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Towards more reliable measurements of sound absorption coefficient in reverberation rooms: an Inter-Laboratory Test

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Abstract

The internationally recognized procedure ISO 354:2003 for measuring sound absorption coefficients under diffuse field conditions is now under revision. The main reason for this revision is the limited reproducibility of absorption coefficients measured in different laboratories that may have significant implications spanning from room acoustic design to material selection. A network of Italian laboratories have come together to carry out an Inter-Laboratory Test (ILT) to assess and compare the measurement uncertainties resulting from the application of the current version of ISO 354:2003 and of the new ISO/CD 354:2019. After detailing the methodological aspects, the paper presents the results of the measurements, discussing the compliance of the laboratories to the standard requirements and new qualification tests, and, more importantly, providing a quantitative estimation of their effects on measurement uncertainty and accuracy.

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1. Introduction

Sound absorption coefficients can be measured, under diffuse field conditions, according to the procedures specified in standards such as ISO 354:2003 [1] or ASTM C423-17 [2], or, under normal incidence conditions, according to ISO 10534-2:1998 [3] or ASTM E1050-12 [4]. However, to be performed in standing wave tubes, the latter methods are only viable for very small samples for which the acoustic behaviour is not affected by the sample dimension, and the subsequent conversion to diffuse field values (required to feed acoustic simulation tools) rely on formulas based on different theories that are not univocally established [5]. Thus, measuring under diffuse field conditions remains the preferred method, involving the use of large samples (of at least 10 m^2 or 6.7 m^2, for ISO and ASTM standards, respectively), mounted under real-world conditions, and also allowing the possibility to characterize absorbing objects. Unfortunately, such methods rely on the measurement of reverberation times with and without the sample to be tested, and on the subsequent calculation of the sound absorption based on the classical Sabine's formula. Thus, as it is an indirect measure, the accuracy of the method is strongly dependent on the accuracy of the formula used to relate absorption with reverberation time, which normally requires an ergodic, mixing and weakly absorbing room in order to ensure the sound field to be sufficiently diffuse [6].

Although standards propose several guidelines and checks to be satisfied in order to ensure that the test room complies with the diffuse field model, and several studies also proposed measures to quantify the degree of diffuseness [7],[8] , experience confirms that obtaining a diffuse sound field is harder than one would think desirable.

As a result, a large number of studies, carried out at almost regular intervals in different regions, have been pointing out the limited reproducibility of absorption coefficients measured in different laboratories [9]-[14]. There can be several explanations for such a large spread. First, and most obvious, the difference between room volume and shape [15]-[17] may affect the interaction between the sound field and the sample resulting in different absorption coefficients. It may not be possible to establish an ideal diffuse sound field either because of modal behaviour [18], or a lack of scattering elements in the test room [18]-[20] and the very presence of the absorbing samples on just one surface [21]-[23], causing an obviously anisotropic distribution. Consequently, even the position of the sample inside the room, as well as that of source and receiver, may influence the results [24],[25]. Another issue related to the presence of large absorbing samples is the use of Sabine's instead of Eyring's formula. In fact, particularly in smaller test chambers, if the average sound absorption coefficient α in the room becomes higher than 0.1, this results in an absorption exponent, equal to $-\log(1-\alpha)$, which differs from α by 5% and the difference increases as α grows. Thus, a very absorbing sample may return inaccurate results if such condition applies. Finally, edge effects, particularly for thick samples, introduce further uncertainties in the measurements [26],[27], including a stronger dependence of the results on sample dimensions (and its perimeter-to-area ratio). The standard approach is to just cover the sample edges, but given the available options in terms of materials, this may well introduce further uncertainties.

In order to tackle some of the above mentioned problems, different strategies could be followed, from a better and more detailed control of the sound field inside the test room [23], to the use of numerical models to account for non-diffuse behaviour [28]. However, while such approaches might be useful in a research environment, they would be impractical for most testing facilities. Thus, a revision of ISO 354 standard is under way [29] in order to provide some remedies to the current situation. A stricter control of the room dimensions and its damping, new and more demanding qualification tests based on decay rate variance quantifiers [7],[8], and the use of a reference absorber are among the most significant innovations under discussion. A more detailed account of the extent of such proposals and of their practical implications will be given in the subsequent sections. However, even though many changes make perfectly sense and it is not difficult to see their potentially good effects, in other cases some proposals would certainly benefit from a scientifically sound background of experimental data which could prove or disprove the validity of the proposal. Thus, in order to constructively contribute to the discussion and test the practical application of the "ISO 354 to be", a network of Italian laboratories (from universities, research institutes and commercial testing companies) have come together to carry out an Inter-Laboratory Test (ILT). By means of a rigorous measurement protocol [30], the measurement uncertainties resulting from the application of the current version of ISO 354 and of the new committee draft ISO/CD 354:2019 were compared. After detailing the methodological aspects, the paper presents the results of the measurements, discussing the compliance of the laboratories to the standard requirements and new qualification tests, and, more importantly, providing a quantitative estimation of their effects on measurement uncertainty.

2. Differences between ISO 354:2003 and ISO/CD 354:2019

The main aim of the ILT was the comparison of the current version of ISO 354, published in 2003 [1], with the new committee draft ISO/CD 354:2019 [29], hereinafter referred to as Draft:2019, for the sake of brevity. Therefore, it is essential to highlight the differences in the two versions of the method, which are summarised below.

2.1. Diffusivity of the sound field in the reverberation room

ISO354:2003 explains in simple terms the meaning of "diffuse sound field" in the introduction and then prescribes a check of the diffusivity with increasing quantities of stationary diffusers: the mean sound absorption coefficient approaches a maximum value and then remains constant when the optimal diffuser area is reached.

The Draft:2019 introduces a qualification test based on the spatial variance of the reverberation time: the relative standard deviation of the reverberation time with the *reference absorber* (see 2.2 below) at the normal measuring position must be determined. The ratio of the measured and theoretical spatial standard deviation, called f_d, is calculated: its value, averaged over the third octave bands from 250 to 3150 Hz, should preferably not exceed 1. According to the Draft:2019, this requirement should be based on the theory developed by Davy [7],[8]. A second test is also prescribed on the linearity of the decay curves, as insufficient diffusivity of the reverberation room may cause non-linearity of these curves.

2.2. Reference absorber

One of the main changes included in Draft:2019 is the use of a reference absorber by means of a two-step procedure:

1. Qualification of the reverberation room by measuring the equivalent absorption area of the reference absorber and by comparing it with a minimum value;

2. Correction of measurement results for any other sample, based on the results obtained from the reference absorber.

The idea behind the use of a reference absorber is that “when using a standard absorber the average result may be used as a reference for correcting measurement results of other samples, based on the difference of the measured absorption of the reference absorber and the average absorption of the absorber” [18]. The material to be used as reference absorber (double-layer glass wool having a total thickness of 200 mm) and the values of its sound absorption coefficient for normal incidence and air flow resistivity are given in the draft. The draft also provides for the minimum and maximum equivalent absorption values to be attained (Step 1) in each octave band, A_{req}, although it contains no specific reference to their origin (whether they are theoretical or measured values). The equivalent absorption of the reference absorber, $A_{s,ref}$, is measured with the laboratory standard measurement procedure and then used to calculate the absorption correction factor γ, as follows:

$$\gamma = \frac{A_{req}}{A_{s,ref}} \tag{1}$$

where A_{req} is given in one-third octave bands.

The draft points out that, for the qualification procedure (Step 1), A_{req} is set in octave bands, to allow for some variations between third octave bands.

Given γ, the equivalent sound absorption area of the test specimen, A_T, in square metres, must be calculated using the formula:

$$A_T = \gamma(A_2 - A_1) \tag{2}$$

where A_2 and A_1 are the equivalent sound absorption areas measured with and without the specimen in the reverberation room, respectively. Clearly, the γ factor has a strong impact on the dispersion of the resulting sound absorption curves as a function of frequency. However, Draft:2019 assumes that in each one-third octave band, both highly absorptive and low absorptive samples have the same γ value.

In the ILT presented here, a different material (double-layer stone wool) was used instead of the reference absorber indicated in Draft:2019 (double-layer glass wool).

2.3. Damping of the reverberation room

One of the main changes included in Draft:2019 is the damping of the reverberation room. As in ISO 354:2003, the equivalent sound absorption area A of the empty room shall not exceed the value indicated in Table 1 for a room volume V=200 m^3. It is an open discussion whether these values should or should not be related to the actual room volume, multiplying the values in Table 1 by the well-known factor from ISO 354:2003, equal to $(V/200)^{2/3}$.

However, Draft:2019 recommends to reduce the reverberation time in the room at the lower frequencies to obtain absorption values just below the values given in Table 1, for example around 6 m^2 for the frequencies 100-315 Hz, without taking into account the actual volume of the room, but referring to a volume of 200 m^3 for any room. In Draft:2019, this is justified by the fact that by increasing the sound absorption also the modal bandwidth and thus the modal overlap increase, with the aim of minimizing the spatial variance.

Table 1 – Maximum equivalent sound absorption areas for a room volume V=200 m^3

Frequency, Hz	Maximum A, m^2	Frequency, Hz	Maximum A, m^2
100	6.5	800	6.5
125	6.5	1000	7.0
160	6.5	1250	7.5
200	6.5	1600	8.0
250	6.5	2000	9.5
315	6.5	2500	10.5
400	6.5	3150	12.0
500	6.5	4000	13.0
630	6.5	5000	14.0

2.4. Positioning and qualification of the loudspeakers

ISO354:2003 provides for different sound source positions, at least 3 m apart. Instead, according to Draft:2019 the loudspeakers must be positioned only in the corners of the room. The possible arrangement of the loudspeakers would require non-conventional (and likely custom-made) loudspeakers to fit the room geometry, particularly in case of non-perpendicular surfaces. A procedure for qualifying the directivity of the loudspeaker is also given.

2.5. Descriptor of the reverberation time

In ISO354:2003, the evaluation range must be 20 dB (T20), while in Draft:2019 it must be 30 dB (T30). No explanation is given for this change. Two methods of measuring decay curves are described in both documents: the interrupted noise method and the integrated impulse response method. However, in Draft:2019, the use of the direct method for acquiring the impulse response (impulse from a pistol shot, balloon burst, spark gap etc.) is no more allowed. Only the so-called indirect method, using tone sweeps or pseudo-random noise (e.g. maximum-length sequences) may be used [31],[32].

