Practical aspects related to the measurement of the diffuse field absorption coefficient in scaled reverberation rooms

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Practical aspects related to the measurement of the diffuse field absorption coefficient in scaled reverberation rooms

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ABSTRACT

The scaled reverberation room has proven to be an excellent tool for acoustic consultants and professionals alike to carry out comparison tests between acoustic materials and 3D systems or structures. The suitability of a scaled reverberation room is currently under investigation for the evaluation of the frequency-dependent sound absorption. At present, no standard is available on the methods that could be used to derive acoustic absorption coefficients from scaled measurements. In this work practical aspects of ISO 354 have been investigated within a 1:5 scaled reverberation room: a balance has been sought between reducing sample size, to reduce the manufacturing costs of materials, and finding the appropriate sample area, thickness, orientation and edges treatment, to obtain reliable values at mid and high frequencies. Four different materials have been tested. The paper discusses some of the findings of the measurements conducted on the same materials in a full-scale reverberation room according to ISO 354, in a 1:5 scaled reverberation room and in an impedance tube according to ISO 10534-2. The absorption coefficients data collected have been effective in proving that small reverberation room tests can provide compatible results compared to standard ones in 400-5000 Hz frequency range.

Keywords: Sound, Absorption coefficient, Reverberation room, Scaled measurements

1. INTRODUCTION

The characterization of the absorption coefficient has been the focus of continuous research even after the consolidation of the reverberation room method described in ISO 354 (1) and ASTM Standard C423(2). However, it has been shown that large discrepancies over the full frequency range of interest may occur between different laboratories even though they fulfill the standard requirements (3). Moreover, a prerequisite for the good reliability of this method is the presence of a diffuse field, which is usually improved by equipping the room with sound diffusers of different types (4,5). However, it should be considered that the efficiency of the diffusers is reduced when the frequency of the sound to be measured decreases (6). This basic assumption, i.e. the diffuse field conditions differences between laboratories has been questioned lately aiming at new requirements to be defined in terms of diffusivity for the laboratories (7).

Given the continuous research on several critical aspects within the full-scale reverberation room measurements, this paper intends to explore also the acoustic conditions and reliability of the random-incidence absorption coefficient within a scaled reverberation room. The need for scale measurements of the absorption coefficient arises for several practical reasons related to the economical and time efforts due to the preparation of the samples. The main advantage of a scaled room is that of being able to analyze samples that are much smaller than the 12 m^2 required by the real scale room measurements (V>200 m^3). Two main difficulties appear when dealing with small reverberation rooms: the lack of a sufficient degree of diffusivity of the acoustic field, and the diffraction due to the finite size of the tested material (edge effects) especially at the low frequencies (8-10).

In particular, the scaled rooms have been of interest in the automotive sector (11), which usually requires absorption data at medium-high frequencies. This interest has led to a SAE (Society of Automotive Engineers) standard (12) on the use of the small rooms for absorption coefficients

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measurements. The common dimensions of these rooms are in the range 3-9.68m^3 and a sample area of 0.4-1.5m^2 is usually sufficient (13). The most well-known one is the Alpha Cabin built by the Swiss company Rieter, with a volume of 6.5m^3, which is largely used in the automotive industry allowing to measure 1.2m^2 of flat samples or trimmed parts. The design and size of the first Alpha Cabin is 1:3 of the large reverberation room located in the Swiss Federal Laboratory of Material Testing and Research Institute (EMPA). It provides accurate measurements in the frequency range of 400-10000Hz. Further smaller scaled rooms are reported in Rey et al. (14) with a volume of 1.12 m^3 and test sample area of 0.3 m^2, and Pacheco et al. (15) with a volume of 0.96 m^{3}and and test sample area of 0.3 m^2.

A few studies have also compared scaled reverberation room measurements with those performed in a full-scale reverberation room. A good match of the results has been shown in the range of frequencies (above 400Hz) in which the small sized reverberation room fulfils the diffusion conditions, i.e. where the degree of diffusion is close to 1 (14, 16-18). However, these studies highlight also larger discrepancies at low frequencies due to the reduced dimensions of the room. This seems to be more critical as the size of the reverberation room becomes significantly smaller, as the resulting smaller sample area produces a larger edge effect (8, 19). These effects are particularly high at low frequencies in those cases when highly absorbing materials with high thicknesses are tested.

