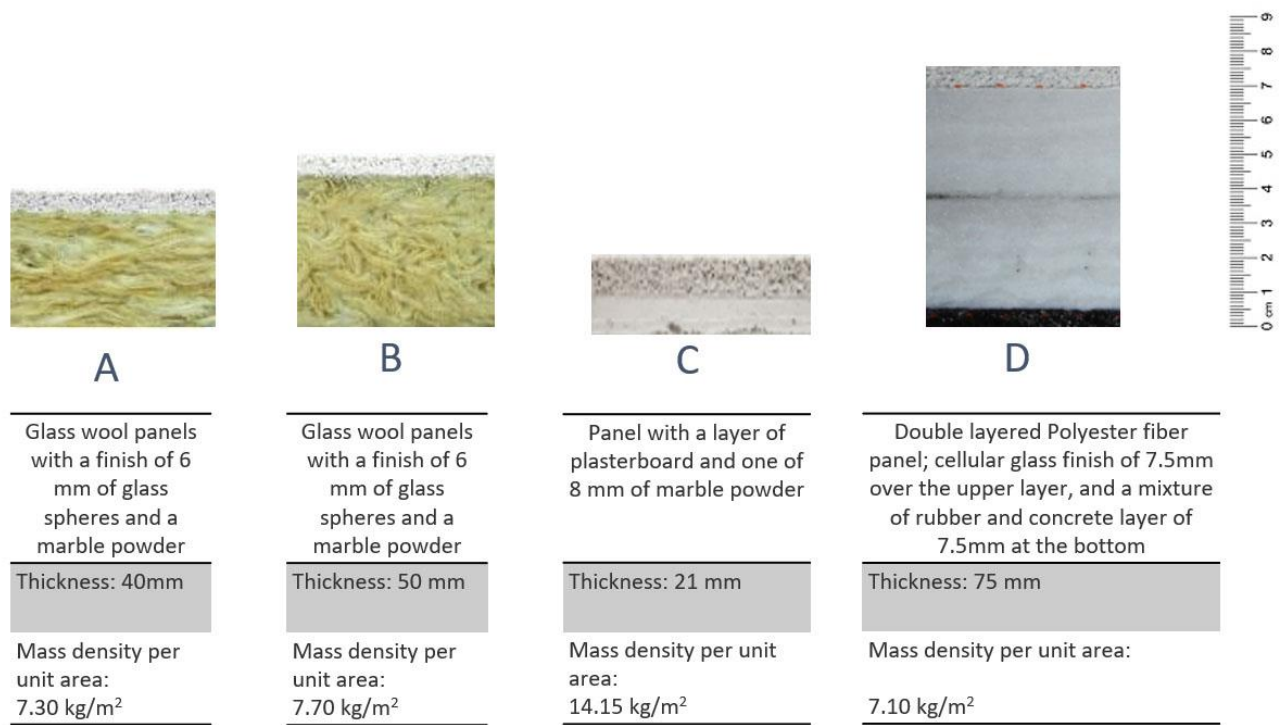
- 128 1) Selection of materials and preparation of samples for the measurements in IT, FSRR and  
129 SSRR;
- 130 2) Measurement of sound absorption in the IT according to ISO 10534-2 [1] and FSRR  
131 according to ISO 354 [2];
- 132 3) Measurement of sound absorption in the SSRR and test the range of application of ISO 354  
133 [2] method by varying the area of the sample and its orientation on the room floor;
- 134 4) Evaluation of the compatibility of the measured SSRR data with the results from IT and  
135 FSRR;
- 136 5) Computation of the indices  $\alpha_w$ , SAA and NRC for the IT, FSRR and SSRR data and  
137 compatibility assessment.

138



139 2.1 Tested Materials

140 Four materials (here labelled A, B, C, D) available at INRiM have been tested (Figure 1). Materials  
141 A and B are made of glass wool panels with a density of  $80 \text{ kg/m}^3$  and a 6 mm finished layer made  
142 of glass spheres and a marble powder with overall thickness of 40 mm and 50 mm, respectively.  
143 Material C is a 21 mm thick panel with a layer of 13 mm of plasterboard and 8 mm finished layer  
144 made of a marble powder. Material D is composed of two superimposed layers of polyester fibre  
145 with a density of  $80 \text{ kg/m}^3$  and a thickness of 30 mm each. Also, this material has a cellular glass  
146 finish of 7.5 mm over the upper layer, and a mixture of rubber and concrete layer of 7.5 mm at the  
147 bottom. Since all these materials are obtained by layers of different characteristics, they can be  
148 considered as non-isotropic. The four materials have been chosen based on commercially available  
149 materials in order to have four different thicknesses: two similar materials A and B with the same  
150 layers characteristics but with slightly different thickness, material C considered as a thin rigid  
151 material and material D was chosen in order to test the SSRR also for significant thicknesses.



152

**Fig. 1.** Sample A and B: Glass wool panels with a finish of glass spheres and a marble powder (40 mm and 50 mm). Sample C: one layer of plasterboard and one of marble powder (21 mm). Sample D: Double layered polyester fibre panel with a cellular glass finish (75 mm).

## 2.2 Impedance tube measurements

Measurements have been performed in the impedance tube in accordance with ISO 10534-2 [1] (two-microphone technique) in order to measure the normal-incidence absorption coefficient ( $\alpha_0$ ) for the four materials. The advantages of this method rely on the possibility to obtain measurements using small samples of less than 0.1 m<sup>2</sup> that are easily obtained and introduced into the impedance tube. These measurements took place in the INRiM laboratory. Two different tubes of 30 mm and 50 mm diameter each (Figure 2), both equipped with two ¼" microphones (Brüel & Kjær 4136), have been used in order to assure a higher accuracy in the whole frequency range of interest, i.e. 100-5000 Hz. The 30 mm tube (length of 45 cm and microphone spacing of 16 mm) allows to measure with a high accuracy in the frequency range of 400-6300 Hz and the 50 mm tube (length of 52 cm and microphone spacing of 26 mm) in the frequency range of 100-3150 Hz. The ISO 10534-2:2001 standard does not define the exact frequency range for a given tube diameter and microphone separation, but recommends the bounds for the lower and upper frequencies; therefore, the frequency range was chosen to satisfy the standard requirements for the level of nonlinearities, frequency resolution, measurement instabilities and signal-to-noise ratio [30].

Both the two tubes are equipped with a white noise source which generates a flat spectrum in the 100-5000 Hz frequency range. The possible gaps among the sample perimeter and the tubes inner surfaces have been sealed by covering the sample border with vaseline without creating local compression on the samples. In this way, the size of the voids between the tested material and the sample holder was reduced so that the circumferential effect discussed in [31] could be considered negligible. The effect of the irregularities in the samples, and in particular at the edges, was taken

178 into consideration by repeating the tests with three different samples. Temperature and atmospheric  
 179 pressure were measured with proper calibrated transducers. For each material type, measurements  
 180 were performed on three samples (nominally equal), obtained from the same larger sample, in order  
 181 to evaluate uncertainty contribution due to reproducibility.

182 The normal-incidence absorption coefficients ( $\alpha_0$ ) data from the two tubes measurements have been  
 183 combined in order to fulfil their covered frequency range, thus considering the values from the 50  
 184 mm tube in the range 100-315 Hz; the mean values from the two tubes in the range 400-3150 Hz  
 185 and the values from the 30 mm tube in the range 4000-5000 Hz. These data are shown in  
 186 Appendices A, B, C and D as IT<sub>n</sub>.

187 These values have been corrected for diffuse incidence based on the approach proposed in Spagnolo  
 188 and Benedetto [32], which uses a physical model to determine the random-incidence absorption  
 189 coefficient ( $\alpha$ ) by integrating a vector of evenly spaced 90 angles between 0° and 90°, i.e. the whole  
 190 hemi-solid angle, allowing to estimate the sound energy density absorption at each angle of  
 191 incidence, randomly, as in near-diffuse field, according to Eq. (1). There are several methods that  
 192 can be used to perform this correction taking into account the finite sample size [33] and a different  
 193 angular integration limit [34].

$$\alpha = \int_0^{\pi/2} \alpha_{\theta} \cos\theta \, d\theta \quad (1)$$

194

195 where  $\theta$  is the angle of incidence of the pressure waves on the sample and  $\alpha_{\theta}$  is the sound  
 196 absorption coefficient at angle  $\theta$  given by Eq. (2);

$$\alpha_{\theta} = 1 - \left| \frac{Z \cos\theta - \rho_0 c}{Z \cos\theta + \rho_0 c} \right|^2 \quad (2)$$

197

198 where  $Z$ , assuming locally reacting surface, is the acoustic impedance of the absorbing material  
 199 given by:

$$Z = \rho_0 c \frac{1 + (1 - \alpha_0)^{1/2}}{1 - (1 - \alpha_0)^{1/2}} \quad (3)$$

where  $\rho_0$  is the density of air,  $c$  is the speed of sound, and  $\alpha_0$  is the normal-incidence absorption coefficient evaluated in the impedance tube.



**Fig. 2.** Measurements set-up in the impedance tube with a diameter of a) 30 mm and b) 50 mm, and c) circular samples of the four materials with a diameter of 30 and 50 mm.