Sound absorption is still calculated from reverberation time using the Sabine's formula, corrected for sound absorption in air.

2.6. Correction for the volume of the sample

In Draft:2019, in case of plane absorbers with a volume of the sample of more than 2 m^3, corresponding to a sample thickness of 17-20 cm, a volume correction is applied, i.e. the volume of the room is reduced by the volume of the sample.

2.7. Volume of the reverberation room

The range of permitted volumes of the room is different in the two documents: in ISO 354:2003 the volume of the reverberation room shall be at least 150 m^3 and for new constructions the volume is strongly recommended to be at least 200 m^3; in Draft:2019 the volume of the reverberation room shall be at least 190 m^3 and not more than 350 m^3, while the preferred volume, 200-250 m^3, is indicated in a note.

2.8. Temperature and relative humidity

In Draft:2019 the requirements on temperature and relative humidity are stricter than before: measurements should be performed in the empty room and in the room containing the test specimen under nearly the same conditions of temperature and relative humidity so that the adjustments due to air absorption do not differ significantly. The influence of changing environmental conditions should be less than 3%. Specifications are given for the accuracy and the reading resolution of the measurement apparatus.

2.9. *Estimation of the absorption coefficient of a sample with different size (edge effect)*

The sound absorption of materials not only depends on material properties but also on the geometrical characteristics of the sample. The absorption coefficient of a small sample will be higher than that of a large sample of the same material. Especially for materials with high absorption properties, the measurement with finite sample size may result in absorption coefficients much greater than one.

In Draft:2019, an informative Annex describes a simplified method to estimate the absorption coefficient of a sound absorbing surface of different size from that of the measured sample, based on the work by Thomasson [33]. The method assumes a locally reacting homogeneous material.

2.10. *Measurement uncertainty*

No information on the measurement uncertainty is given in ISO 354:2003, because, at the time of writing that standard, it was still under investigation.

In Draft:2019 the accuracy is described by trueness and precision according to ISO 5725-1 [34]. The two conditions of precision to be described are repeatability and reproducibility. Moreover, a list is presented of several factors influencing the variability of the measurement of absorption and of absorption coefficients. Among them the uncertainty due to the sound field in the room: “A diffuse field is assumed, but the presence of the sample has a negative influence on the diffusivity of the sound field. This influence may be different for different samples and different laboratories”.

In Draft:2019 the repeatability conditions actually refer to the within-laboratory standard deviation. It must be underlined that in ISO 5725-2 [35] the estimate of the repeatability variance, s_r^2, is the arithmetic mean of the estimate of the within-laboratory variance, s_w^2, and this arithmetic mean is taken over all those laboratories taking part in the accuracy experiment (ILT) which remain after the outliers have been excluded.

Draft:2019 states that the measurement uncertainty under reproducibility conditions is to be obtained from ISO 12999-2 [36], unless more accurate results are available. However, the uncertainty presented in ISO 12999-2 is based on the 2003 version of this standard [36], which means that accurate information on the uncertainty can only be obtained after implementation of Draft:2019. An indication of the uncertainty that can be expected by following the Draft is also given, without citing the source.

3. Inter-laboratory Test design

3.1. *Laboratories*

Eleven laboratories agreed to participate in the ILT. The plans are given in Figure 1, while geometric properties such as volumes, floor surfaces of the laboratories are given in Table 2, together with the reverberation time (T20) as per ISO 354:2003 [1], of the empty room, averaged from 100 to 5000 Hz.

In order to comply with the requirements of Draft:2019, the laboratories participating in the ILT, in case they were characterized by an overall equivalent absorption area well below the limits given in Table 1, had to damp their room to fulfil the above discussed requirement (see 2.3). Figure 2 shows the laboratories that had to damp their rooms, finally changing the overall absorption from the equivalent absorption area of the empty room measured in the ISO 354:2003 configuration, $A_{1\text{-}354}$, to the equivalent absorption area of the empty room measured in the Draft:2019 configuration, $A_{1damped}$. In this figure, the maximum equivalent absorption area values are plotted for both the 200 m^3 volume, A_{max200}, and the actual volume of the room, A_{max}. Damping was obtained using different devices described in detail in Table 3.

Table 2 – Geometric properties and mean reverberation time of the rooms

Lab ID	Volume / m^3	Floor surface / m^2	Diffusers area (one side) / m^2	T20 empty / s
1	294.0	59.5	5.0	10.0
2	200.0	45.4	10.2	7.3
3	252.5	49.5	17.4	4.6
4	218.8	54.9	39.1	5.5
5	191.0	42.1	14.0	5.8
6	161.3	43.0	26.0	4.7
7	219.0	54.9	10.4	11.3
8	286.0	83.3	7.5	6.4
9	250.0	49.8	14.0	8.4
10	211.0	38.0	none	11.4
11	187.0	41.6	none	5.0

Table 3 – Description of the damping treatments applied by the different labs.

Lab ID	Summary of damping treatments
Lab 1	Panels (total thickness: 42+3+1=46 mm) made of: Glass wool (density 80 kg/m³, thickness 42 mm) + Mixture of glass balls with acrylic binder 3 mm-thick., particle size 0.5-1 mm, with acrylic binder applied to the glass wool panel + Marble powder, particle size 0.5 mm, with 1 mm-thick acrylic binder.
Lab 2	Three 120 cm x 60 cm, 10 cm-thick polyester fiber panels obtained by binding together two 5 cm panels, mounted on a stand and located at three corners to maximize the low frequency effect
Lab 4	Three hemi-wedges hanging on the longest opposite walls with a wooden structure, thickness 15 mm, and a melamine upper plug, thickness 40 mm and density 9 kg/m³
Lab 7	The room was damped by adding on the walls two different types of panels: 3 perforated panels and 2 smooth panels. The smooth panels are boxes of 19 mm pine wood with mineral wool inside and closed by a 2 mm extruded PVC panel. The perforated ones are boxes of 19 mm pine wood with wrapped mineral wool inside and closed by a 15/10 mm thick metal sheet with 10 mm diameter holes and 36 mm pitch

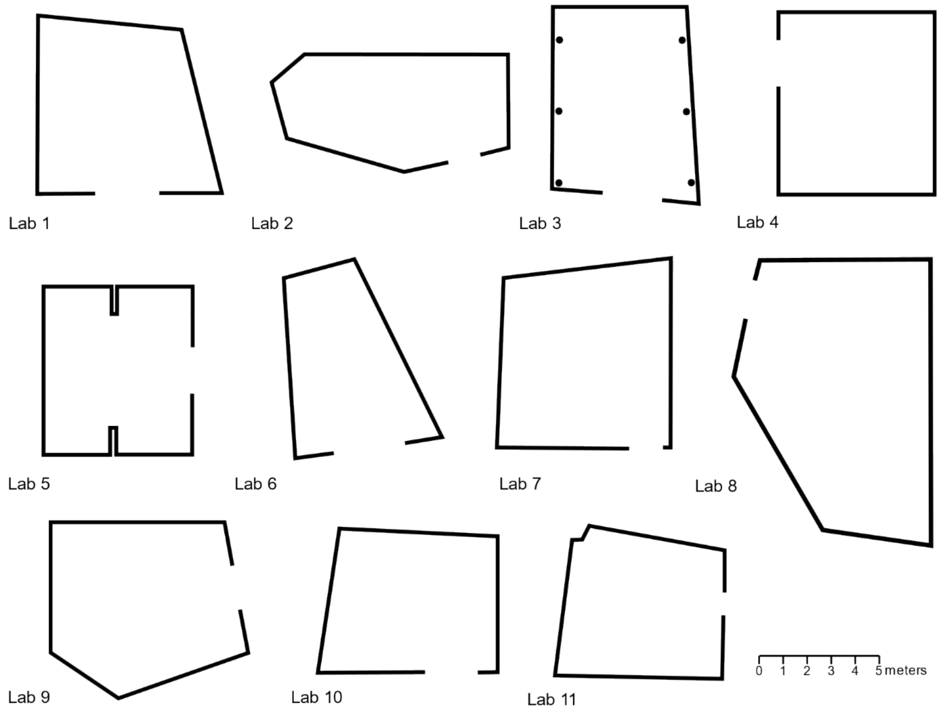

Figure 1 – Schematic plot of the floor plan of the different rooms in the ILT. Same scale for all labs.

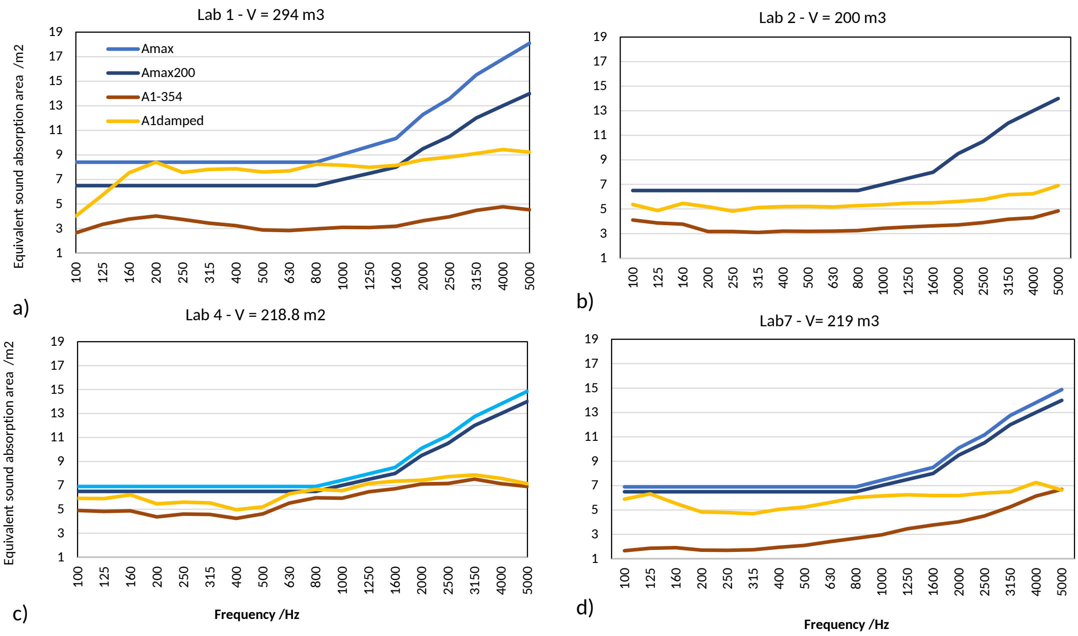

Figure 2 – Equivalent sound absorption area of damped and non-damped empty room: yellow $A_{1damped}$; red $A_{1\text{-}354}$; dark blue, A_{max200}; light blue A_{max}.