Further investigation is needed to clarify the compromise between reducing the sample size to reduce the manufacturing costs and finding the appropriate room conditions to obtain reliable results.

This study examines the measurements over four different materials in a 1:5 scale reverberation room in the laboratories of the Energy Department (DENERG) of Politecnico di Torino, with the aim of evaluating the validity of the sound absorption coefficient measurements. Three different dimensions, three orientations and two conditions of the sample edges have been investigated. The work involves a comparison with two other different measurements made on the same materials, that is, in a full-scale reverberation room (ISO 354) and in the impedance tube or Kundt's tube (ISO 10534-2).

2. METHODS

2.1 Tested Materials

A set of four materials has been tested (Figure 1) in scaled reverberation room. These materials were available at INRiM (National Institute for Metrological Research), where have been also performed the measurements in a full-scale reverberation room according to ISO 354 (1) and in an impedance tube (or Kundt's tube) according to ISO 10534-2 (20).

Materials A and B are made of glass wool panels with a density of 80 kg/m^3 and an overall thickness of 40mm and 50mm, respectively. Material C is a 15mm thick panel with a layer of 12.5 mm of plasterboard. These three panels have a layer of 12.5mm of finish made of glass spheres and a marble powder. Material D is composed of two superimposed layers of polyester fiber with a density of 80kg/m^3 and a thickness of 30mm each. Also, this material has a cellular glass finish of 12.5mm over the upper layer, and a mixture of rubber and concrete layer of 12.5mm at the bottom.

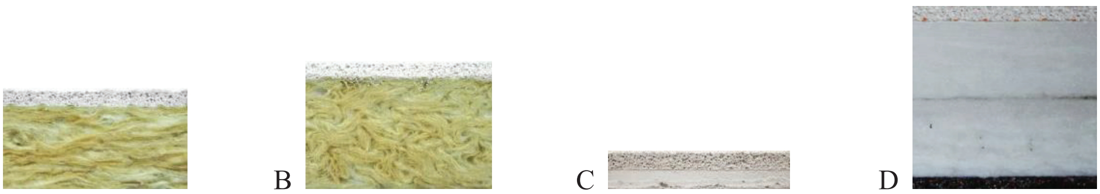
A 

Figure 1 – A) e B) Glass wool panels with a finish of glass spheres and a marble powder (40 and 50mm). C) Panel with a layer of plasterboard and one of glass spheres and a marble powder (15mm). D) Double layered Polyester fiber panel (75mm).

Since the sound field in the reverberation room is strongly dependent on the configuration of the measured material, the following parameters have been tested in order to evaluate the optimal configuration of the scaled reverberation room. Measurements have been performed considering:

- three different sample sizes for all the materials (0.6x0.4m; 0.6x0.6m; and 0.6x0.8m);
- three different orientations on the floor (Fig.2) for the 0.6x0.4m and 0.6x0.8m sample sizes and each material. It should be noted that the ISO standard recommends an oblique orientation (orientation 2).

- two conditions with and without isolated borders (for A and B material only). An aluminum adhesive tape has been used seal the edges of each sample. It should be noted that the ISO standard recommends to seal the edges of the sample with reflective material.

Three repetitions have been performed for each condition in order to evaluate the measurements repeatability.

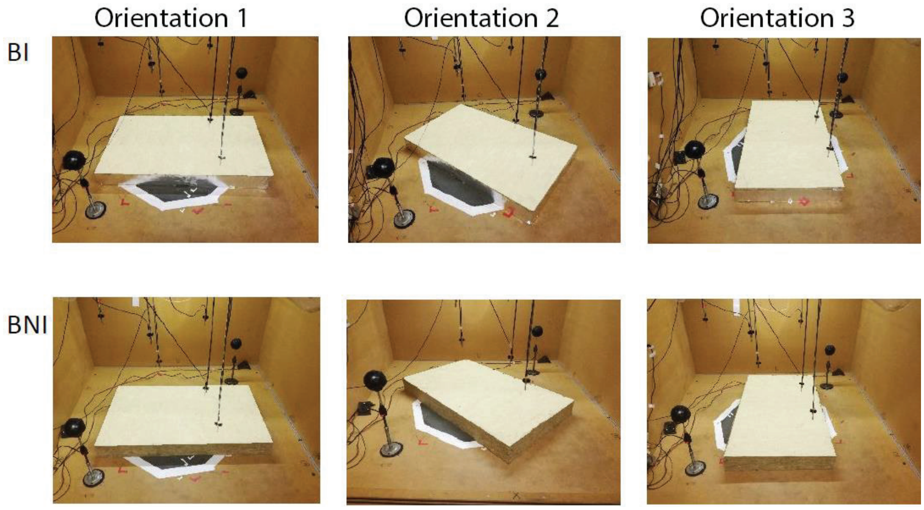


Figure 2 – Measurements in the scaled reverberation room of one of the samples with three different orientations, and with sealed (BI) and unsealed (BNI) edges.