### 2.3 Full-scale reverberation room measurements

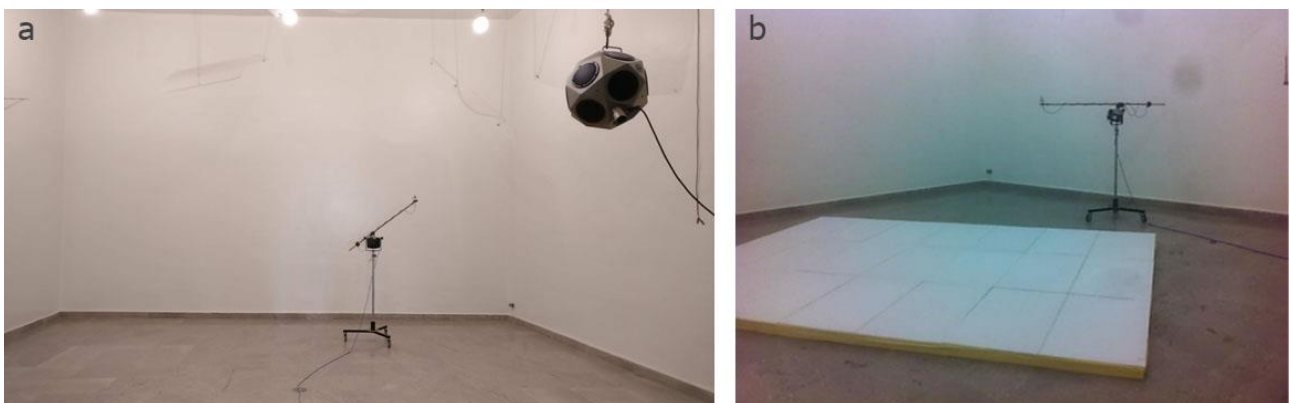
All the materials have been tested in the full-scale reverberation room at INRiM, which is a qualified room for measurements in accordance with ISO 354 [2]. The method allows to estimate the random-incidence absorption coefficient ( $\alpha_s$ ) in the 100-5000 Hz frequency range. The room has a floor surface of 59.4 m<sup>2</sup> and a height of 4.95 m, which lead to a volume of 294 m<sup>3</sup>. Room plan is irregular with non-parallel side walls. The indoor surfaces are characterized by strongly reflective walls and a marble floor characterized by an equivalent sound absorption area lower than 5 m<sup>2</sup> in the 100-5000 Hz frequency range. The mean reverberation time of the empty room between 100 Hz and 5000 Hz is of 10.3 s, thus the Schroeder frequency  $f_s$  is 374 Hz. Five diffusers are hung over the ceiling in order to assure diffusivity. The tested samples have an area of 12 m<sup>2</sup> and have been located on the floor of the room within a wooden frame, which is recommended to be used to seal the edges of the tested material. In this experiment the frame has been used for all the samples

220 except for the case of sample C, which has a negligible thickness. The porous layer for this material  
221 is of 8 mm, which was taken into account in the estimation of the overall area of the sample by  
222 increasing it of 0.11 m<sup>2</sup>.

223 The set-up and the samples of each material have been arranged in accordance with the  
224 recommendations of the ISO 354 standard (Figure 3):

- 225 • microphones should be positioned at a minimum distance of 1.5 m from each other, 1 m  
226 from the room surfaces and 2 m from the sources;
- 227 • the two sources must be at least 3 m apart from each other. A spatial averaging is performed  
228 considering all the 12 sources and microphones combination;
- 229 • the interval of frequencies of interest is reported as third-octave bands in the range 100-5000  
230 Hz;
- 231 • controlled conditions of temperature (> 15 °C) and humidity (between 30-90 %);
- 232 • the sample must be rectangular with a ratio between width and length within the range 0.7-1.  
233 In this specific case, the test specimens were composed of 25 single small panels with size  
234 60×80 cm<sup>2</sup> combined in order to cover an area of 4×3 m<sup>2</sup>;
- 235 • the sides of the sample must be distant from the walls of the room by at least 1 m.

236



237

238 **Fig. 3.** Measurements in the full-scale reverberation room a) without and b) with the sample.

239

240 The procedure consists in using the interrupted noise method [2] on six different microphone  
 241 positions in two conditions, i.e. with and without the sample on the floor of the room. The  
 242 measurement chain is composed of a 1/2" microphone (Brüel & Kjær 4943), sequentially located at  
 243 different positions, and two dodecahedral sources (Brüel & Kjær 4292 and Brüel & Kjær 4296).  
 244 The applied recording system is the SINUS, Apollo system with software Samurai 2.6; while the  
 245 sound equalizer is Yamaha (DEQ 5) and the power amplifier is Amcron Crown (MICRO-TECH  
 246 1200). In these measurements two sound sources are used for the simultaneous excitation, therefore  
 247 the number of spatially independent measured decay curves may be reduced to six [2]. For each of  
 248 the six positions, measurements are repeated four times, and the reverberation time relative to a 20  
 249 dB decay, i.e.  $T_{20}$ , is evaluated and used to estimate the  $T_{60}$ , i.e. the reverberation time occurring for  
 250 a 60 dB decay. The data are spatially averaged with the ensemble averaging method in order to  
 251 obtain  $T_1$  and  $T_2$  without and with the sample on the room floor, respectively. The difference  
 252 between the two measures is used to calculate the variation of the equivalent sound absorption area  
 253  $A_T$  based on Sabine's theory:

$$A_T = 55.3V \left( \frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_2 - m_1) \quad (4)$$

254  
 255 where  $T_1$  and  $T_2$  are the reverberation times of the empty reverberation room and after the test  
 256 specimen has been introduced, respectively;  $V$  is the volume of the empty reverberation room;  $c_1$   
 257 and  $c_2$  is the propagation speed of sound in air in the room without the sample:  $c_1 = 331 + 0,6 t_1$ ,  $t_1$   
 258 is the air temperature;  $m_1$  and  $m_2$  is the power attenuation coefficient of the climatic conditions in  
 259 the reverberation room without and with the sample (calculated according to ISO 9613-1 [35]);

260  
 261 The random-incidence absorption coefficient is defined as:

$$\alpha_s = \frac{A_T}{S} \quad (5)$$

262

263 Where  $S$  is the area covered by the test sample.

264

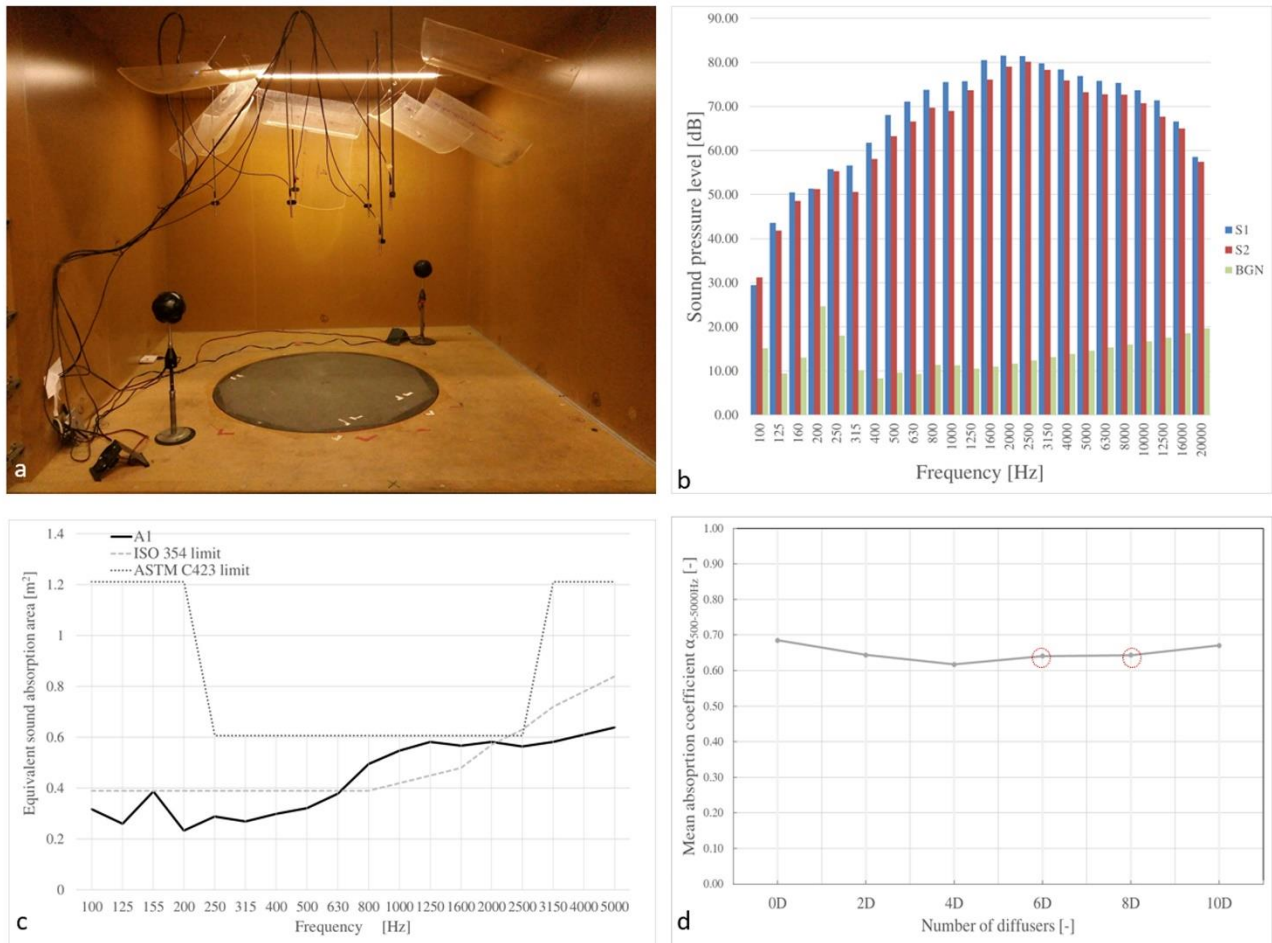
#### 265 2.4 Small-scale reverberation room measurements (SSRR)