3.2. *Samples*

The samples used for the purposes of an ILT, could consist in one individual object that is sent to all the participating laboratories, or in different samples of the nominally same material sent to the different laboratories. In this ILT, samples from the same production batch were sent to the different laboratories participating in the ILT.

The main requirement for the reference absorber proposed in the Draft:2019 is a broad band sound absorption as close as possible to one. As this study did not receive any external funding, various producers were asked to provide materials, free of charge, to be used as reference absorbers. Among those that could be potentially used, one having characteristics comparable with those prescribed by the Draft:2019 was chosen. Thus, the sample used in this study was a stone wool material, 70 kg/m^3 density, 10 cm-thick, arranged in double-layer with a total thickness of 20 cm (Fig. 3a).

In order to analyse and quantify the effects of the changes proposed in the standard, two more samples were used: a single layer (10 cm-thick) of the same stone wool material mentioned above (Fig. 3b), and, to include much lower absorption in the low-medium frequency range, a polyester fibre matt, 2 cm-thick, density 50 kg/m^3 (Fig. 3c). The technical features of the two materials tested are shown in Table 4.

Figure 3 - Photographs of the three samples under test in three different laboratories participating in the ILT: a) 20 cm sample; b) 10 cm sample; c) 2 cm sample

Table 4 – Technical features of tested materials.

Characteristic		Stone wool fibres	Polyester fibres
Thickness	t [mm]	105.0	17.8
Apparent Density	ρ' [kg·m^{-3}]	72.3	42.7
Airflow resistivity	r [kPa·s m^{-2}]	30.3±3.8	15.0±0.6
Fibre diameter	d [µm]	3-10	10-30

The fibre diameter d is expressed as an average range of values, available from technical data-sheets. The apparent density ρ' is measured from the actual sample volume and weight. The thickness is an average of independently determined values.

Airflow resistivity has been determined by applying the alternating airflow method, according to literature [38] and to the procedures stated in the previous ISO 9053:1991 [39]: measurements were carried out in 3 different laboratories and the experimental data are expressed as the average value with its standard deviation.

Measurements of sound absorption at normal incidence were performed according to ISO 10534-2:2001 [3] in 4 laboratories, by using different impedance tubes with diameters ranging between 100 mm and 30 mm. Results are expressed as the average of the 4 laboratory results. Figure 4 shows the experimental results. The red line is the average value of sound absorption coefficient, within the related standard deviation, and the grey marks are the actual distribution of experimental data. It is important to note that the observed scattering in measured values might be related to inhomogeneous material samples, possibly emphasized by the difficulty of cutting them neatly. However, all the participating labs reported that the proper placement of the material inside the sample holder was difficult and caused possible compression of the material, as well as friction along the internal perimeter of the tube.

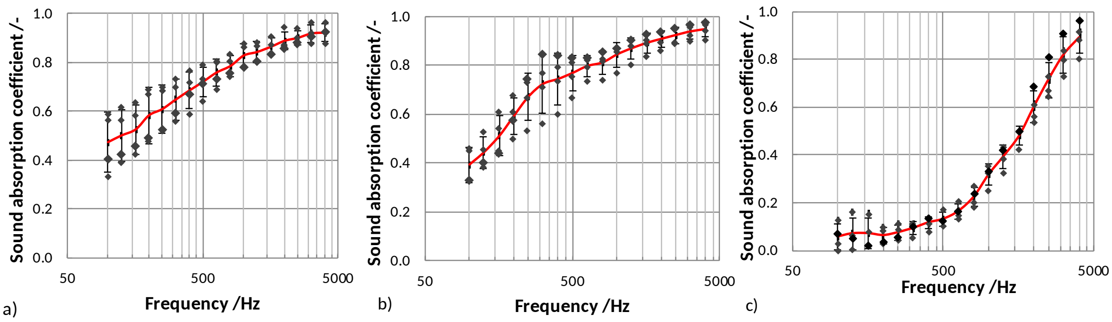

Figure 4 –Sound absorption coefficient, measured at normal incidence in an impedance tube, averaged over the four laboratories, in red the average. a) 20 cm mineral fibres; b) 10 cm mineral fibres; c) 2 cm polyester fibres.

3.3. Inter-laboratory Test protocol

A measurement protocol was agreed among all participating laboratories. As the main goal of the ILT is the comparison between the accuracy and precision of results measured with the standard ISO 354 in force (2003) and the ones measured following the changes proposed in Draft:2019, the protocol was divided into two main parts: “ISO 354” measurements and “Draft” measurements.

In order to calculate both repeatability and reproducibility standard deviations according to ISO 5725-2 [34], each laboratory participating in the ILT repeated each measurement five times for each sample, as specified in the ILT protocol; one repetition consisted in the measurement of the reverberation time with and without the sample in the room, performed directly one after the other.

When possible, five repetition of each measurement had to be repeated in the same day, in order to keep the environmental conditions as constant as possible. When performing repeated measurements, most laboratories reinstalled the test specimen at exactly the same position. Except for one laboratory, which changed the microphones positions each time, all the labs used fixed microphones and sound source positions. In any case, temperature, relative humidity and ambient atmospheric pressure were constantly measured and their effect on measured parameters was compensated according to ISO 9613-1 [41].

To prevent extra absorption from the exposed border of the thicker samples, a frame was used for both stone wool samples, 20 cm and 10 cm thickness. The frame was made of plywood, 18 mm-thick, exactly as suggested in Draft:2019 [28]. Given its small thickness, no frame was requested for the polyester fibre sample.

3.3.1. ISO 354 measurements

Each laboratory had to follow the procedure usually adopted for the measurements according to ISO 354:2003, sending to the ILT coordinator the following data, for each sample under test, for each repetition:

- the reverberation time for both evaluation ranges, T20 and T30, with and without sample in the room;

- the equivalent absorption area for both evaluation ranges, T20 and T30, with and without sample in the room;
- the environmental conditions: temperature, relative humidity and ambient atmospheric pressure, with and without sample in the room;
- the values of the sound absorption coefficient α_s, the practical absorption coefficient α_p and the weighted absorption coefficient α_w [42].

3.3.2. Draft measurements

Among the prescriptions suggested by Draft:2019, customized loudspeakers positioned in the corners of the room should be used. However, for the purposes of this ILT, the sound sources (usually dodecahedrons) normally used for the measurements pursuant to ISO 354:2003 were used in the corner positions. Some laboratories used one single loudspeaker facing the corner of the room in order to better excite room modes [43]. Apart from this aspect, each laboratory had to comply with the draft requirements and consequently proceeded to damp the room according to the details given above (Sec. 3.1), calculated the f_d value described in Sec. 2.1, and then proceeded to measure the three samples again (with five repetitions each).

In addition to the same parameters requested for the "ISO 354" measurement, each laboratory had to send to the ILT coordinator also the following data:

- materials and method used in order to damp the room (where relevant);
- the ratio of the measured and theoretical spatial standard deviation, f_d, for both damped and non-damped room (where relevant);
- a set of figures with sound energy decays, in order to estimate the proper signal-to-noise ratio in each significant frequency band (18).

4. Results

4.1. Measurements according to ISO 354:2003 method

The first set of collected results refers to the three samples measured according to the existing standard. Both T20 and T30 measurements were used, in order to take into account the change introduced in the draft standard about the reverberation time calculation and in order to compare the uncertainties of the two methods. Only the nine laboratories having a sufficiently large area of diffusers were considered, since they comply with the standardised qualification test. Results shown in Figure 5 demonstrated that, despite the compliance with requirements, as anticipated by other studies [12] the inter-laboratory differences were high throughout the entire spectrum of frequencies, whatever the characteristics of the tested materials. However, interesting differences could be pointed out depending on the sample to be tested.

The 20 cm mineral wool sample showed a large spread in the low frequency range values (spanning from about 0.4 to 1.2), often including intra-laboratory variations but even in the medium-high frequency range some extreme situations appeared. Clearly, such a highly absorbing sample determined a substantial anisotropy of the sound field, making the measurements critical even in the best rooms.