2.2 Reverberation Room Measurements (1:5 scale)

The scaled reverberation room (Figure 2) is a laboratory at DENERG (Department of Energy, Politecnico di Torino, Italy). It is a 1:5 scale reproduction of the reverberation room of INRiM, which has a volume of 296 m^3. The room has been primarily built for random-incidence scattering coefficient measurements according to ISO 17497-1 (21). It is an oblique angled room with pairs of nonparallel walls. The average room dimensions are 1.53 x 1.56 x 1.20 m, which lead to a volume of 2.86 m^3. One of the sides consist of two movable parts that allow to have a large opening to ease the positioning of the sample. The construction material is self-supporting lightweight partitions of MDF (Medium Density Fibreboard) with a thickness of 3.8 cm, which has been further covered by a layer of adhesive film in order to maximize its reflective properties. The structure is raised from the ground on a wooden structure and damping layers have been used along the joints and openings. In order to assure a high diffusivity of the sound field (22), 8 diffusers (13.5% of the total room area) have been hanged over the ceiling, which is considered as a more economical solution compared to boundary diffusers leading to an almost equivalent effect on the diffusion of the sound field (5). A systematic study of the sound field diffusivity evaluation of the room has been shown in (23). The diffusivity check has been performed in accordance with ISO 354 based on the measurements of the equivalent absorption area of a highly sound absorptive panel made of polyester fiber.

The measurement chain is composed of six BSWA Tech MPA45 microphones and two ITA dodecahedral sources in order to perform 12 measurements (the minimum number required by ISO 354). The software used for the measurements is Matlab, combined with the functions of the ITA-Toolbox (an opensource toolbox from RWTH-Aachen, Germany).

The set-up and the samples of each material have been produced in accordance with the recommendations of the ISO 354 standard:

- Microphones should be positioned at a minimum distance of 1.5m from each other, 1m from the room surfaces and 2m from the sources (0.3m; 0.2m and 0.4m in 1:5 scale).
- The two sources must be at least 3m apart (0.6m in 1:5 scale) between them. A spatial averaging is performed considering all the 12 source and microphones combination.
- The interval frequencies of interest is reported as third-octave-bands in the range 100-5000Hz.
- Controlled conditions of temperature (> 15 ° C) and humidity (between 30-90%). A sensor has been installed within the room.
- The sample must be rectangular with a ratio between width and length of 0.7-1.

- The sides of the sample must be distant from the walls of the room by at least 1m (0.2m in 1:5 scale).

2.3 Reverberation Room (full-scale) and Kundt's Tube Measurements

All the materials have been tested in the full-scale reverberation room at INRiM in accordance with ISO 354 considering samples of 12m^2. In this way the random-incidence absorption coefficient has been obtained for each material in the frequency range 100-5000Hz.

Further measurements have been performed in the Kundt's tube in accordance with ISO 10534-2 in order to measure the normal-incidence absorption coefficient. These values have been corrected for diffuse incidence based on the approach proposed in Spagnolo and Benedetto (24), which is shown in all graphs as "Kundt's tube S-B". Two different tubes with 30mm and 50mm diameters have been used in order to assure a higher accuracy at different frequency ranges. The 30mm tube allows to measure with a high accuracy in the frequency range of 1075-5733Hz and the 50mm in the frequency range of 661-3440Hz.