266 The small-scale reverberation room (Figure 4, a and Figure 5) is a laboratory at DENERG  
267 (Department of Energy, Politecnico di Torino, Italy). It is a 1:5 scale reproduction of the  
268 reverberation room described above. The room has been primarily built for random-incidence  
269 scattering coefficient measurements according to ISO 17497-1 [36, 37]. It is an oblique angled  
270 room with pairs of nonparallel walls. The floor area is about  $2.38 \text{ m}^2$  and the height in the range 1-  
271 1.2 m, which lead to a maximum volume of  $2.86 \text{ m}^3$  and a total area of  $12.12 \text{ m}^2$ . The structure is  
272 raised from the ground on a wooden structure and damping layers have been used along the joints  
273 and openings. One of the sides consists of two movable parts that allow to have a large opening to  
274 ease the positioning of the sample. The construction material is self-supporting lightweight  
275 partitions of MDF (Medium Density Fibreboard) with a thickness of 3.8 cm, which has been further  
276 covered by a layer of adhesive film in order to maximize its reflective properties. The equivalent  
277 sound absorption area of the empty room ( $A_1$ ) and ISO [2] and ASTM [3] limits are shown in  
278 Figure 4, c. The ISO limit values have been multiplied by the factor  $(V/200)^{2/3}$ , while the ASTM  
279 limit value is given in terms of mean absorption coefficient ( $\alpha_m \leq 0.05$  in the 250-2500 Hz interval,  
280 and  $\alpha_m \leq 0.10$  below 250 Hz and above 2500 Hz) and has been converted into equivalent sound  
281 absorption area for comparison purposes. Given that the ISO limit is not specifically indicated for  
282 rooms below a volume of  $150 \text{ m}^3$ ,  $A_1$  can be considered acceptable even though slightly above the  
283 limit in the range 800-1600 Hz. However, the average absorption coefficient of the indoor surfaces  
284 is lower than  $\alpha_m = 0.05$  in the frequency range of interest (100-5000 Hz). The mean reverberation  
285 time of the empty room between 100 Hz and 5000 Hz of 0.95 s, thus the Schroeder frequency  $f_s$  is  
286 1152 Hz.

287 In order to assure a high diffusivity of the sound field [38], 8 diffusers (13.5% of the total room  
288 area) have been hung over the ceiling, which is considered as a more economical solution compared



289 to boundary diffusers leading to an almost equivalent effect on the diffusion of the sound field [18].  
 290 A systematic study of the sound field diffusivity evaluation of the room has been performed in [39].  
 291 The diffusivity check has been performed in accordance with ISO 354 based on the measurements  
 292 of the mean absorption coefficient (500-5000 Hz) of a highly sound absorptive panel made of 5 cm  
 293 thick polyester fibre (Figure 4, d). The final number of diffusers was set to 8, which was a  
 294 compromise between the rule set by the standard i.e. the mean sound absorption coefficient  
 295 approaches a constant value (6D to 8D), and limited effect on the volume reduction of the room due  
 296 to the total coverage of the ceiling, i.e the condition with 10 diffusers (10D).



297 **Fig. 4.** a) Empty small-scale reverberation room; b) spectral characteristics of the two sound sources  
 298 (S1 and S2) and background noise; c) comparison of the equivalent sound absorption area of the  
 299 empty room ( $A_1$ ), ISO and ASTM limits; d) mean absorption coefficient of a polyester panel of 5  
 300 cm measured in the room with no diffusers (0D) and 2-10 diffusers (2D-10D).  
 301



302

303 The procedure consists in using the integrated impulse response method [2] for simultaneous  
304 measurements on six different microphone positions in two conditions, i.e. with and without the  
305 sample on the floor of the room as in section 2.3. The measurement chain is composed of six 1/4”  
306 BSWA Tech MPA451 microphones and ICP104 (BSWA Technology Co., Ltd., Beijing, China);  
307 two ITA High-Frequency Dodecahedron Loudspeakers with their specific ITA power amplifiers  
308 (ITA-RWTH, Aachen, Germany) and a sound card Roland Octa-Capture UA-1010 (Roland  
309 Corporation, Japan) in order to perform 12 measurements (the minimum number required by ISO  
310 354 [2]). The software used for the measurements, i.e. sound generation, recording and signal  
311 processing, is MATLAB combined with the functions of the ITA-Toolbox (an opensource toolbox  
312 from RWTH-Aachen, Germany) [40]. The sound source should fulfil the ISO 354 spectral  
313 characteristics, that is, the sound pressure levels in the room shall be less than 6 dB in adjacent one-  
314 third-octave bands and the level of the excitation signal before the decay shall be sufficiently high  
315 so that the lower decibel level of the evaluation range is at least 10 dB above the background noise  
316 level, i.e. 35 dB below the initial sound pressure level. The first criterion is fulfilled for the entire  
317 frequency range, while the second is fulfilled only above the 250 Hz (Figure 4, b).

318 For each of the 12 measurements the reverberation time is evaluated. The data are spatially  
319 averaged in order to obtain  $T_1$  and  $T_2$  without and with the sample on the room floor, respectively.

320 Equations 4 and 5 are then applied to estimate the random-incidence absorption coefficient.

321 The set-up and the samples of each material have been arranged in agreement with the  
322 recommendations of the ISO 354 standard (Figure 5):

- 323     • “microphones should be positioned at a minimum distance of 1.5 m from each other, 1 m  
324         from the room surfaces and 2 m from the sources”. This leads to 0.3 m; 0.2 m and 0.4 m in  
325         1:5 scale;

- “the two sources must be at least 3 m apart”. This leads to 0.6 m in 1:5 scale. A spatial averaging is performed considering all the 12 sources and microphones combination;
- the frequencies of interest are reported as third-octave bands in the range 100-5000 Hz. Given the background noise criterion, this is valid for 250-5000 Hz;
- controlled conditions of temperature ( $> 15\text{ }^{\circ}\text{C}$ ) and humidity (between 30-90 %). A sensor has been installed inside the room;
- “the sides of the sample must be distant from the walls of the room by at least 1 m”. This leads to 0.2 m in 1:5 scale;

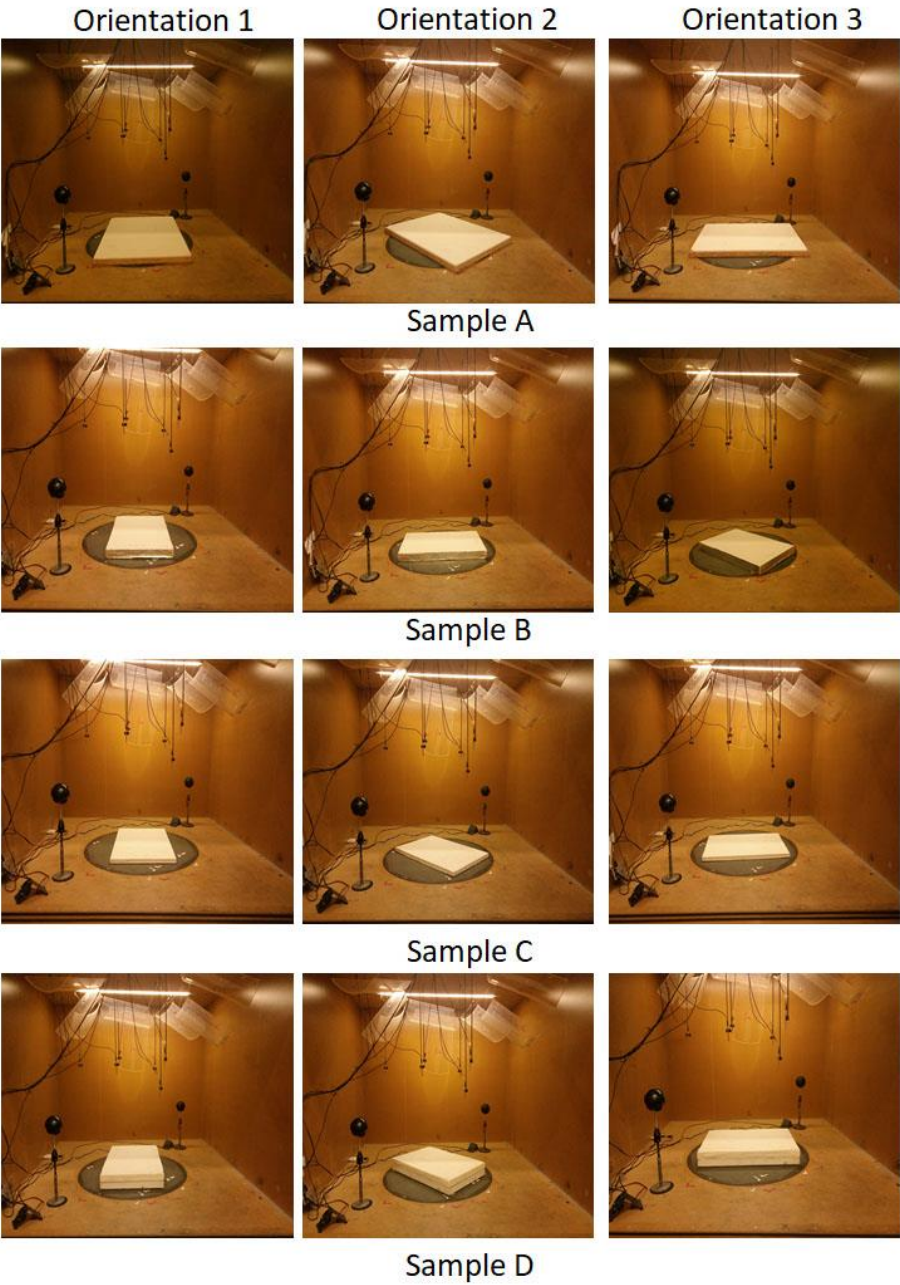
#### 2.4.1 Sample configuration

One of the aims of this study is to define the sample configuration that could lead to accurate results of the absorption coefficient measurements in the small-scale reverberation room. Given the small size of the SSRR, the sound field is expected to be strongly dependent on the configuration of the measured material. Therefore, it is crucial to define the application range of this type of measurements.