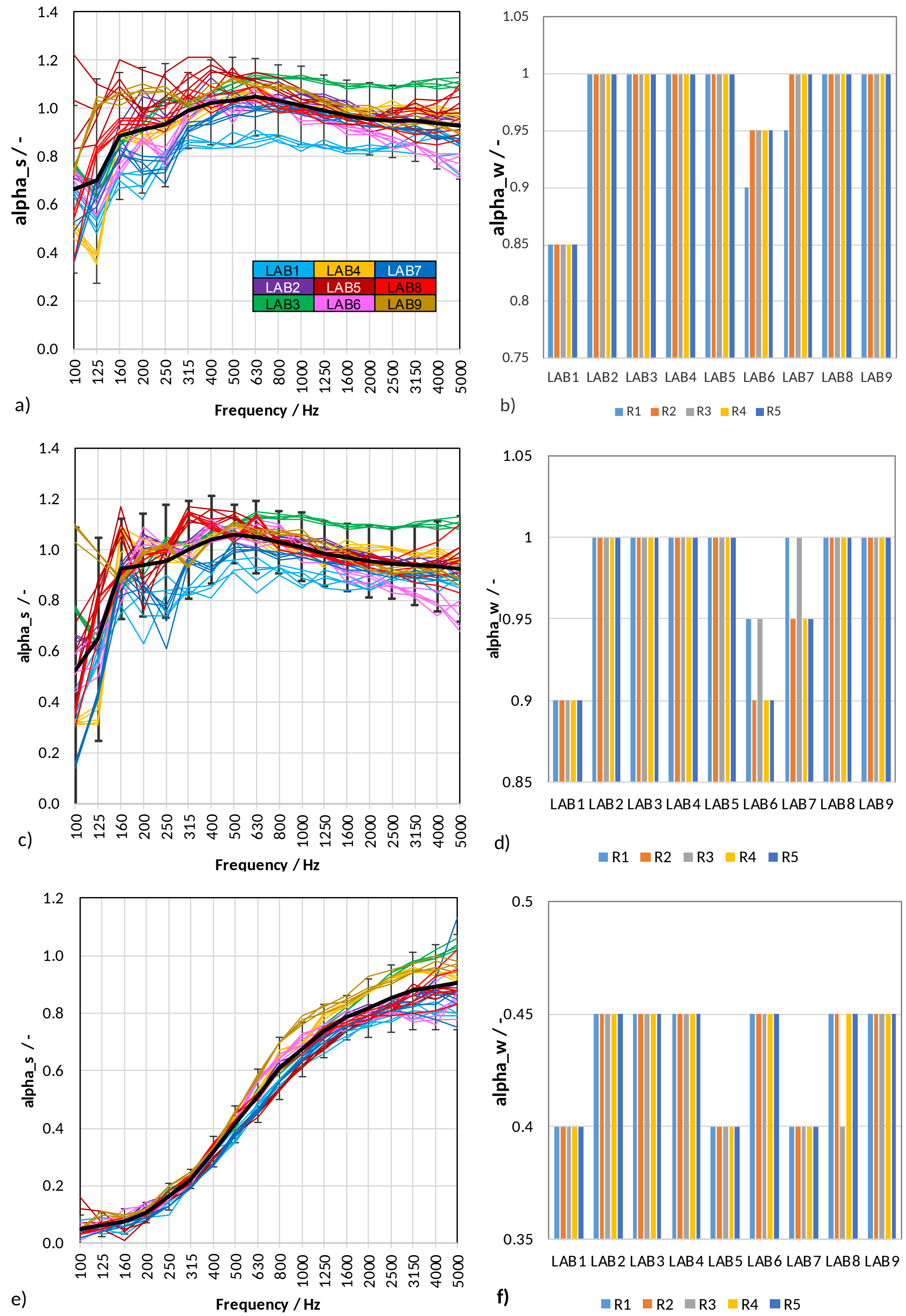

Figure 5 – Plot of absorption coefficients for: a,b) mineral wool fibres, 20 cm thick; c,d) mineral wool fibres, 10 cm thick; e,f) polyester fibres, 2 cm thick. All measurements according to ISO 354, using T20 values, in the nine selected Labs. Panels b), d), and f) give the resulting α_w calculated according to ISO 11654. Error bars in panels a), c), and e) correspond to $2s_R$.

In particular, one lab returned α_S values systematically close to 1.1, while another lab returned values around 0.85. Interpretation of such differences, based on both literature and theoretical considerations, suggests that the laboratory returning lower α_S would have probably needed more diffusion. Similarly, values higher than one are usually associated with diffraction effects at the edges [21], as well as potential shielding of portions of room volume (and change of the mean free path [20]) due to suspended panels, being emphasized by a lack of reflections from the floor because of the sample placement. Even in the last case, according to Embleton [21] an increase in diffusers surface should contribute to have more realistic absorption values. Values of the α_W coefficients were the same in all the cases except in Lab 1 (with the lowest absorption), and Lab 6 which was the smallest laboratory in the study and reported slightly lower values than the others, but the lowest values at very high frequencies.

When the 10 cm mineral wool sample was considered, the variations associated with the α_S values were as large as those observed with the 20 cm sample over the entire spectrum of frequencies. The lab with the lowest absorption values showed larger intra-laboratory variations, but a slightly increased α_W. Lab 6 and 7 also showed larger intra-laboratory fluctuations.

Finally, the polyester fiber mat showed much smaller absolute variations in the low frequency range, where this sample is low absorbing, and a gradually increasing dispersion as the frequency and absorption grow. Again, the scattering of results might be related to the anisotropy of the sound field related to the amount of extra absorption introduced by the sample. Lab 1 provided once again the lowest absorption values (also in terms of α_W). Considering the single number values, two more laboratories (with completely different features) showed lower values, while, Lab 6, even if it still showed lower values at highest frequencies, did not present a low value of α_W. Lab 3 still presented the same behaviour at highest frequencies (i.e. highest values), while Lab 9 and 4 showed the highest values in the medium-high frequency range.

The prescriptions of ISO 5725 [34][35] were followed as far as the statistical analysis is concerned. The four statistical tests (Mandel's h and k, Cochran and Grubbs tests) incorporated in ISO 5725- 2 [35] in order to identify stragglers or outliers were applied for the ILT. At first sight, Lab1 and Lab3 should have been discarded from the statistical analyses. Lab1 because it always shows the lowest results (5 stragglers and 2 outliers according to Mandel's h test), Lab 3 because it always shows the highest results, in particular at higher frequencies (4 stragglers according to Mandel's h test). However, in the following discussion, Lab3 was taken into account because its behaviour is indicated in the Draft:2019 as the "correct" behaviour, always showing a higher value compared to the reference ones, while Lab 1 is substantially an outlier when measuring according to the Draft:2019 (see section 4.2.2 below) and then was discarded. Moreover, keeping Lab 1 in the pool of laboratories for the Draft:2019 would have altered the required equivalent absorption area (A_{req}) values for the reference absorber (see 4.2.3) and therefore all the following analyses. Of course, in order to make a fair comparison among the standard deviations of repeatability and reproducibility for the ISO 354:2003 case and the Draft:2019 case, it is necessary to consider the same number of laboratories and then leave out Lab 1 also from the analysis of measurements according to ISO 354:2003.

4.2. Measurements according to ISO 354 draft method

4.2.1. Qualification of the rooms (f_d measurements)

One key aspect of the draft document is based on the qualification of the room by means of the f_d coefficient, calculated as the average over the third octave bands from 250 to 3150 Hz of the ratio of measured and theoretical spatial standard deviation of reverberation times with the reference absorber and diffusers in the room. The inherent hypothesis of the draft is that laboratories with f_d values greater than one may have non-ideal diffuse conditions and should, consequently, add diffusers and dampers to comply with the requirement. Figure 6 shows the measured f_d values for all the participating laboratories and it can be observed that in four cases the values obtained were lower than one. Laboratories 3, 5, 6 and 8 were considered already damped and therefore they did not modify their room in order to comply with the draft requirement. Conversely, Lab 9, which cannot be considered as already damped, due to lack of time did not damp its room. For all the other laboratories, despite several changes in room configuration (including damping, diffusers number and locations, and source and receiver placement), no significant (and reliable) change in f_d could be detected. With the exception of Lab 10 and Lab 11 which, having no diffusers, were characterized by higher f_d values, it was not possible to find any obvious relationship between f_d values and number and position of diffusers. Thus, it was confirmed that this parameter is substantially meaningless and should not be considered for room qualification purposes (see also [48]).

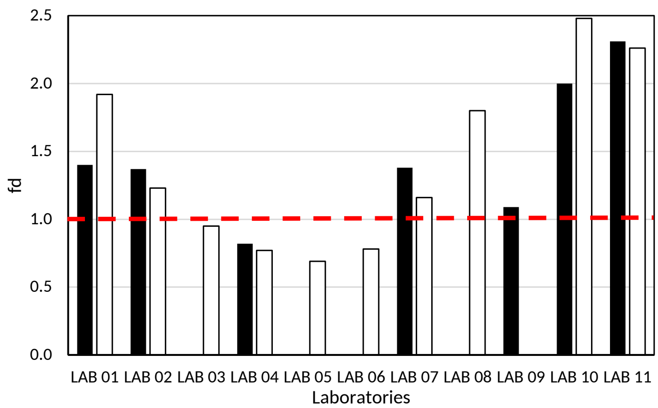

Figure 6 – Plot of f_d coefficients, for rooms without any damping (black) and with damping (white), calculated according to ISO 354 CD, obtained as ratios of the measured and theoretical spatial standard deviation of reverberation times.

4.2.2. Results without γ-correction

In order to consider the influence of all the changes introduced by Draft:2019 method, Laboratories were asked to perform measurements calculating both T20 and T30, and locating all the sound sources in the corner positions with the undamped and damped room (where relevant).

Results of the measurements carried out according to "Draft:2019 method" (i.e. using T30 to calculate absorption, damp the rooms and locate all the sources at the corners), without the application of γ correction derived from the reference absorber, are collected in Figure 7. The adoption of the proposed variations resulted in a remarkable reduction of the scattering in the low frequencies for the 20 cm samples, where some of the most extreme behaviours (likely due to uneven mode distribution) appeared to be significantly smoothed. However, unfortunately, some odd behaviours appeared in the medium high frequencies where Lab 1 kept underestimating α_S showing even lower values (α_W dropped to 0.7), while Lab 6 confirmed its tendency to underestimate absorption at the highest frequencies.

Similar trends were observed for the 10 cm and the 2 cm samples, with Lab 1 systematically underestimating absorption coefficients compared to the other laboratories. This unexpected behaviour was possibly due to the placement of the damping panels at the corners and on the floor, which probably emphasized the anisotropy already caused by the samples to be tested and by the reduced surface of scattering elements. Conversely, other labs showed an increase in the absorption coefficients at the highest frequencies. These results suggest that room damping needs to be carefully optimized in order to be effective, otherwise it might result in a worsened performance.

According to Mandel's h test, Lab 1 shows 4 stragglers (at 160 Hz, 315 Hz, 2000 Hz and 2500 Hz) and 8 outliers (at 200 Hz and from 400 Hz to 1600 Hz) with the 20 cm sample. It shows 7 outliers (at 200 Hz and from 400 Hz to 1250 Hz) and 3 stragglers (at 315 Hz, 1600 Hz and 2000 Hz) with the 10 cm sample. Finally, it shows 4 stragglers (at 200 Hz and from 1250 Hz to 2000 Hz) with the 2 cm sample. In the following discussion, Lab 1 was excluded because of this odd behaviour.