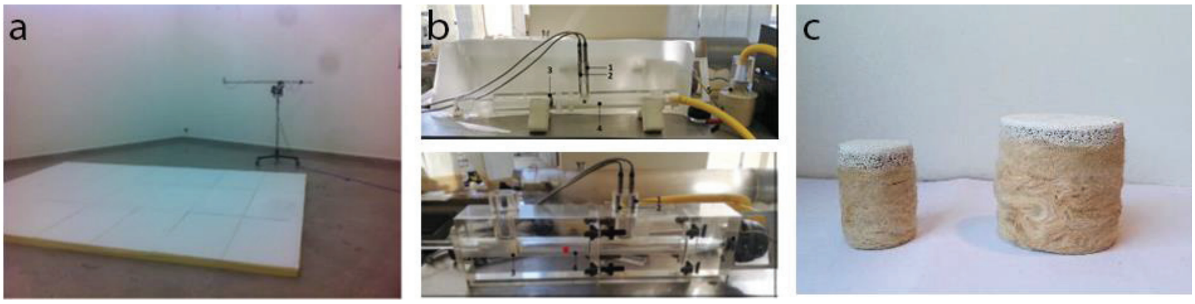


Figure 3 – a) Full-scale reverberation room set-up of one of the samples, b) measurements set-up in the Kundt's tube with a diameter of 30mm (upper image) and 50mm (bottom image), and c) two circular samples of the same material with a diameter of 30 and 50mm.

3. RESULTS

For the analysis of the results, the SPSS Statistics software has been used to perform the ANOVA (ANalysis Of VAriance). Specifically, the evaluated factors, i.e. the independent variables, are sample size, sample orientation, and edge condition. The data have been first analyzed with a normality test (Kolmogorov-Smirnov test), which showed a skewness and kurtosis within the range of -2 to +2 (25). The uncertainty of the measurements has been assessed according to GUM (ISO / IEC Guide 98-3: 2008). The absorption coefficients obtained, together with the standard deviations of the results, are shown in Figures 4-6. These graphs show also the data from the full-scale reverberation room and Kundt's tube measurements for an easier comparison. Moreover, the graphs include also the Kundt's tube measurements corrected for the diffuse incidence condition (Kundt's tube S-B).

3.1 Effect of the Sample Dimensions

The effect of the sample size has been analyzed for all the materials considering the recommended orientation and edges condition, i.e. oblique orientation (Orientation 2) and sealed edges (BI). The ANOVA showed that the variable related to the sample dimension (Fig. 4), is statistically significant for all the samples except for sample C (panel with a thickness of 15 mm). Specifically the results show: for Sample A → $F(2, 162) = 30.351$; $p = 0.000$; Sample B → $F(2, 162) = 25.351$; $p = 0.000$; Sample C → $F(2, 108) = 1.354$; $p = 0.263$; and Sample D → $F(4, 180) = 62.153$; $p = 0.000$.

This exception for the sample C is probably due to its reduced thickness, which entails less edge diffraction. Conversely, the edge effect becomes critical for panels with higher thickness (i.e. A, B, D) when the panel reaches the smallest dimensions 0.6x0.4m. In these cases are evident irregular peaks at mid and high frequencies for panels A and B, and also at low and mid frequencies for panel D. It can be noticed that the sound absorption increases at 160-400Hz and above 800Hz with decreasing samples size. The same result has been highlighted also in full-scale rooms by Jain et al. (26). This can also be observed for the three different orientations as shown in Figure 5.

The correct scaling of the sample dimensions with respect to the room volume has been investigated in Veen et al. (9). This study shows that a sample of 1.12m^2 could be considered in order to have reliable results in a small reverberation room with a volume of about 6.4m^3. The ratio between the room volume and the sample area is comparable to that obtained with the room volume of 2.86m^3 and the sample dimensions 0.6x0.8m (0.48m^2) used in the present study (i.e. ≈6).

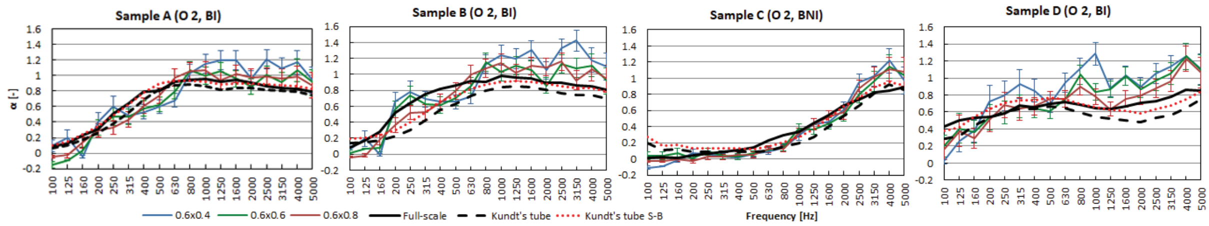


Figure 4 – The absorption coefficients obtained, together with the standard deviations of the results for each material and sample dimension. Orientation 2 and sealed edges (BI) have been considered for samples A, B, D, and unsealed edges (BNI) for sample C.