The following variables have been considered, tested and the results have been compared with the IT and FSRR measurements:

- three different sample sizes for each material ( $60\times 40\text{ cm}^2$ ;  $60\times 60\text{ cm}^2$ ; and  $60\times 80\text{ cm}^2$ ). It should be noted that the ISO 354 recommends a ratio between width and length in the range 0.7-1;
- three different orientations on the floor (Fig.5) for the  $60\times 40\text{ cm}^2$  and  $60\times 80\text{ cm}^2$  sample sizes and two different orientations for sample  $60\times 60\text{ cm}^2$ . Orientation 1 assumed the long edge of the sample parallel to the side wall, orientation 2 assumed the axis of symmetry of the sample aligned over the diagonal of the room floor giving an oblique orientation, and

350 orientation 3 assumed the long edge of the sample parallel to the rear wall. It should be  
351 noted that the ISO 354 standard recommends an oblique orientation (orientation 2).  
352 Three repetitions have been performed for each configuration.



353  
354 **Fig. 5.** Measurements in the small-scale reverberation room of one of the samples with three  
355 different orientations; Sample A ( $60 \times 80 \text{ cm}^2$ ), Sample B ( $60 \times 40 \text{ cm}^2$ ), Sample C ( $60 \times 40 \text{ cm}^2$ ) and  
356 Sample D ( $60 \times 40 \text{ cm}^2$ ).

### 3 Analyses

An analysis based on the estimation of the normalized error ( $E_n$ ) has been performed in order to assess the compatibility of the absorption coefficient data measured in the SSRR with respect to the FSRR ( $E_{n,FSRR}$ ), considered as reference value for random incidence sound absorption, and IT extended for random-incidence absorption coefficients ( $E_{n,IT}$ ). Moreover, also the normalized error of IT results has been assessed with respect to the FSRR values.  $E_n$  is defined as the ratio of the difference between the reference value ( $\alpha_x$ ) and the reported value ( $\alpha_y$ ) compared to the root sum square of associated expanded uncertainties ( $U_x$  and  $U_y$ ) at a confidence level of 95% ( $k=2$ ). According to ISO/IEC 17043:2010 [41], it is evaluated as follows:

$$E_n = \frac{|\alpha_x - \alpha_y|}{\sqrt{U_x^2 + U_y^2}} \quad (6)$$

The data can be considered compatible when  $E_n < 1$ . This is an indicator of accuracy/inaccuracy as compared to an assigned reference value (FSRR or IT) with respect to the associated uncertainties. The uncertainty of the impedance tube measurements has been assessed according to GUM-JCGM 100:2008 [42]), taking into account, as type B uncertainty contribution, the difference between the maximum and minimum values coming from the measurement on three nominally equal samples with a uniform rectangular distribution. The specific guidelines given by Wittstock (2018) (see Eq. (2) and Table II – smooth case) [43], which are currently the most reliable reference for the uncertainty evaluation in reverberation rooms based on a database of Interlaboratory Tests, have been applied for the SSRR and FSRR measurement uncertainties. Nevertheless, as shown by the author itself [43], larger uncertainties might occur, especially for highly absorptive materials with ISO 354 method, thus entailing a possible underestimation of the  $E_n$  values. Such aspect should be taken into account in the conclusions. The measured frequency dependent absorption coefficients of the four materials and the estimated measurement uncertainties are shown for further details in Appendices A, B, C and D.

381 The normalized error data have been further analysed with a focus on the effects of the independent  
382 factors, i.e. the sample size and orientation. The SPSS Statistics software [44] has been used to  
383 perform the ANOVA (ANalysis Of VAriance). The data have been first analysed with a normality  
384 test (Kolmogorov-Smirnov test):  $E_{n,IT}$  showed a skewness of 0.793 (std.error = 0.105) and kurtosis  
385 of 0.004 (std.error = 0.210);  $E_{n,FSRR}$  showed a skewness of 0.793 (std.error = 0.105) and kurtosis of  
386 0.004 (std.error = 0.210), thus falling within the acceptable range of  $\pm 2$  [44].  
387 Moreover, the single indices for sound absorption ( $\alpha_w$ , NRC and SAA) are derived from the IT,  
388 FSRR and SSRR measurements and compared in terms of compatibility.  
389

390 Table 1: ANOVA results for  $E_{n,IT}$  and  $E_{n,FSRR}$  data set.

	$E_{n,IT}$				$E_{n,FSRR}$			
	Size		Orientation		Size		Orientation	
Material	F	p	F	p	F	p	F	p
A	(2, 135) 21.580	0.000	(2, 135) 0.095	0.910	(2, 135) 15.248	0.000	(2, 135) 0.110	0.896
B	(2, 135) 13.910	0.000	(2, 135) 0.093	0.980	(2, 135) 5.496	0.005	(2, 135) 0.090	0.914
C	(2, 135) 0.827	0.440	(2, 135) 0.468	0.628	(2, 135) 0.501	0.607	(2, 135) 0.235	0.791
D	(2, 135) 5.481	0.005	(2, 135) 0.308	0.736	(2, 135) 20.018	0.000	(2, 135) 0.255	0.776

391

## 392 4 Results and discussion

### 393 4.1 Effects of the independent factors

394 The ANOVA performed on the overall  $E_n$  set of data showed that the four materials are  
395 significantly different from each other at a confidence level of 95% for  $E_{n,IT}$  with respect to IT ( $F(3, 540) = 14.143$  and  $p < 0.001$ ) and at a confidence level of 90% for  $E_{n,FSRR}$  with respect to FSRR ( $F(3, 540) = 2.277$  and  $p = 0.079$ ). Therefore, sample size and orientation variables have been  
396 analysed for each material separately (Table 1).

399 The effect of the sample size is statistically significant for all the samples typologies ( $p < 0.05$ ),  
400 except for sample C. This result might be due to the limited edge effect for thinner samples, as  
401 sample C is 21 mm thick. Appendices A, B, C and D show the absorption coefficient values for  
402 each material. For panels with higher thickness (i.e. A, B, D) and when the panel reaches the  
403 smallest dimensions  $60 \times 40 \text{ cm}^2$ , there are evident irregular high peaks at mid and high frequencies  
404 for panels A and B, and also at low and mid frequencies for panel D. It can be noticed that the  
405 sound absorption increases at 160-400 Hz and above 800 Hz with decreasing samples size  
406 (Appendices A, B, and D). This behaviour might be due to a combination of edge effects and to  
407 diffusivity effects, caused by the influence of the material on the modal behaviour of the room with  
408 and without the sample inside, whereas for low absorbing materials (Appendix C) it can be considered  
409 equivalent in terms of spatial distribution and amplification of standing waves. Schiavi and Prato [45]  
410 showed these discrepancies by comparing full scale reverberation room, impedance tube, and  
411 airflow resistivity methods. The same result has been highlighted also in full-scale rooms by Jain et  
412 al. [46], for samples size smaller than  $1 \text{ m}^2$ , which is due to diffraction occurring at the sample  
413 edges. Anyway, in general terms, depending on the sample thickness, the small room gives higher  
414 sound absorption values as compared to large reverberation rooms [15]. Samples A, B and D  
415 showed this trend above 800 Hz, while sample C above 2000 Hz.