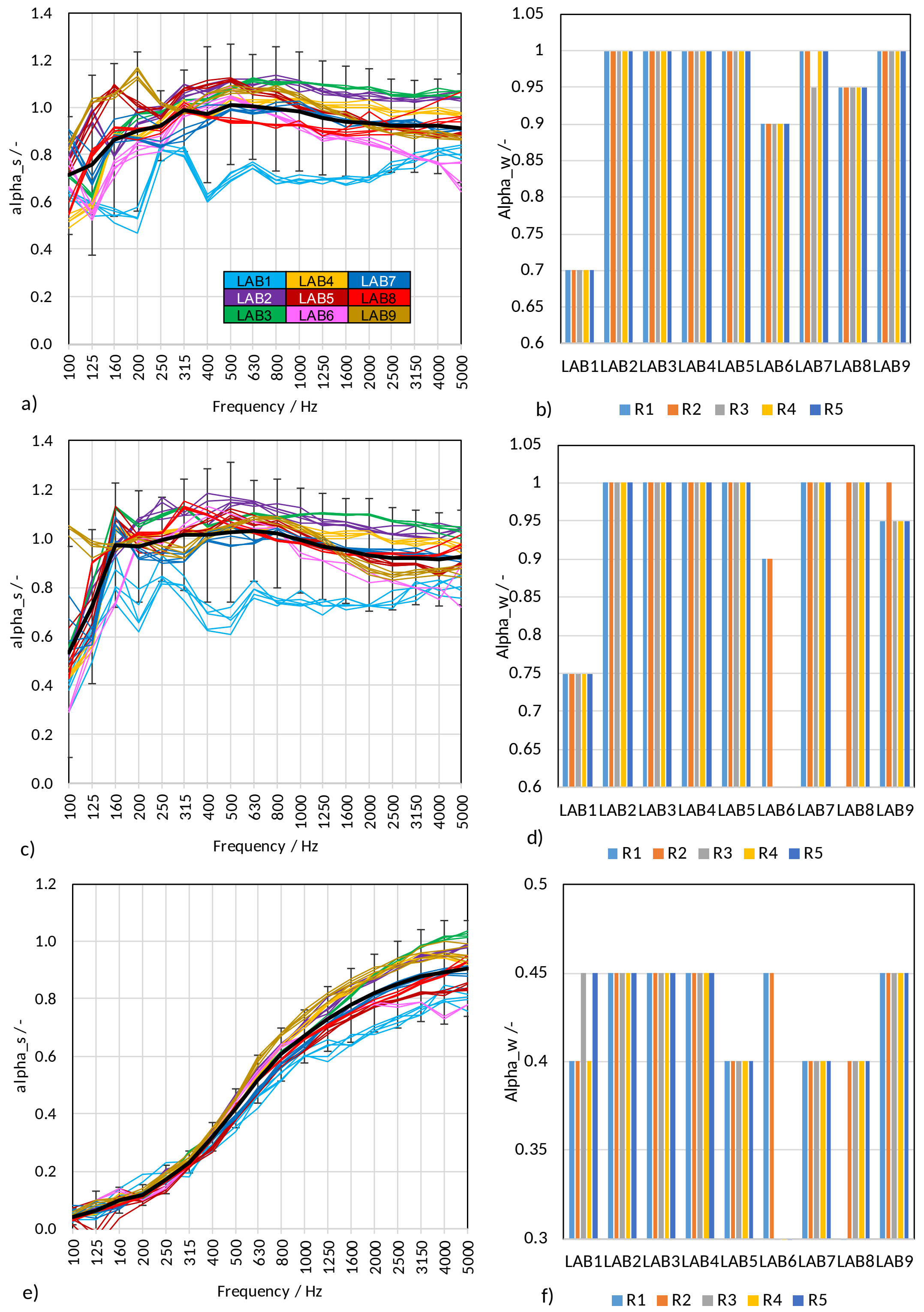

Figure 7 – Plot of absorption coefficients for: a,b) mineral wool fibres, 20 cm thick; c,d) mineral wool fibres, 10 cm thick; e,f) polyester fibres, 2 cm thick. All measurements according to Draft:2019, using T30 values, in the eight selected Labs that could be considered damped. Panels b), d), and f) give the resulting α_w calculated according to ISO 11654. Error bars in panels a), c), and e) correspond to $2s_R$.

4.2.3. Results with γ-correction

Once the data for the 20 cm stone wool sample (i.e. the reference absorber) were collected by each laboratory, the correction procedure proposed in the draft was applied, and the γ values were calculated according to the steps described in Sec. 2.2. As the material differed from that proposed in Draft:2019, it was not deemed to be appropriate to assume the values given in Draft:2019 as a reference.

At this point, in order to proceed with the application of the γ correction it was necessary to set the required equivalent absorption area (A_{req}) values to be used for the calculation. A quite obvious option was represented by the average values coming from the ILT itself (after removing Lab 1 which proved to be a clear outlier, and Lab 9 whose room was not damped because of timing factors). This consideration takes into account the well-known fact that, due to the typology of the sample test in acoustic measurements, a reference value of the measurand does not exist; therefore an estimated value has to be used [44][43]. Of course, the best evaluation of the measurand is the average value coming from an ILT (Figure 8). In accordance with the prescriptions of Draft:2019, the reference absorber value was determined with the damped reverberation rooms (i.e. without considering Lab 9). The use of the average values (best-estimate values) from the ILT itself had the obvious consequence that the laboratories could not comply with STEP 1 for what concerns the use of the reference absorber (see paragraph 2.2 above), i.e. to modify the room in order to measure the minimum value of the equivalent absorption area of the reference absorber (A_{req}). Another unavoidable consequence resulting from the adoption of a reference value calculated as stated above is that there will always be laboratories having an equivalent absorption area lower than A_{req}, and thus a γ value greater than one. Conversely, Draft:2019 inherently implies that laboratories complying with the standard should have γ values below one. Consequently, a viable option may be to use a reference value calculated as a function of the flow resistivity of the selected sample. In fact, Figure 7 shows that, with reference to the normal incidence absorption values, there is an almost perfect agreement between values calculated using the Delany-Bazley-Miki [45] model and those measured. Thus, it seems reasonable to start from flow resistivity to obtain the diffuse field absorption coefficient assuming a finite dimension sample. In [46] Allard and Atalla introduce a 'true' diffuse field absorption coefficient obtained by accounting for the size effect both in the absorbed and in the incident power, as a function of the normal impedance calculated with the Transfer Matrix Method (TMM). 'True' is used in [46] in the sense that its value is always less than one; the results of this formulation, analytically calculated with the Bonfiglio *et al.* formulation [47] are shown in Figure 8. Moreover, this absorption coefficient value, used as reference, permits to understand the consequences of the use of a minimum reference absorber, as required in Draft:2019.

Based on the two proposed approaches, γ values were calculated in one-third octave bands as suggested by Draft:2019 and are given in Figure 9. As expected, in the first case (Fig. 9a) some of the labs show values higher than one and others lower than one, with the largest corrections appearing at the extremes of the frequency range and particularly in the lowest bands. In the second case (Fig. 9b), with the exception of one laboratory (Lab 6), all the others were very close to or below one, thus ideally complying with Draft:2019 requirements. Figure 9 shows the γ correction factor of eight laboratories. Considering the ILT average as reference, also Lab 9 was included in the calculation, even if it was not included in the average from which the reference values were calculated.

This was decided because the behaviour of Lab 9, although its room has not been damped, is very close to the behaviour of all the other laboratories. In the case of TMM, obviously Lab 9 can be considered in the calculation, as the reference is theoretical and not referred to the ILT itself.

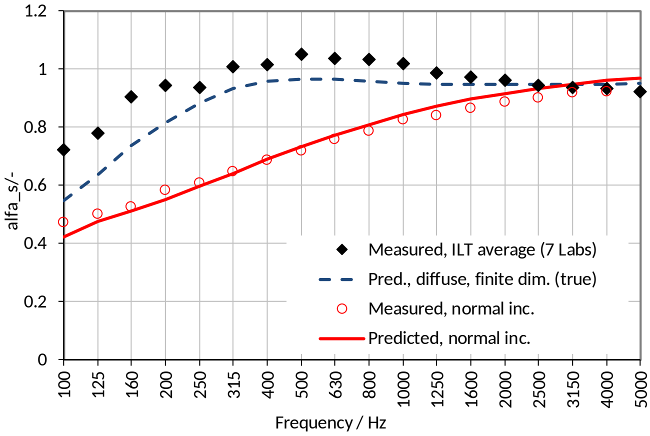

Figure 8 – Comparison of absorption coefficients to be used as “reference” values for the calculation of γ. Measured diffuse-field values are based on the ILT average resulting from the 7 laboratories according to Draft:2019 method. Predicted diffuse field values for finite dimension samples are based on the use of TMM according to Allard and Atalla [46] formulation. Measured and predicted normal incidence values are also given for comparison.

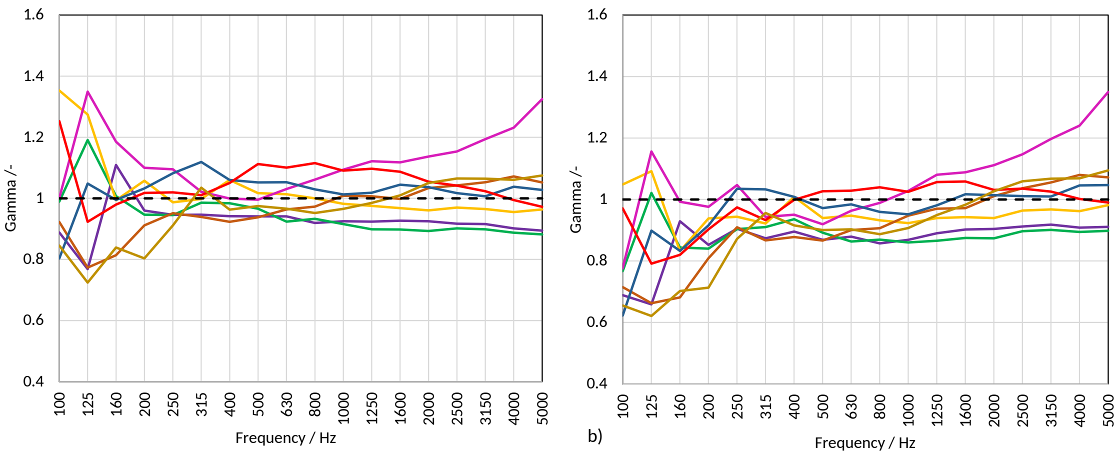

Figure 9 – Plot of γ coefficients calculated according to ISO 354 draft, obtained as ratios between measured absorption coefficients for each laboratory and: a) the average of the 7 damped laboratories; b) a theoretical value calculated assuming a finite size sample having the same flow resistivity as the sample under investigation. Eight laboratories were considered, excluding Lab 1 due to its odd behaviour.