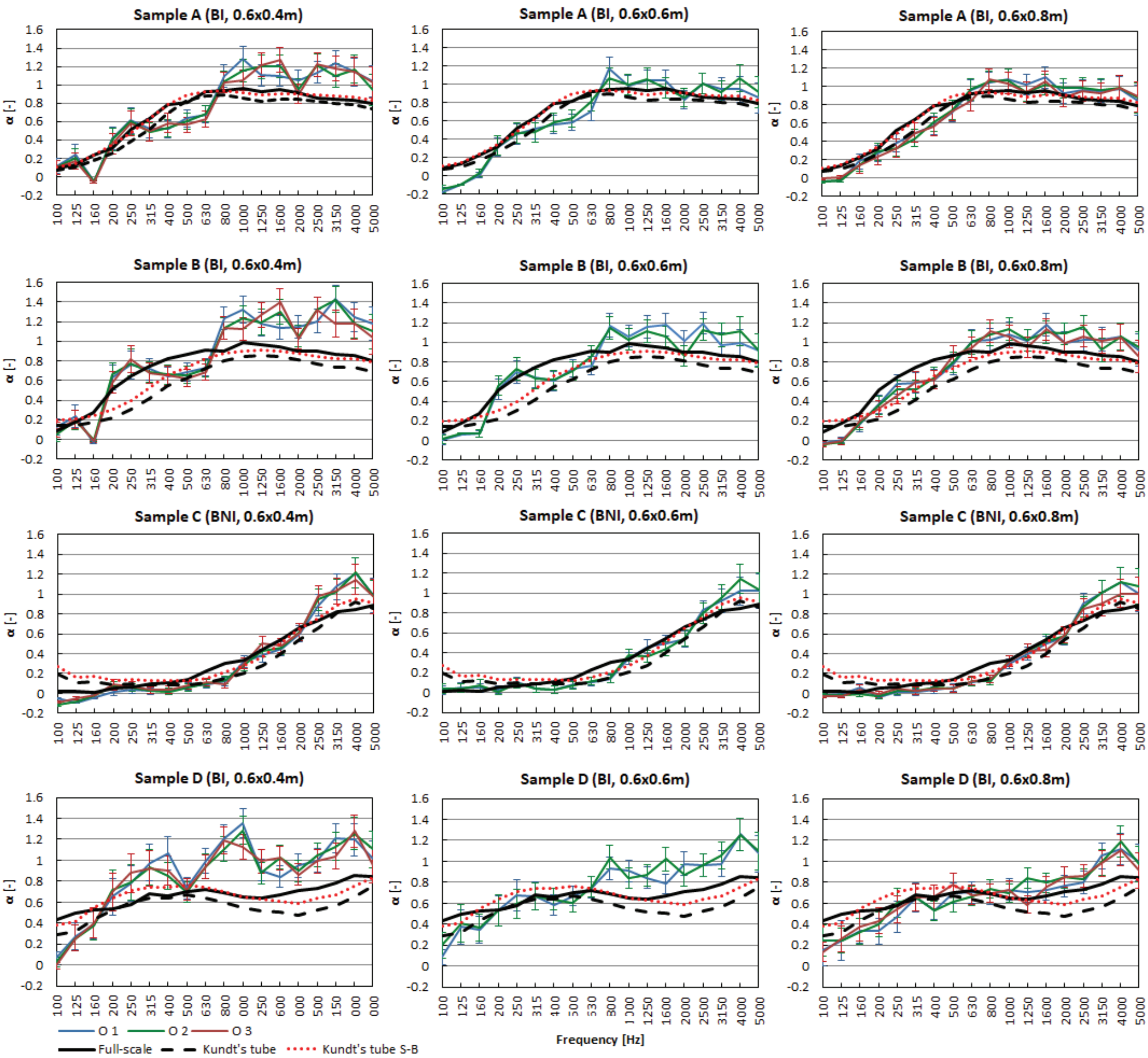


Figure 5 –The absorption coefficients obtained, together with the standard deviations of the results for each material and sample orientation. Sealed edges (BI) have been considered for samples A, B, D, and unsealed edges (BNI) for sample C for the different dimensions.