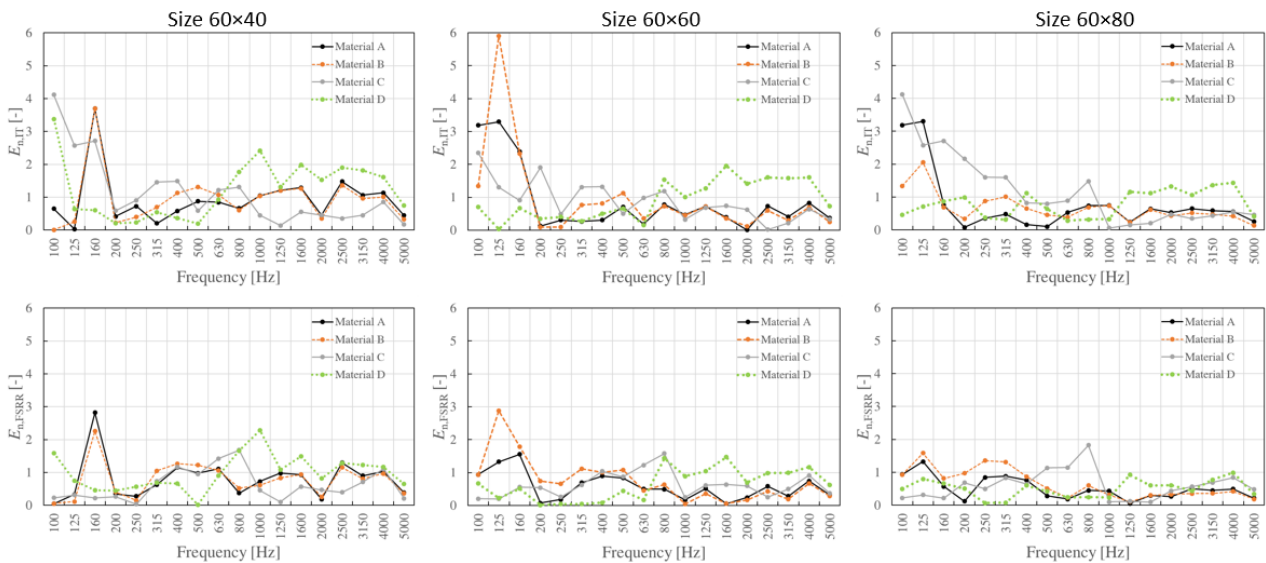
416 The correct scaling of the sample size with respect to the room volume has been investigated also in  
 417 Veen et al. [28]. This study shows that a sample of  $1.12 \text{ m}^2$  could be considered in order to have  
 418 reliable results in a small reverberation room with a volume of about  $6.4 \text{ m}^3$ . The ratio between the  
 419 room volume and the sample area is comparable to the one obtained with the room volume of  
 420  $2.86 \text{ m}^3$  and the sample size  $60 \times 80 \text{ cm}^2$  ( $0.48 \text{ m}^2$ ) used in the present study (i.e. ratio  $\approx 6$ ).  
 421 The effect of the sample orientation has been analysed for all the materials and all the sample sizes.  
 422 Table 1 shows that the differences due to sample orientations are not statistically significant for all  
 423 the materials considered ( $p > 0.05$ ). It is therefore possible to choose an oblique panel orientation  
 424 (Orientation 2), as suggested in the standard for full-scale measurements. Previous research [16] has  
 425 shown that different orientations may cause discrepancies at lower frequencies (below 400 Hz) and  
 426 that the smoothest curve is obtained for the oblique orientation, which is the most asymmetric one.  
 427 This study also highlighted that the other two orientations cause strong peaks in the absorption  
 428 coefficient, which were unrealistic for the tested porous materials. The authors argued that this  
 429 behaviour might be due to the parallel orientation of two edges of the material against two side  
 430 walls of the reverberation room. However, this effect is not fully observed in the study presented in  
 431 this paper. Some differences between the three orientations are observed at specific frequencies for  
 432 the smallest sample size, i.e.  $60 \times 40 \text{ cm}^2$  (Appendixes A, B, C, and D). Discrepancies at lower  
 433 frequencies are reduced when the material has lower thickness, i.e. these differences are more  
 434 evident in the case of panel D, which has a thickness of 75 mm. This finding is coherent with the  
 435 results of Cops et al. [16], which showed the same discrepancies between different orientations for  
 436 samples with thickness higher than 100 mm in full-scale measurements.

437

#### 438 4.2 Compatibility of SSRR with IT and FSRR data

439 Figure 6 shows the maximum normalized error values estimated in each third octave band  
 440 frequency range for the SSRR data with respect to FSRR and IT data. SSRR data are reliable from

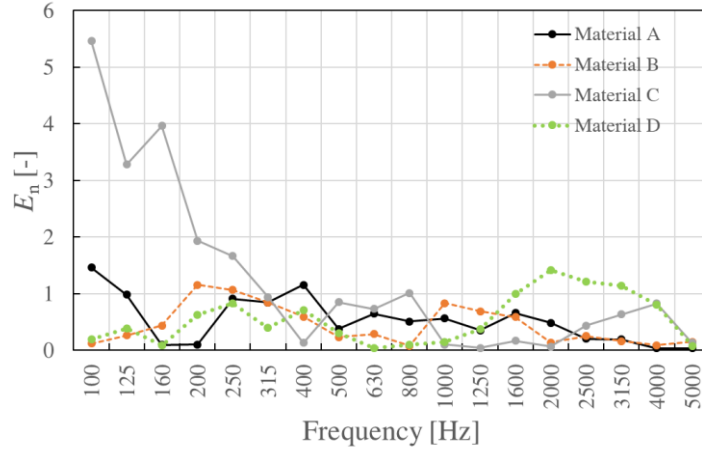
250 Hz upward, due to the background noise criterion previously discussed, however, for the sake of completeness, results are reported from 100 Hz. These plots show the  $E_n$  for material A, B, C and D at three sample sizes ( $60 \times 40 \text{ cm}^2$ ,  $60 \times 60 \text{ cm}^2$ , and  $60 \times 80 \text{ cm}^2$ ) and Orientation 2 only, since this factor was not found to be statistically significant. The results show that the normalized error ( $E_n$ ) is minimized for sample size  $60 \times 80 \text{ cm}^2$  for all the materials.  $E_{n,\text{FSRR}}$  values are lower than 1 in the frequency range 400-5000 Hz, for materials A, B and D. Sample C presents  $E_{n,\text{FSRR}}$  values lower than 1 at 400 Hz and in the frequency range 1000-5000 Hz. Values slightly higher than 1 result between 500 Hz and 800 Hz. As highlighted in the previous section, this might be due to the limited effects of this low absorbing and thinnest sample on the modal behaviour of the room it-self. This result suggests further future investigation on the room diffusivity. The same conclusions can be obtained for  $E_{n,\text{IT}}$  for materials A, B and C. For what concern material D, it can be noted that  $E_{n,\text{IT}} < 1$  only at 500-1000 Hz. This could be due to the fact that IT method tends to underestimate the sound absorption at mid-high frequencies as shown in Appendix and in Figure 6.  $E_{n,\text{IT}}$  values are higher than  $E_{n,\text{FSRR}}$  values, which leads to a higher compatibility of the SSRR with respect to the FSRR. These differences are maximized for the thickest material D, i.e.  $E_{n,\text{IT}} > 1$  and  $E_{n,\text{FSRR}} < 1$  at 1250-4000 Hz. The same behaviour can be observed also when evaluating the normalized error of the IT data with respect to the FSRR (Figure 7), i.e.  $E_n > 1$  at 1600-3150 Hz.



458



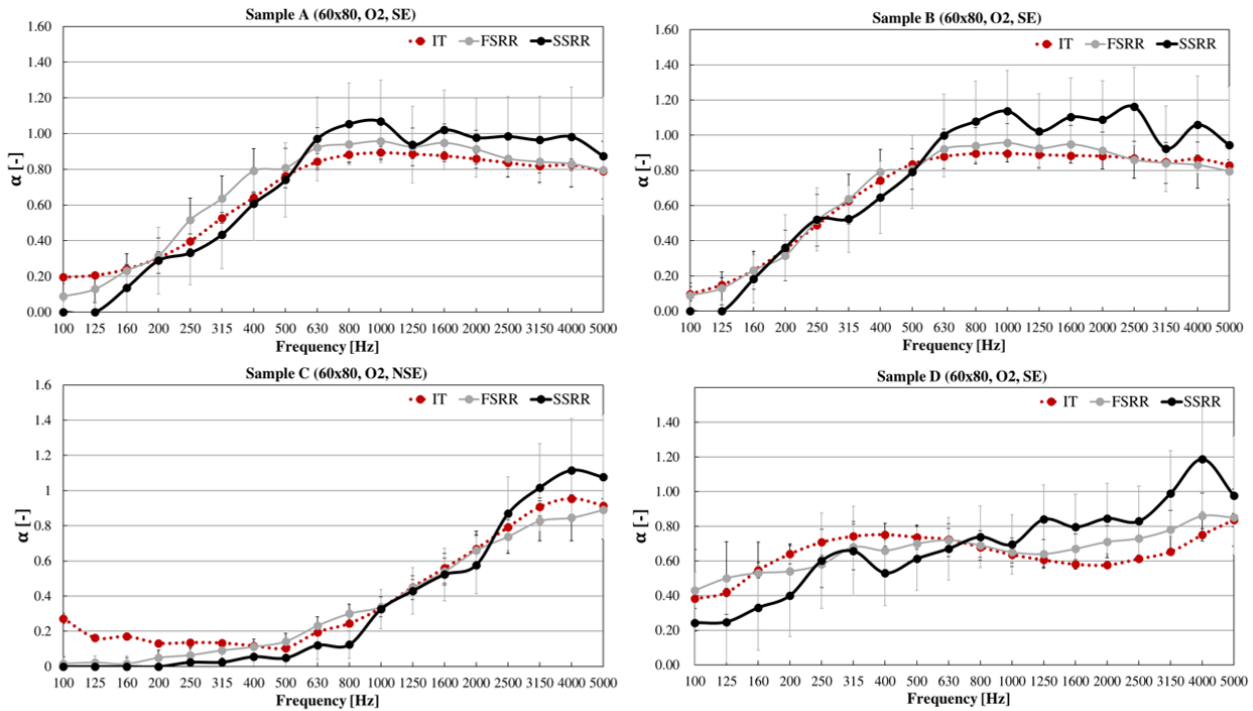
459 **Fig. 6.** Normalized error ( $E_n$ ) for SSRR results (material A, B, C and D) with respect to IT ( $E_{n,IT}$ )  
 460 and FSRR ( $E_{n,FSRR}$ ) values for the three sample sizes ( $60 \times 40 \text{ cm}^2$ ,  $60 \times 60 \text{ cm}^2$ , and  $60 \times 80 \text{ cm}^2$ ) and  
 461 orientation 2. The data can be considered compatible when  $E_n < 1$ .



462  
 463 **Fig. 7.** Normalized error ( $E_n$ ) for IT results (material A, B, C and D) with respect to the FSRR  
 464 values. The data can be considered compatible when  $E_n < 1$ .

465  
 466 The absorption coefficient data of the optimal condition i.e. size  $60 \times 80 \text{ cm}^2$  and sample orientation  
 467 2, together with the uncertainty values of the results, are shown in Figures 8. The plots show that  
 468 the SSRR values tend to be higher for frequencies above 800 Hz for samples A, B and D and above  
 469 2000 Hz for sample C. One of the causes for this behaviour is that the absorption coefficient  
 470 approaches to 1 at these frequency ranges and influences the diffusivity of the sound field generated  
 471 within the small-scale room. This has been observed also in Veen et al. [28], where higher  
 472 discrepancies around 1000 Hz for samples with thickness above 25 mm were found. Also, Jain et al.  
 473 [46] showed a good match at mid frequencies from 400-1000 Hz between FSRR and SSRR and an  
 474 overestimation of sound absorption values above 1000 Hz for the small-scale reverberation room.  
 475 This is attributed to the use of Sabine's formulas instead of Eyring's as highlighted by Vercammen  
 476 [21]. Moreover, it should be highlighted that the differences obtained here between the small- and

477 full-scale room or impedance tube measurements are comparable with those obtained from  
 478 absorption coefficient measurements in 13 different laboratories Vercammen [21].