As expected, the use of the γ factor calculated from the ILT average works well when applied to the 20 cm sample (Fig. 10a,b). In fact, with the exception of a few intra-laboratory fluctuations, mostly located at the lowest frequency bands, most of the variations observed before (Fig. 8) completely disappeared. However, the supposed usefulness of the γ factor should appear when applied to different samples. Application to the 10 cm sample (Fig. 10c,d) showed a significant reduction of the dispersion in the high frequency range (where absorption coefficients are very similar to those of the

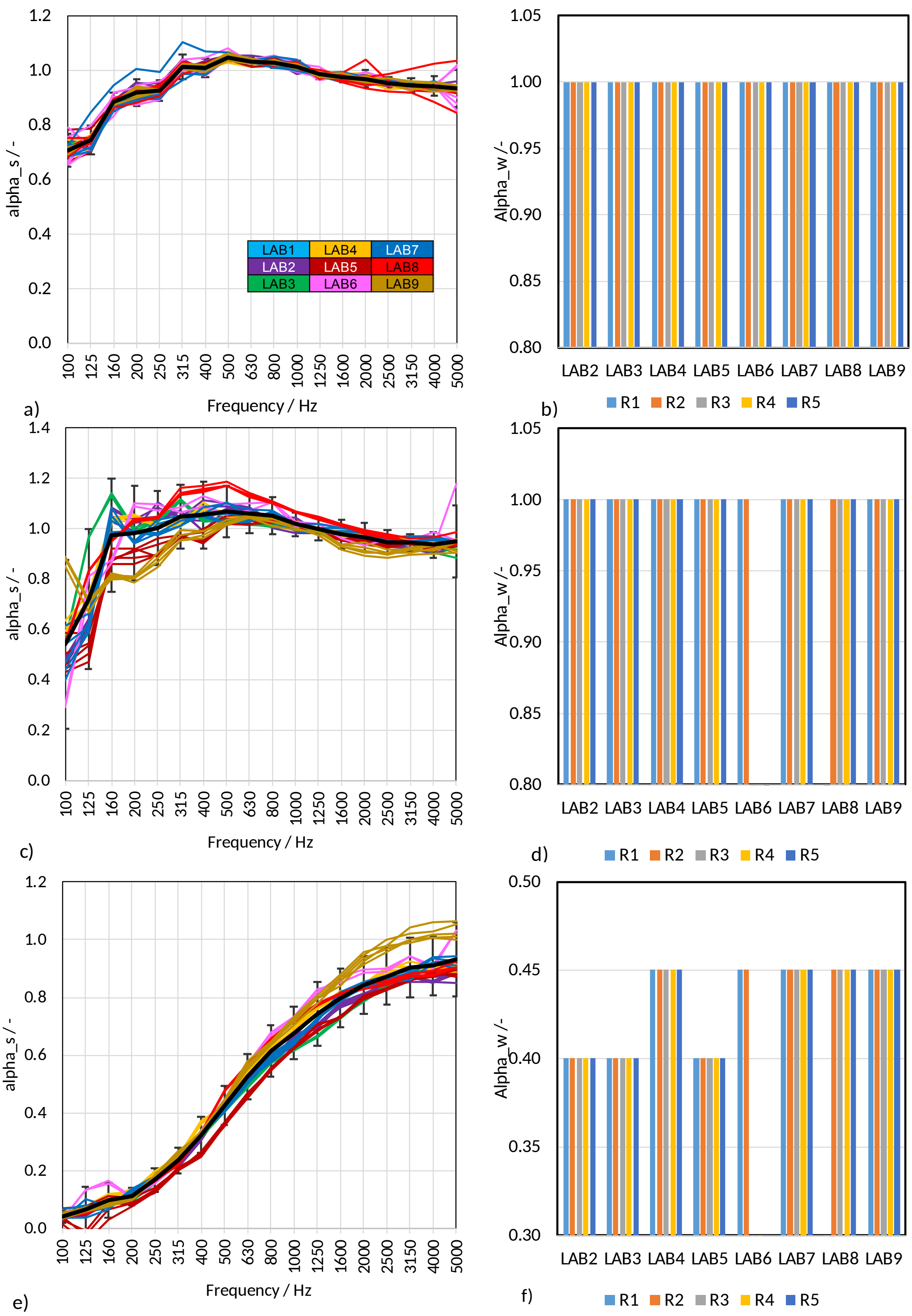

Figure 10 – Plot of absorption coefficients for: a,b) mineral wool fibres, 20 cm thick; c,d) mineral wool fibres, 10 cm thick; e,f) polyester fibres, 2 cm thick. All measurements according to ISO 354 draft, using T30 values, in the eight selected Labs, including γ correction based on ILT average. Panels b), d), and f) give the resulting α_w calculated according to ISO 11654. Error bars in panels a), c), and e) correspond to $2s_R$.

thicker sample), while some odd behaviours were observed in the low frequency range, although to a very limited extent. In terms of α_w all the labs returned the same value, apparently confirming the usefulness of the γ correction. However, some very odd behaviours appeared with the polyester fiber mat (Fig. 10e,f), because the Labs that originally returned the highest values of absorption coefficients were strongly affected by the application of the γ correction which (being lower than one) caused a change in the shape of the absorption curve and a reduction of α_w from 0.45 to 0.40. Conversely, as an obvious consequence of having chosen the reference value as the average among the different laboratories, two of the Labs that returned α_w equal to 0.4 with no correction applied, increased their value to 0.45 after its application.

Considering the critical points that emerged from the use of the γ correction based on the ILT average, it was particularly interesting to analyse whether adopting a reference based on the analytical calculation of diffuse field absorption coefficient [46], with a value always less than one; in this case γ values are consistently lower than one, and all the measured data, corrected with this γ values, tend to be less than one. Figure 11a,b shows that once again, apart from the slightly different shape of the absorption curve, almost all the anomalies are eliminated when the γ correction is applied, with the exception of a few intra-laboratory fluctuations. The flatter behaviour in the central frequency zone of the reference curve determines a systematic reduction of α_w which now equals 0.95 in nearly all Labs and repetitions. Even if the single number value is lower than in the other case, it is very interesting to understand the consequences of the application of γ correction when the reference value is always lower than the measured ones, as required in the Draft:2019.

When the 10 cm sample was used, again the high frequency fluctuations were greatly attenuated and those in the low frequency range significantly reduced. However, inter-laboratory differences were consistent with those appearing when γ_{ILT} was used (Fig. 11c,d). Considering α_W, results varied between 0.95 and 1.0, with the lowest values appearing in some of the Labs where γ produced the lowest values in the medium frequency range. Particularly, it is worth to notice that Lab 3, which always showed the highest values, with the γ correction, returned a lower value. Finally, with reference to the polyester sample (Fig. 11e,f), the sound absorption coefficients were systematically "depressed" by the application of the γ factor. Lab 9 was the only exception as it showed (for both ISO 354:2003 and Draft:2019 with no γ correction) lower-than-average medium-high frequency absorption coefficients for the 20 cm sample, and higher-than-average absorption coefficients for the 2 cm sample. Consequently, application of γ correction to the polyester fibre coefficients further increased absorption, resulting in the odd behaviour observed. However, in terms of α_W, as this parameter is strongly influenced by medium frequency behaviour, all the Labs showed a reduction to 0.40, with the only exception of Lab 8 which was characterized by a $\gamma > 1$ from 400 Hz on up.

By comparing the results obtained for the three samples, it seems that the application of γ correction to samples that significantly differ from the "reference" ones may result in an unwanted alteration of the shape of the absorption coefficients and, with reference to single-number parameters, like α_W, that it may be very sensitive to variations appearing in the medium frequency range, and may very likely lead to a systematic reduction of the index. Further considerations will be drawn in the subsequent Section, taking also into account implications on measurement uncertainty.