3.2 Effect of the Sample Orientation

The effect of the sample orientation has been analyzed for all the materials and all the sample sizes. The ANOVA shows that the differences due to the different orientations of the sample are not statistically significant for all the materials considered. Specifically, for sample A → $F(2.162) = 1.086$

and $p = 0.340$; sample B $\rightarrow F(2, 162) = 0.738$ and $p = 0.480$; Sample C $\rightarrow F(2, 108) = 0.137$; $p = 0.872$; and Sample D $\rightarrow F(2, 216) = 0.368$; $p = 0.692$. It is therefore possible to choose to keep the panel obliquely oriented (Orientation 2), as suggested in the standard for full-scale measurements, or to calculate the absorption coefficients for the three orientations and perform an average of the three data. In this way, it is possible to take into account the small variations of the sound field due to the sample orientation.

Previous research (27) has shown that different orientations may cause discrepancies at lower frequencies (below 400Hz) and that the smoothest curve is obtained for the oblique orientation, which is the most asymmetric one. This study also highlighted that the other two orientations cause strong peaks in the absorption coefficient, which were unrealistic for the tested porous materials. The authors argued that the reason for this might be the parallel orientation of two edges of the material versus two of the side walls of the reverberation room.

However, this is not observed in the study presented in this paper. Some differences between the three orientations are observed at specific frequencies for the smallest sample dimensions, i.e. 0.6x0.4m. It can be observed that discrepancies at lower frequencies become lower when the material has lower thickness, i.e. these differences are more evident in the case of panel D, which has a thickness of 75mm. This finding is coherent with the results of Cops et al. (27), which showed the same discrepancies between different orientations for samples with thickness higher than 100mm in full-scale.

3.3 Effect of the Sample Edges

The effect of the samples edges has been analyzed for sample A and B only (all corresponding sample sizes). The results are shown in Figure 6. This factor did not result statistically significant for sample A with $F(1, 216) = 2.621$ and $p = 0.107$. Conversely, it resulted statistically significant for sample B with $F(1, 216) = 127.806$ and $p = 0.000$.

It should be noted that the absorption due to the edges of the sample is of little significance only for sample A, which is 40 mm. This might be considered as a threshold that allows to avoid further efforts when performing measurements below this thickness. This finding is coherent with what is reported in (10), i.e. values of the absorption coefficient obtained with the sealed and unsealed edges may differ by more than 10% for noninotropic materials of thickness >50mm. Therefore, the measurements with sample C (15mm) have been performed without any edge sealing, and conversely, for sample D (75mm) only with sealed edges.

As it is shown from Figure 6, the main discrepancies between sealed (BI) and unsealed (BNI) edges occur at frequencies below 630Hz (maximized around 250 Hz) for the smallest sample dimensions, i.e. 0.6x0.4m.