479  
 480 **Fig. 8.** Absorption coefficient of four materials in the conditions that minimized the normalized  
 481 error: samples with a size of 60×80 cm<sup>2</sup>, orientation 2, with sealed edges (Sample A, B, and D) and  
 482 with unsealed edges (Sample C). Also, the FSRR data report measurements with sealed edges and  
 483 no sealed edges, respectively. IT data are given after correction for diffuse incidence.

484  
 485  
 486 **4.3 Single number acoustic indices  $\alpha_w$ , NRC, and SAA**

487 Based on the above results, sound absorption indices  $\alpha_w$ , NRC, and SAA are derived from the IT,  
 488 FSRR and SSRR measurements. These single indices are useful for an immediate and practical  
 489 comparison of the performance of different materials. The higher the  $\alpha_w$ , SAA or the NRC values,  
 490 the better is the material capability in sound absorption. Their values normally range from 0 to 1,  
 491 with 1 meaning 100% sound absorption for 1 m<sup>2</sup> of material. These three indices have been  
 492 compared in former studies in order to estimate the differences and any possible drawback that  
 493 could lead to flaws in the performance comparison [47].

494 The weighted sound absorption coefficient  $\alpha_w$  is derived from practical sound absorption  
 495 coefficients,  $\alpha_p$ . They are frequency-dependent values of the sound absorption coefficient, based on  
 496 measurements on one-third octave bands (according to EN ISO 354 [2]) and calculated in octave  
 497 bands in accordance with EN ISO 11654 [48]. An averaged  $\alpha_p$  is calculated for the three one-third  
 498 octave sound absorption coefficients within the octave. Weighted sound absorption coefficient  $\alpha_w$   
 499 can be obtained with the reference curve ( $\alpha_{250}=0.8$ ;  $\alpha_{500}=1$ ;  $\alpha_{1000}=1$ ;  $\alpha_{2000}=1$ ;  $\alpha_{4000}=0.9$ ). The curve is  
 500 shifted in steps of 0.05 towards the  $\alpha_p$  values until the sum of unfavourable deviations (this occurs  
 501 when the measured value is lower than the value of the curve) is less or equal to 0.10. Finally, the  
 502 weighted sound absorption coefficient is the value of the adjusted reference curve at 500 Hz.

503 The single number rating obtained from ASTM C423 [3] is the Sound Absorption Average (SAA).  
 504 This is the average of the absorption coefficients for the twelve one-third octave bands from 200 Hz  
 505 to 2500 Hz. The SAA supersedes the Noise Reduction Coefficient (NRC), which is the arithmetic  
 506 average of the absorption coefficients determined at the octave bands of 250 Hz, 500 Hz, 1000 Hz  
 507 and 2000 Hz, rounded to the nearest multiple of 0.05. The SAA value is rounded off the nearest  
 508 0.01 increment. The ASTM standard does not introduce any shape indicators as the ISO method  
 509 described above.

510 The expanded uncertainty, at a confidence level of 95% ( $k=2$ ), of the measured data under  
 511 reproducibility conditions for  $\alpha_w$  has been evaluated according to Wittstock (2018) [43] and is equal  
 512 to 0.07, i.e. twice the reproducibility standard deviation; the same value has been considered also  
 513 for SAA and NRC, since no information is given on this regard in literature. As can be noticed in  
 514 table 2, there are a few differences among the single indices within each material data. The  
 515 differences SSRR and FSRR related to  $\alpha_w$  are within a 0.10 for samples A and B, and 0.05 for  
 516 samples C and D; differences related to NRC and SAA are within 0.05 for all the samples. Table 2  
 517 shows also the normalized error which has been evaluated for IT and SSRR measurements with  
 518 respect to the FSRR data and SSRR with respect to the IT single values. The results can be

519 considered compatible in most of the cases ( $E_n < 1$ ). However, it can be noticed that the differences  
 520 between SSRR and FSRR are comparable to those between IT and FSRR.

521

522 Table 2: Comparison of results of single acoustic indices (NRC, SAA and  $\alpha_w$ ) for the four samples  
 523 (A, B, C, D) and three different test methods (IT, FSRR, and SSRR). Normalized error of the IT and  
 524 SSRR measurements with respect to the FSRR data and SSRR measurements with respect to IT  
 525 data.  $E_n > 1$  are indicated in bold.

Sample	A			B			C			D		
Test Method	$\alpha_w$	SAA	NRC	$\alpha_w$	SAA	NRC	$\alpha_w$	SAA	NRC	$\alpha_w$	SAA	NRC
IT	0.70	0.73	0.75	0.75	0.77	0.75	0.20	0.32	0.30	0.65	0.67	0.65
FSRR	0.75	0.79	0.75	0.85	0.84	0.75	0.20	0.31	0.30	0.70	0.66	0.70
SSRR	0.65	0.78	0.80	0.75	0.87	0.85	0.15	0.26	0.25	0.70	0.68	0.70
$E_n$ (IT-FSRR)	0.51	0.61	0.00	<b>1.01</b>	0.71	0.00	0.00	0.10	0.00	0.51	0.10	0.51
$E_n$ (SSRR-FSRR)	<b>1.01</b>	0.10	0.51	<b>1.01</b>	0.30	<b>1.01</b>	0.51	0.51	0.51	0.00	0.20	0.00
$E_n$ (SSRR-IT)	0.51	0.51	0.51	0.00	<b>1.01</b>	<b>1.01</b>	0.51	0.61	0.51	0.51	0.10	0.51

526

527

#### 528 4.4 Comparison among the three methods

529 Finally, a summary of the advantages and disadvantages of the three methods are listed in Table 3.  
 530 It can be noticed that the SSRR presents a series of practical advantages that could allow for faster  
 531 measurements applying less resources, i.e. allows for an explorative phase in the early stages of the  
 532 design process as well as reduces the amount of material used for the production of the samples  
 533 leading to more sustainable ways of performing acoustic measurements. Moreover, these practical  
 534 features and faster feedback could ease the dissemination and increase awareness related to the  
 535 acoustic performance among designers and architects.

## 536 5 Conclusions

537 This work explored the range of application and reliability of the random-incidence absorption  
 538 coefficient measured within a small-scale reverberation room. Four different materials have been  
 539 measured with three different methods in the impedance tube (IT), full-scale (FSRR) and small-

scale (SSRR) reverberation room. It was shown that the SSRR presents several advantages compared to the other methods, which have a practical relevance in the explorative design process of sound absorptive building materials. After the research and development phase, the final material can be sent to an independent acoustical laboratory for qualified ISO 354:2003 measurements.

Table 3: Synthetic comparison among IT, FSRR and SSRR methods.

Method	Sound incidence	Frequency range [Hz]	Sample area (m <sup>2</sup> )	Advantages	Disadvantages
IT	Normal	100-5000 (depending on the tube diameter)	< 0.1	<ul style="list-style-type: none"> <li>• reduced sample size</li> <li>• affordable measurement costs</li> <li>• limited wasted material</li> <li>• measurement time duration (&lt; 30 min)</li> </ul>	<ul style="list-style-type: none"> <li>• limited frequency range</li> <li>• normal sound incidence</li> <li>• 3D absorbing systems</li> </ul>
FSRR	Random	100-5000	10-12	<ul style="list-style-type: none"> <li>• sound incidence</li> <li>• limited edge effect</li> <li>• broad frequency range</li> <li>• 3D absorbing systems</li> </ul>	<ul style="list-style-type: none"> <li>• large sample size</li> <li>• huge measurement costs</li> <li>• high quantity of material to be dismantled</li> <li>• measurement time duration (&gt; 60 min)</li> </ul>
SSRR	Random	400-5000 (for porous materials) 1000-5000 (for thin rigid materials)	0.2-1.5	<ul style="list-style-type: none"> <li>• sound incidence</li> <li>• reduced sample size</li> <li>• affordable measurement costs</li> <li>• limited wasted material</li> <li>• measurement time duration (&lt;30 min)</li> <li>• 3D absorbing systems</li> </ul>	<ul style="list-style-type: none"> <li>• limited lower frequency range</li> <li>• edge effect</li> <li>• limited sample height</li> </ul>

The SSRR-based results have been compared against FSRR measurement, used as a reference, and IT measurements. The analyses showed that normalized errors smaller than 1 – i.e. compatible results – can be generally achieved, provided that some recommendations in measurement setup are needed. First, to have reliable data a sample size close to 60×80 cm<sup>2</sup> is recommended; the size

551 should be placed with an oblique orientation on the room floor. Second, the sound absorption  
552 coefficients data showed that the edge effect is more evident for thicker panels ( $>50\text{cm}$ ) and smaller  
553 samples ( $60\times40\text{cm}^2$ ). For samples sizes of  $60\times80\text{cm}^2$  the edge effect has been shown to be reduced  
554 also for thicker samples. This aspect should be investigated in a more systematic way including  
555 panels with thicknesses above those considered here in order to find a threshold of validity due to  
556 this parameter. Third, a sound absorption overestimation can take place depending on the sample  
557 thickness. Fourth, due to the limited diffusivity of the sound field, the SSRR method can be  
558 profitably adopted when the frequencies of interest lie above 400 Hz for porous materials and above  
559 1000 Hz for thin low absorptive rigid materials. Nevertheless, as previously stated, since larger  
560 uncertainties in SSRRs and in FSRRs might occur especially for higher absorptive materials with  
561 ISO 354 method [43], compatibility ranges could be wider. Future research will be aimed at  
562 investigating this aspect.