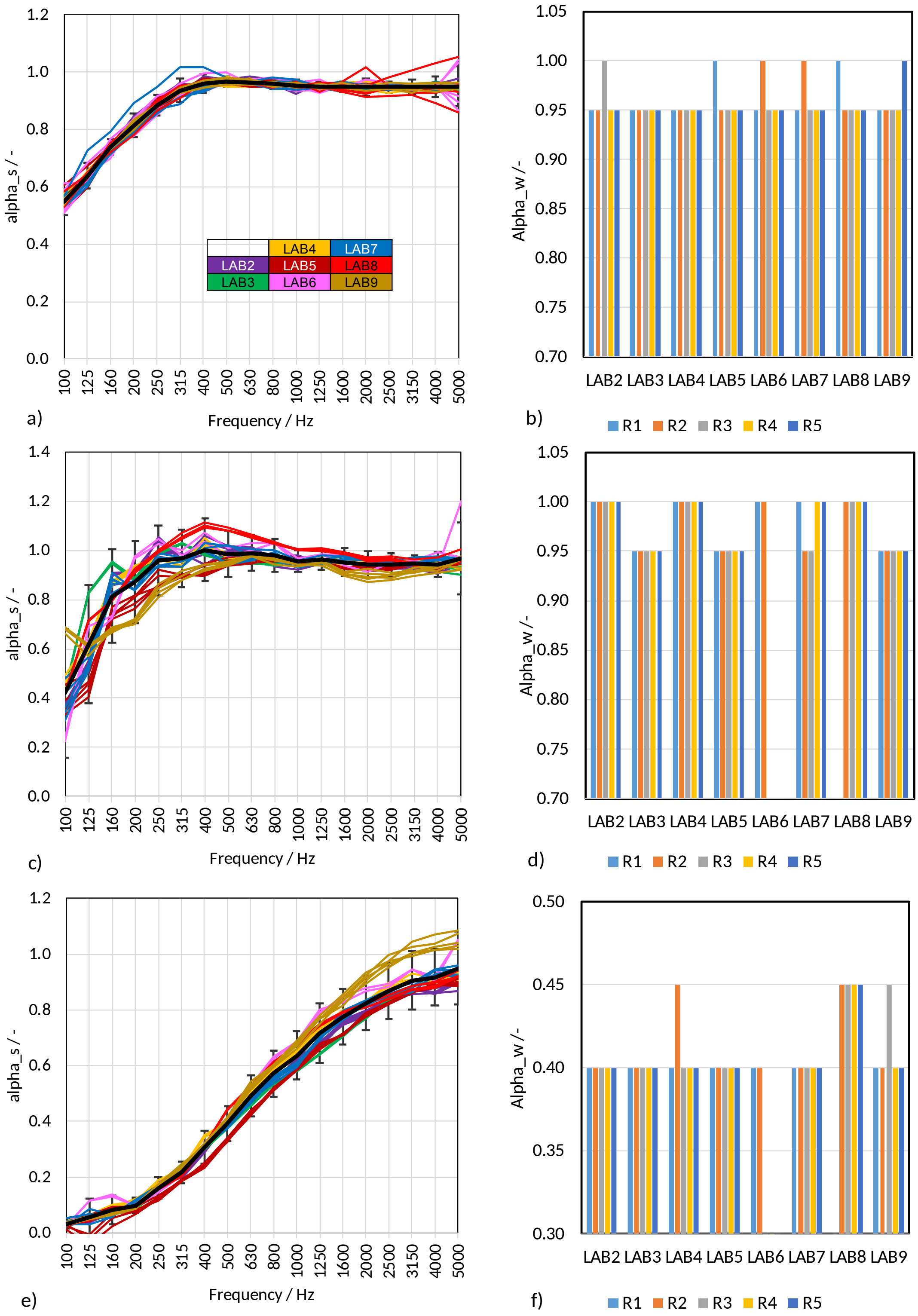

Figure 11 – Plot of absorption coefficients for: a,b) mineral wool fibres, 20 cm thick; c,d) mineral wool fibres, 10 cm thick; e,f) polyester fibres, 2 cm thick. All measurements according to ISO 354 draft, using T30 values, in the eight selected Labs that could be considered damped, including γ correction based on

predicted finite dimension diffuse field value. Panels b), d), and f) give the resulting α_w calculated according to ISO 11654. Error bars in panels a), c), and e) correspond to $2s_R$.

5. Discussion

In order to provide a quantitative estimate of the effect of the application of different standards (and their variations), sound absorption values (frequency based and single-number) and uncertainties were compared and discussed. For comparison purposes, results referred to ISO 354:2003 in force were expressed both as a function of T20 and T30 reverberation times, and with reference to Draft:2019 the effect of room damping is also discussed together with the use of different γ corrections.

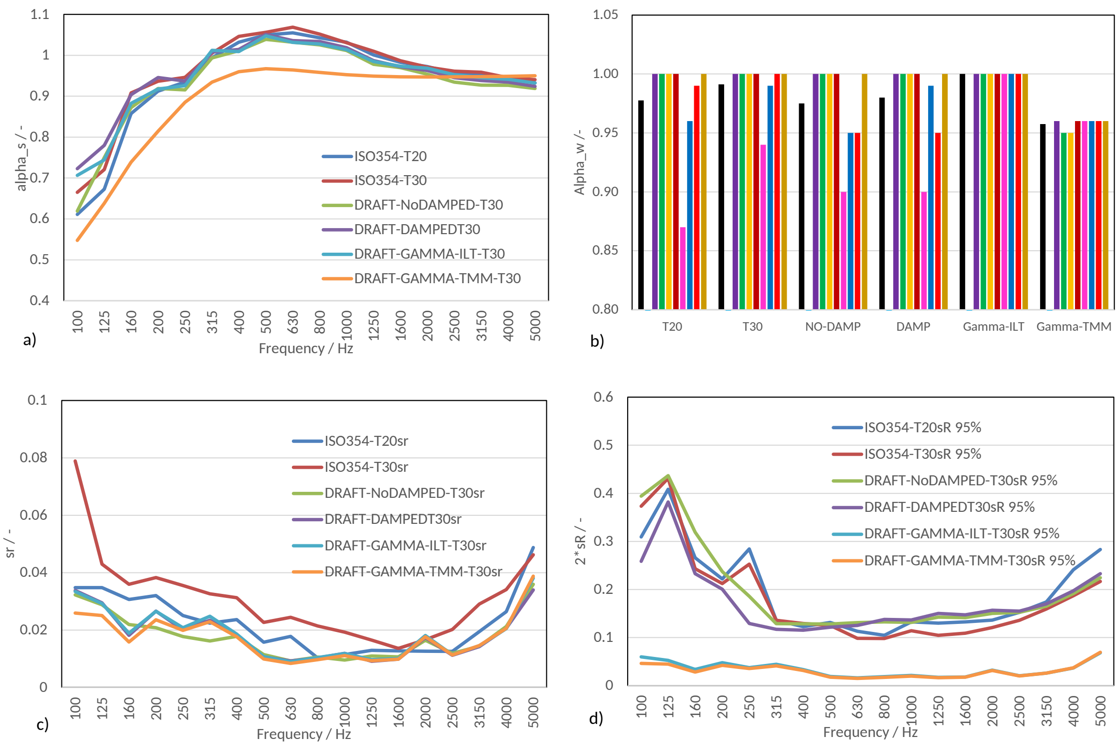

Figure 12 – Summary of results for 20 cm sample: a) ILT average (8 Labs) of sound absorption as a function of frequency and measurement configuration; b) ILT average (in black) and individual Labs α_W resulting from different measurement configurations; c) repeatability standard deviation as a function of frequency and measurement configuration; d) 95% probability (reproducibility standard deviation with coverage factor k=2) as a function of frequency and measurement configuration.

With reference to the 20 cm sample (Fig. 12 and Tab. A.1) it can be observed that the use of T30 instead of T20 under current ISO 354 measurement conditions resulted in a slight increase in absorption coefficients and, more importantly, in a substantial increase in the repeatability standard deviation balanced by a reduction of the reproducibility standard deviation that, at frequencies above 400 Hz, was at its lowest without the application of the γ correction. The use of Draft measurement configuration without γ correction returned slightly lower sound absorption coefficients in the medium frequency range and a mixed behaviour in the lowest bands, where the "damped" configuration returned the highest absorption coefficients, while the non-damped rooms returned values comparable to those obtained with ISO 354/T20. In terms of repeatability standard deviation the adoption of the Draft configuration yielded a general improvement, while in terms of reproducibility standard deviation values, results were substantially comparable to those obtained with ISO 354/T20 above 400 Hz, but in the lowest bands the use of damping proved effective in reducing the differences. Finally, the application of γ correction had obvious effects on the absorption coefficients, which coincided with the "reference" values adopted in the two cases; it also had a small positive effect on the repeatability standard deviations (particularly when using γ_{TMM}), and, as expected, it caused a dramatic reduction of reproducibility standard deviations.

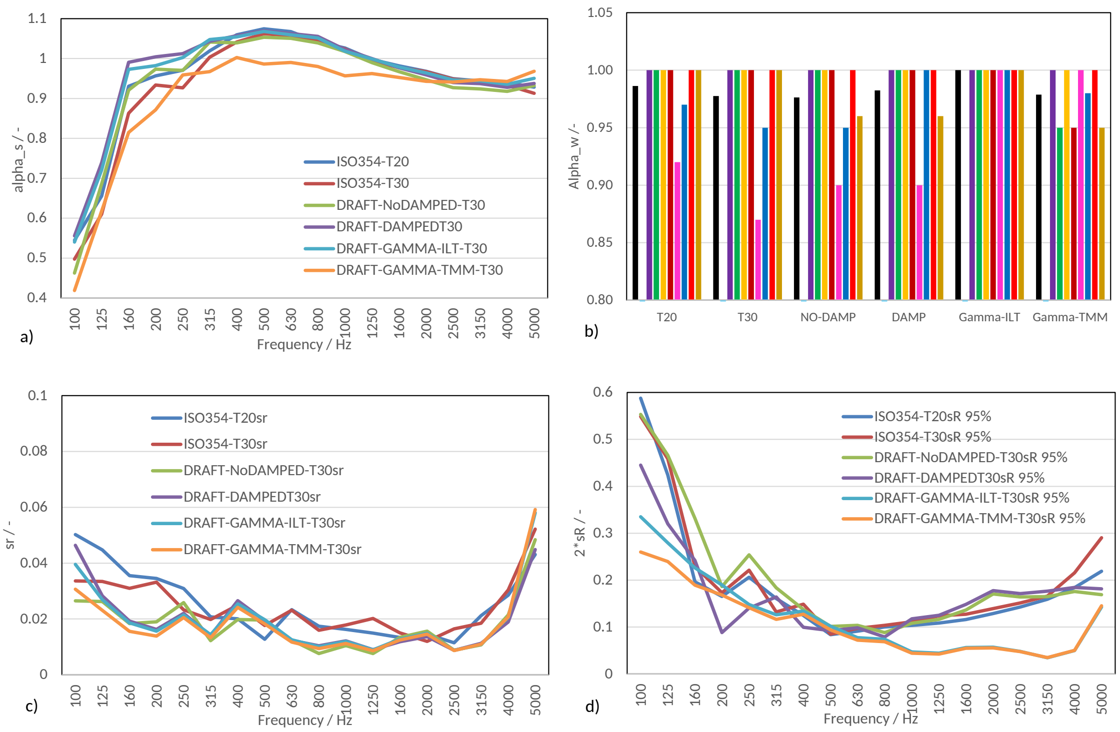

Figure 13 – Summary of results for the 10 cm sample: a) ILT average (8 Labs) of sound absorption as a function of frequency and measurement configuration; b) ILT average (in black) and individual Labs α_W resulting from different measurement configurations; c) repeatability standard deviation as a function of frequency and measurement configuration; d) 95% probability (reproducibility standard deviation with coverage factor k=2) as a function of frequency and measurement configuration.