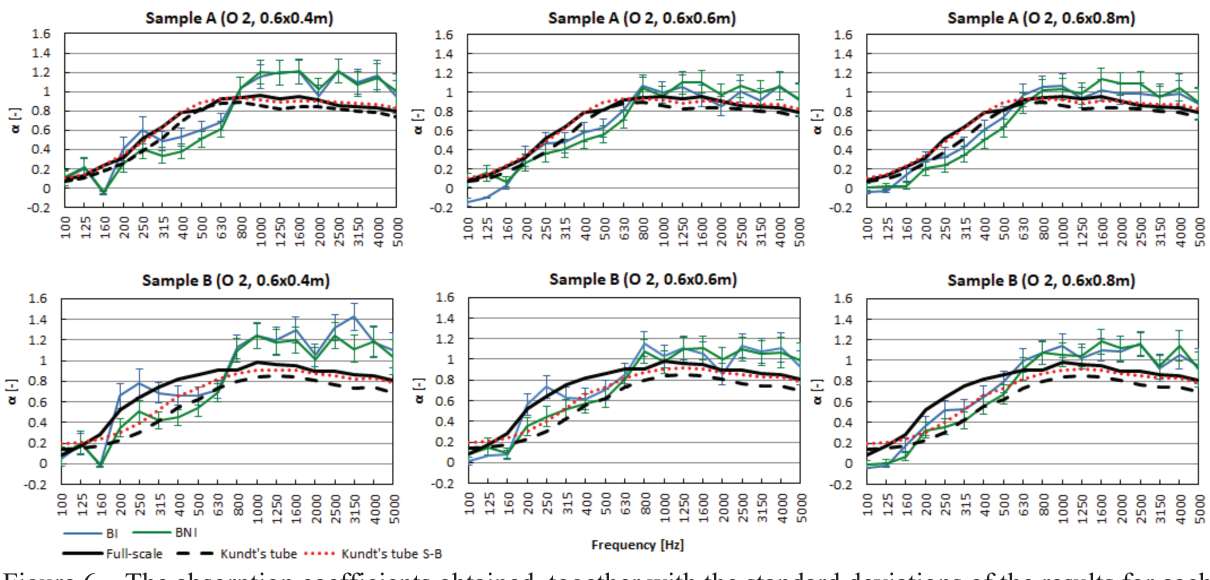


Figure 6 – The absorption coefficients obtained, together with the standard deviations of the results for each material and edge condition, i.e. sealed (BI) and unsealed (BNI). Orientation 2 has been considered for all samples and dimensions.

3.4 Comparisons with full-scale reverberation room and Kundt's tube measurements

The comparisons of the absorption coefficient with the full-scale reverberation room and Kundt's tube measurements show that these differences are minimized when the sample size is 0.6x0.8m with an oblique orientation (O2) and with sealed edges (BI). Moreover, the differences are reduced when the sample thickness is below 40mm (i.e. Sample A and C). The differences are higher for frequencies above 800 Hz for samples A, B and D and above 2000Hz for sample C. One of the causes is that the absorption coefficient tends to a value close to 1 at these frequency ranges and influences the diffusivity of the sound field generated within the scaled room. This has been observed also in Veen et al. (9), that showed higher discrepancies around 1000Hz for samples with thickness of 25mm. Conversely, the phenomenon did not appear for smaller thickness of about 6mm. Moreover, this effect, i.e. the effect of the room volume differences, has been highlighted in Jain et al. (26). In this study both full-scale and small-scale reverberation rooms showed a good match in sound absorption coefficient at mid frequencies from 400 Hz - 1000 Hz. However, the small room overestimates sound absorption values above 1000 Hz. This is attributed to the use of Sabine's formulas instead of Eyring's as highlighted by Vercammen (3).

Moreover, it can be highlighted that the differences obtained here between the scaled and full-scale room or Kundt's tube measurements (sample A and C) are comparable with based the reproducibility of the absorption coefficient measurements in 13 laboratories. This value is around 0.2 based on Vercammen (3).

4. CONCLUSIONS

This paper aimed to explore the acoustic conditions and reliability of the random-incidence absorption coefficient measured within a scaled reverberation room based on its main advantage is that of being able to analyze samples of very reduced dimensions. The main difficulties that appear when dealing with small reverberation rooms are the lack of a sufficient degree of diffusivity of the acoustic field, especially in the low frequencies due to the small size of the room and diffraction due to the finite size of the tested material (edge effects). Moreover, the absorption coefficient is overestimated at high frequencies even for thinner panels, which might be due to the use of Sabine's formula. Future comparisons will also test the results using Eyring's formulas.

However, the small reverberation room demonstrated to be a reliable tool for mid and high frequency acoustic measurements for panels with limited thickness, which showed differences comparable to the reproducibility in full scale. However, it should be highlighted that due to limited diffusivity of the sound field, the range of useful frequencies is to be considered above 400Hz for materials that do not present an extremely high absorption (≈1). For very absorptive materials overestimated values can occur also at high frequencies.

The measurements carried out over four different materials show that the use of a scaled room might be an alternative to the measurements in full-scale or to the measurements in the Kundt's tube.

Overall the results showed that in order to have reliable data:

- the sample size should be of about 0,6x0,8m;
- the sample thickness should be not higher than 50mm;
- an oblique orientation of the sample is preferred;
- the edges of the sample should be sealed with reflective material.

It should be noted that the main aim of the reduced-size room is that of being a very useful tool for acoustic consultants, engineers and architects to carry out comparison tests between acoustic materials and 3D systems or structures of limited dimensions. This results of great importance at the early phases of a design project, when a great number of alternatives are compared.

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