563 Within these use-cases, the discussed results show that that the small reverberation room is a  
564 reliable measurement tool in the frequency range 400-5000 Hz (for porous materials) and 1000-  
565 5000 Hz (for thin rigid materials), and therefore, can be considered as a valid alternative to the  
566 measurements in the full-scale or in the impedance tube. These might require a more systematic  
567 study that would consider also other variables (e.g. room volume variations) in order to define the  
568 proper range of application.

569 Finally, this work has pointed out the advantages related to the possibility to test small-size  
570 samples, thus potentially leading to limited wasted material and transportation costs for the tested  
571 samples. Moreover, the sample arrangement in the SSRR set-up requires a shorter time, enabling in  
572 turn to dedicate an increased time to test different alternatives. Moreover, this could ease the  
573 dissemination and increase awareness related to the acoustic performance among designers and  
574 architects while pursuing more sustainable ways to perform acoustic measurements.

575



583

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585

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# Appendix A

Sound absorption coefficient ( $\alpha_s$ ) and related uncertainty ( $U$ ) for material A measured in SSRR, IT and FSRR. Given the background noise criterion (section 2.4), the SSRR data are valid for 250-5000 Hz. IT<sub>n</sub> shows the data for normal-incidence sound absorption coefficients.

SSRR			Frequency [Hz]																	
Size [cm <sup>2</sup> ]	Orientation		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
60x40	O1	$\alpha_s$	0.11	0.24	0.00	0.42	0.61	0.53	0.52	0.64	0.68	1.10	1.29	1.10	1.10	1.05	1.13	1.23	1.14	1.04
		$U$	0.17	0.23	0.06	0.24	0.28	0.22	0.18	0.19	0.18	0.24	0.27	0.24	0.23	0.23	0.24	0.28	0.30	0.35
	O2	$\alpha_s$	0.10	0.20	0.00	0.40	0.60	0.48	0.53	0.60	0.68	1.03	1.15	1.20	1.20	0.96	1.21	1.10	1.17	0.94
		$U$	0.15	0.20	0.06	0.24	0.28	0.21	0.19	0.18	0.18	0.23	0.24	0.26	0.25	0.22	0.25	0.26	0.30	0.34
	O3	$\alpha_s$	0.09	0.17	0.00	0.36	0.58	0.49	0.58	0.56	0.63	1.02	1.05	1.22	1.27	0.90	1.22	1.18	1.15	1.02
		$U$	0.15	0.18	0.06	0.22	0.27	0.21	0.20	0.17	0.17	0.22	0.23	0.26	0.26	0.21	0.25	0.27	0.30	0.35
60x60	O1	$\alpha_s$	0.00	0.00	0.01	0.32	0.46	0.51	0.56	0.59	0.70	1.17	0.98	1.04	1.04	0.83	1.00	0.95	0.94	0.85
		$U$	0.06	0.06	0.06	0.20	0.23	0.21	0.19	0.18	0.19	0.25	0.22	0.23	0.23	0.20	0.22	0.24	0.27	0.33
	O2	$\alpha_s$	0.00	0.00	0.04	0.33	0.47	0.47	0.58	0.63	0.80	1.06	1.00	1.06	0.96	0.86	1.00	0.92	1.07	0.91
		$U$	0.06	0.06	0.08	0.21	0.23	0.20	0.20	0.19	0.20	0.23	0.22	0.23	0.21	0.20	0.22	0.24	0.29	0.33
60x80	O1	$\alpha_s$	0.00	0.00	0.18	0.26	0.38	0.49	0.57	0.72	0.96	1.04	1.08	1.02	1.09	0.92	0.96	0.95	0.97	0.85
		$U$	0.06	0.06	0.16	0.18	0.20	0.21	0.20	0.20	0.23	0.23	0.23	0.23	0.23	0.21	0.22	0.24	0.28	0.33
	O2	$\alpha_s$	0.00	0.00	0.14	0.29	0.33	0.43	0.61	0.74	0.97	1.05	1.07	0.94	1.02	0.98	0.98	0.96	0.98	0.87
		$U$	0.06	0.06	0.14	0.19	0.18	0.19	0.21	0.21	0.23	0.23	0.23	0.21	0.22	0.22	0.22	0.24	0.28	0.33
	O3	$\alpha_s$	0.00	0.01	0.14	0.24	0.32	0.49	0.56	0.73	0.85	1.07	1.03	0.94	1.05	0.88	0.95	0.92	0.98	0.88
		$U$	0.06	0.07	0.14	0.16	0.18	0.21	0.19	0.21	0.21	0.23	0.23	0.21	0.23	0.21	0.22	0.24	0.28	0.33
IT		$\alpha$	0.20	0.21	0.24	0.30	0.40	0.53	0.64	0.76	0.84	0.88	0.89	0.89	0.88	0.86	0.84	0.82	0.83	0.79
		$U$	0.01	0.02	0.03	0.04	0.04	0.03	0.03	0.04	0.05	0.04	0.03	0.03	0.02	0.03	0.04	0.04	0.03	0.02
IT <sub>n</sub>		$\alpha_0$	0.14	0.15	0.17	0.22	0.30	0.42	0.53	0.66	0.76	0.81	0.83	0.82	0.80	0.78	0.75	0.73	0.74	0.69
		$U$	0.01	0.02	0.03	0.04	0.04	0.03	0.03	0.04	0.05	0.04	0.03	0.03	0.02	0.03	0.04	0.04	0.03	0.02
FSRR		$\alpha_s$	0.09	0.13	0.23	0.32	0.52	0.64	0.79	0.81	0.92	0.94	0.96	0.93	0.95	0.91	0.86	0.84	0.83	0.79
		$U$	0.07	0.08	0.09	0.10	0.12	0.13	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10	0.11	0.13	0.16

## Appendix B

Sound absorption coefficient ( $\alpha_s$ ) and related uncertainty ( $U$ ) for material B measured in SSRR, IT and FSRR. Given the background noise criterion (section 2.4), the SSRR data are valid for 250-5000 Hz. IT<sub>n</sub> shows the data for normal-incidence sound absorption coefficients.

SSRR			Frequency [Hz]																	
Size [cm <sup>2</sup> ]	Orientation		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
60x40	O1	$\alpha_s$	0.11	0.24	0.00	0.42	0.61	0.53	0.52	0.64	0.68	1.10	1.29	1.10	1.10	1.05	1.13	1.23	1.14	1.04
		$U$	0.17	0.23	0.06	0.24	0.28	0.22	0.18	0.19	0.18	0.24	0.27	0.24	0.23	0.23	0.24	0.28	0.30	0.35
	O2	$\alpha_s$	0.10	0.20	0.00	0.40	0.60	0.48	0.53	0.60	0.68	1.03	1.15	1.20	1.20	0.96	1.21	1.10	1.17	0.94
		$U$	0.15	0.20	0.06	0.24	0.28	0.21	0.19	0.18	0.18	0.23	0.24	0.26	0.25	0.22	0.25	0.26	0.30	0.34
	O3	$\alpha_s$	0.09	0.17	0.00	0.36	0.58	0.49	0.58	0.56	0.63	1.02	1.05	1.22	1.27	0.90	1.22	1.18	1.15	1.02
		$U$	0.15	0.18	0.06	0.22	0.27	0.21	0.20	0.17	0.17	0.22	0.23	0.26	0.26	0.21	0.25	0.27	0.30	0.35
60x60	O1	$\alpha_s$	0.00	0.00	0.01	0.32	0.46	0.51	0.56	0.59	0.70	1.17	0.98	1.04	1.04	0.83	1.00	0.95	0.94	0.85
		$U$	0.06	0.06	0.06	0.20	0.23	0.21	0.19	0.18	0.19	0.25	0.22	0.23	0.23	0.20	0.22	0.24	0.27	0.33
	O2	$\alpha_s$	0.00	-0.09	0.04	0.33	0.47	0.47	0.58	0.63	0.80	1.06	1.00	1.06	0.96	0.86	1.00	0.92	1.07	0.91
		$U$	0.06	-0.01	0.08	0.21	0.23	0.20	0.20	0.19	0.20	0.23	0.22	0.23	0.21	0.20	0.22	0.24	0.29	0.33
60x80	O1	$\alpha_s$	0.00	0.00	0.18	0.26	0.38	0.49	0.57	0.72	0.96	1.04	1.08	1.02	1.09	0.92	0.96	0.95	0.97	0.85
		$U$	0.06	0.06	0.16	0.18	0.20	0.21	0.20	0.20	0.23	0.23	0.23	0.23	0.23	0.21	0.22	0.24	0.28	0.33
	O2	$\alpha_s$	0.00	0.00	0.14	0.29	0.33	0.43	0.61	0.74	0.97	1.05	1.07	0.94	1.02	0.98	0.98	0.96	0.98	0.87
		$U$	0.06	0.06	0.14	0.19	0.18	0.19	0.21	0.21	0.23	0.23	0.23	0.21	0.22	0.22	0.22	0.24	0.28	0.33
	O3	$\alpha_s$	0.00	0.01	0.14	0.24	0.32	0.49	0.56	0.73	0.85	1.07	1.03	0.94	1.05	0.88	0.95	0.92	0.98	0.88
		$U$	0.06	0.07	0.14	0.16	0.18	0.21	0.19	0.21	0.21	0.23	0.23	0.21	0.23	0.21	0.22	0.24	0.28	0.33
IT		$\alpha$	0.10	0.15	0.23	0.35	0.49	0.63	0.74	0.84	0.88	0.90	0.90	0.89	0.88	0.88	0.87	0.85	0.86	0.83
		$U$	0.04	0.04	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03
IT <sub>n</sub>		$\alpha_0$	0.07	0.10	0.17	0.26	0.38	0.52	0.64	0.75	0.81	0.83	0.83	0.82	0.81	0.81	0.79	0.77	0.79	0.74
		$U$	0.04	0.04	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03
FSRR		$\alpha_s$	0.09	0.18	0.28	0.52	0.65	0.75	0.82	0.86	0.91	0.90	0.99	0.96	0.95	0.90	0.90	0.87	0.85	0.80
		$U$	0.07	0.09	0.11	0.14	0.15	0.14	0.13	0.12	0.11	0.10	0.11	0.11	0.11	0.10	0.11	0.12	0.13	0.16

# Appendix C

Sound absorption coefficient ( $\alpha_s$ ) and related uncertainty ( $U$ ) for material C measured in SSRR, IT and FSRR. Given the background noise criterion (section 2.4), the SSRR data are valid for 250-5000 Hz. IT<sub>n</sub> shows the data for normal-incidence sound absorption coefficients.

SSRR			Frequency [Hz]																	
Size [cm <sup>2</sup> ]	Orientation		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
60x40	O1	$\alpha_s$	0.00	0.00	0.00	0.01	0.03	0.02	0.02	0.07	0.10	0.12	0.32	0.38	1.12	1.12	1.12	1.07	1.21	0.98
		$U$	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.11	0.12	1.07	1.07	1.07	0.26	0.31	0.34
	O2	$\alpha_s$	0.00	0.00	0.00	0.08	0.06	0.03	0.02	0.06	0.10	0.14	0.28	0.43	1.21	1.21	1.21	1.02	1.22	0.97
		$U$	0.06	0.06	0.06	0.09	0.08	0.07	0.06	0.07	0.08	0.08	0.11	0.13	1.18	1.18	1.18	0.25	0.31	0.34
	O3	$\alpha_s$	0.00	0.00	0.00	0.09	0.07	0.03	0.04	0.08	0.11	0.09	0.30	0.51	1.32	1.32	1.32	1.03	1.15	0.97
		$U$	0.06	0.06	0.06	0.10	0.09	0.07	0.07	0.08	0.08	0.07	0.11	0.14	1.28	1.28	1.28	0.25	0.30	0.34
60x60	O1	$\alpha_s$	0.02	0.05	0.05	0.03	0.10	0.04	0.03	0.08	0.11	0.14	0.34	0.46	0.50	0.54	0.82	0.93	1.02	1.02
		$U$	0.08	0.10	0.09	0.07	0.10	0.07	0.07	0.08	0.08	0.08	0.11	0.14	0.15	0.16	0.20	0.24	0.28	0.35
	O2	$\alpha_s$	0.04	0.04	0.08	0.01	0.09	0.04	0.03	0.07	0.12	0.14	0.37	0.36	0.44	0.55	0.79	0.96	1.14	1.03
		$U$	0.10	0.09	0.10	0.06	0.09	0.07	0.07	0.07	0.08	0.08	0.12	0.12	0.14	0.16	0.20	0.24	0.30	0.35
60x80	O1	$\alpha_s$	0.00	0.00	0.05	0.00	0.02	0.02	0.03	0.06	0.12	0.15	0.30	0.40	0.50	0.57	0.90	1.01	1.12	1.00
		$U$	0.06	0.06	0.09	0.06	0.07	0.06	0.07	0.07	0.08	0.08	0.11	0.13	0.15	0.16	0.21	0.25	0.29	0.34
	O2	$\alpha_s$	0.00	0.00	0.00	0.00	0.02	0.03	0.06	0.05	0.12	0.12	0.33	0.43	0.52	0.58	0.87	1.02	1.12	1.08
		$U$	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.08	0.08	0.11	0.13	0.15	0.16	0.21	0.25	0.29	0.35
	O3	$\alpha_s$	0.00	0.00	0.04	0.00	0.04	0.03	0.05	0.05	0.13	0.15	0.32	0.43	0.44	0.59	0.85	0.90	1.00	1.00
		$U$	0.06	0.06	0.08	0.06	0.08	0.07	0.07	0.07	0.08	0.08	0.11	0.13	0.14	0.17	0.21	0.24	0.28	0.34
IT		$\alpha$	0.27	0.16	0.17	0.13	0.14	0.13	0.12	0.10	0.19	0.24	0.33	0.45	0.56	0.67	0.79	0.91	0.95	0.91
		$U$	0.03	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.10	0.07	0.05	0.01	0.04
IT <sub>n</sub>		$\alpha_0$	0.20	0.11	0.12	0.09	0.09	0.09	0.08	0.07	0.14	0.18	0.25	0.35	0.45	0.56	0.70	0.85	0.92	0.86
		$U$	0.03	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.10	0.07	0.05	0.01	0.04
FSRR		$\alpha_s$	0.02	0.02	0.02	0.05	0.06	0.09	0.11	0.14	0.23	0.30	0.34	0.45	0.54	0.66	0.74	0.83	0.85	0.89
		$U$	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.13	0.17



# Appendix D

Sound absorption coefficient ( $\alpha_s$ ) and related uncertainty ( $U$ ) for material D measured in SSRR, IT and FSRR. Given the background noise criterion (section 2.4), the SSRR data are valid for 250-5000 Hz. IT<sub>n</sub> shows the data for normal-incidence sound absorption coefficients.

SSRR			Frequency [Hz]																	
Size [cm <sup>2</sup> ]	Orientation		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
60x40	O1	$\alpha_s$	0.07	0.28	0.39	0.65	0.78	0.98	1.07	0.74	1.00	1.21	1.36	0.90	0.85	0.95	1.00	1.21	1.20	1.01
		$U$	0.12	0.26	0.28	0.35	0.34	0.35	0.32	0.21	0.24	0.25	0.28	0.21	0.20	0.22	0.22	0.27	0.30	0.35
	O2	$\alpha_s$	0.03	0.26	0.38	0.72	0.79	0.93	0.85	0.70	0.94	1.11	1.29	0.88	1.03	0.90	1.05	1.13	1.25	1.10
		$U$	0.09	0.25	0.27	0.38	0.34	0.34	0.26	0.20	0.23	0.24	0.27	0.20	0.22	0.21	0.23	0.26	0.31	0.35
	O3	$\alpha_s$	0.00	0.26	0.40	0.70	0.88	0.92	0.90	0.72	0.94	1.19	1.13	0.99	1.02	0.87	0.99	1.04	1.28	0.96
		$U$	0.06	0.25	0.29	0.37	0.38	0.34	0.28	0.20	0.23	0.25	0.24	0.22	0.22	0.21	0.22	0.25	0.31	0.34
60x60	O1	$\alpha_s$	0.09	0.37	0.35	0.53	0.68	0.67	0.58	0.67	0.75	0.93	0.91	0.84	0.78	0.98	0.96	0.98	1.26	1.07
		$U$	0.14	0.33	0.26	0.29	0.30	0.26	0.20	0.19	0.20	0.21	0.21	0.20	0.19	0.22	0.22	0.25	0.31	0.35
	O2	$\alpha_s$	0.20	0.41	0.37	0.54	0.59	0.67	0.64	0.61	0.76	1.04	0.84	0.87	1.02	0.87	0.97	1.05	1.25	1.09
		$U$	0.25	0.35	0.27	0.30	0.27	0.26	0.21	0.18	0.20	0.23	0.19	0.20	0.22	0.21	0.22	0.25	0.31	0.35
60x80	O1	$\alpha_s$	0.15	0.24	0.34	0.33	0.47	0.66	0.53	0.69	0.70	0.69	0.73	0.71	0.72	0.76	0.80	1.05	1.12	0.99
		$U$	0.21	0.23	0.25	0.21	0.23	0.26	0.19	0.20	0.19	0.17	0.18	0.18	0.18	0.19	0.20	0.25	0.29	0.34
	O2	$\alpha_s$	0.24	0.25	0.33	0.40	0.60	0.66	0.53	0.61	0.67	0.74	0.69	0.84	0.80	0.85	0.83	0.99	1.19	0.98
		$U$	0.29	0.24	0.24	0.24	0.28	0.26	0.19	0.18	0.18	0.18	0.17	0.20	0.19	0.20	0.20	0.25	0.30	0.34
	O3	$\alpha_s$	0.14	0.26	0.38	0.43	0.54	0.65	0.66	0.78	0.68	0.70	0.73	0.59	0.76	0.85	0.86	0.98	1.11	0.92
		$U$	0.19	0.25	0.27	0.25	0.25	0.26	0.22	0.22	0.18	0.17	0.18	0.16	0.18	0.20	0.21	0.25	0.29	0.34
IT		$\alpha$	0.38	0.42	0.55	0.64	0.71	0.74	0.75	0.74	0.72	0.68	0.64	0.61	0.58	0.58	0.61	0.65	0.75	0.84
		$U$	0.06	0.02	0.04	0.06	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.04	0.04
IT <sub>n</sub>		$\alpha_0$	0.29	0.32	0.44	0.53	0.60	0.64	0.65	0.63	0.62	0.57	0.53	0.50	0.47	0.47	0.50	0.54	0.65	0.75
		$U$	0.06	0.02	0.04	0.06	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.04	0.04
FSRR		$\alpha_s$	0.43	0.50	0.53	0.54	0.58	0.68	0.66	0.70	0.72	0.69	0.65	0.64	0.67	0.71	0.73	0.78	0.86	0.85
		$U$	0.24	0.21	0.18	0.15	0.13	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.09	0.09	0.10	0.11	0.13	0.16