With reference to the 10 cm sample (Fig. 13 and Tab. A.2) it can be observed that the use of T30 instead of T20 under current ISO 354 measurement conditions resulted in a notable decrease in absorption coefficients below 500 Hz (which is some cases also affected the single number value). In terms of repeatability standard deviation, the use of T30 returned slightly better values in the low frequencies, while they were substantially the same in the highest bands. Finally, the use of T30 instead of T20 resulted in a very small increase of reproducibility standard deviation, being a little bit more evident in the highest frequency bands. Use of Draft measurement configuration without γ correction returned slightly higher sound absorption coefficients in the medium frequency range and a mixed behaviour in the lowest bands, where the "damped" configuration returned again the highest absorption coefficients, while the non-damped rooms returned values comparable to ISO 354/T20. In terms of repeatability standard deviations, the adoption of Draft configuration yielded again a general improvement, while in terms of reproducibility standard deviations, results were substantially comparable to ISO 354/T20 above 400 Hz, but in the lowest bands the use of damping proved effective in reducing the differences. Finally, the application of γ correction caused a notable decrease of absorption coefficients when γ_{TMM} was used, with a reduction of α_W in half of the Labs. The effect on repeatability standard deviation was barely noticeable, with more evident improvement only at the lowest frequencies when γ_{TMM} was used. With reference to reproducibility standard deviation, the comparison offered the first important check of the usefulness of γ correction, showing that a significant decrease appears above 800 Hz (where the 10 cm sample and the 20 cm sample behave similarly), and below 160 Hz, while between 160 Hz and 800 Hz (included) the use of γ correction does not yield markedly evident benefits.

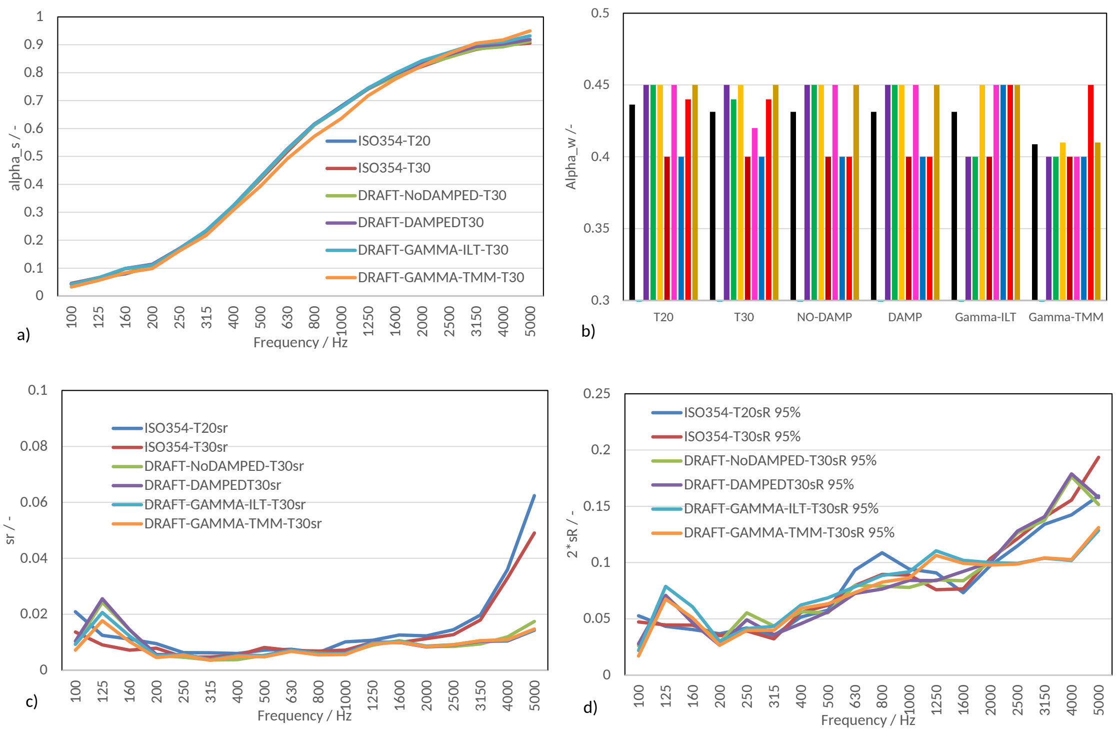

Figure 14 – Summary of results for 2 cm sample: a) ILT average (8 Labs) of sound absorption as a function of frequency and measurement configuration; b) ILT average (in black) and individual Labs α_W resulting from different measurement configurations; c) repeatability standard deviation as a function of frequency and measurement configuration; d) 95% probability (reproducibility standard deviation with coverage factor k=2) as a function of frequency and measurement configuration.

With reference to the 2 cm sample (Fig. 14 and Tab. A.3), it can be observed that the use of T30 instead of T20 under current ISO 354 measurement conditions resulted in barely noticeable differences in terms of sound absorption (although α_W changed in some of the Labs), while, in general, using T30 resulted in a smaller uncertainty. The use of Draft measurement configuration without γ correction returned negligible variations in absorption coefficients, with just one Lab recording a lower α_W, with substantially similar results between damped and non-damped configurations. Repeatability standard deviation also decreased with the only exception of the 125 Hz and 160 Hz bands where an odd peak was observed. The same odd behaviour at the same frequencies appeared in the reproducibility standard deviation while in the other bands (except for 1250 Hz, where another odd peak is evident) no noticeable variation could be detected in comparison with results derived from the current ISO 354 configuration (particularly if T30 was used). Starting from 2500 Hz, an improvement of inter-laboratory behaviour is noticeable, being the absorption coefficient values higher than and closer to 1, where the γ correction had proved to be effective. Finally, as anticipated, the application of γ correction caused some changes that need to be carefully discussed. First, in terms of absorption coefficient, the use of γ_{ILT} resulted in some "inversions" in the assignment of the α_W values because some of the Labs that previously yielded a 0.45 value (e.g. Labs 2 and 3) were reduced to a 0.40, while others (Lab 7) moved from 0.40 to 0.45. When γ_{TMM} was used, the shape of the sound absorption curve changed, particularly in the range from 400 Hz to 2 kHz, with an almost generalized reduction to 0.40 for the resulting single number values. In terms of repeatability standard deviation, the same trend shown by uncorrected values was observed, with the odd peak at 125 Hz and 160 Hz still appearing although slightly attenuated. Finally, with reference to reproducibility standard deviation both γ corrections showed a comparable performance, with an effective improvement appearing only above 2.5 kHz (once again where absorption coefficients were comparable with those of the reference sample), while in the remaining part of the spectrum not only the variance remained the same but, in some cases, it also showed a worsened performance (like at 125, 160, 1250 and 1600 Hz).

Draft:2019 assumes the linearity of the systematic deviation of the laboratory as a function of the absorption coefficient. As a consequence, it is assumed that the absorption correction factor obtained for a highly absorptive material (reference absorber) will also apply for a material with a much lower absorption factor. The results of the ILT clearly show that this linearity cannot be assumed.

As an example, Figure 15 shows the results of Lab 3 according to ISO 354:2003 for both T20 and T30 and according to Draft:2019 with both γ corrections. It is evident that the corrections produce important changes in the absorption coefficient values, reducing the high frequencies values and increasing the low frequencies values with the appearance of peaks in some frequencies.

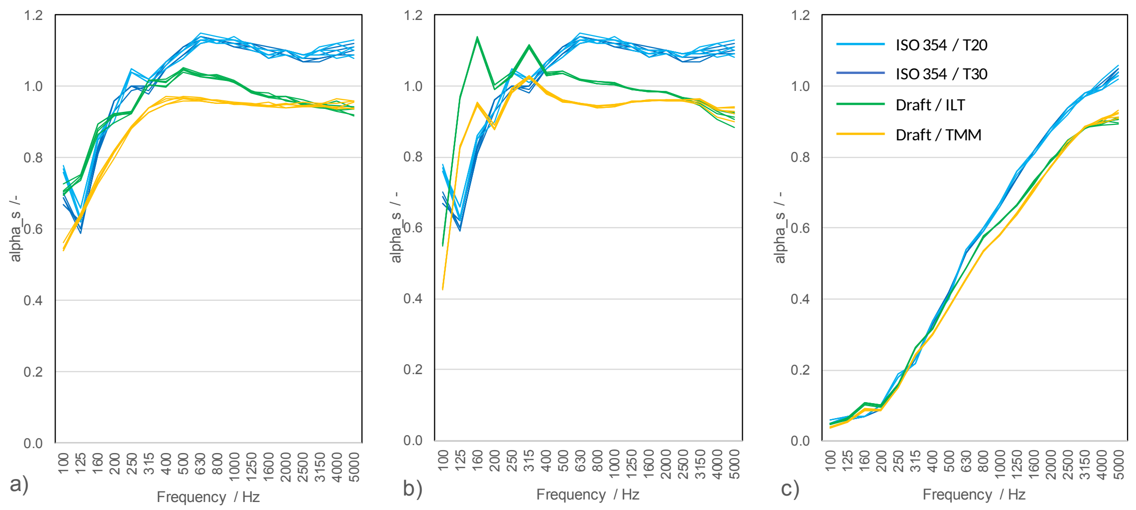

Figure 15 – Summary of results as a function of frequency (for all repetitions) and as a function of different calculation methods in Lab 3: a) 20 cm sample; b) 10 cm sample; c) 2 cm sample.

6. Conclusions

This paper presents the results of an inter-laboratory test aimed at measuring sound absorption coefficients in a reverberant room according to ISO 354:2003 in force and the modified version circulated since 2017 and recently licensed in the form of a Committee Draft in December 2019. The Draft:2019 introduced some changes in the laboratory methodology and in the room qualification, as well as some variations in the calculation of sound absorption coefficients. In particular, a correction factor (named γ coefficient) was introduced to "normalize" the absorption coefficients based on the comparison with the performance of a reference absorber.

11 Labs were originally involved in the ILT, but only 8 were selected for the final analysis based on their strict compliance with both current and forthcoming versions of ISO 354 standard. A strict measurement protocol was defined, requiring five measurement repetitions for each sample and for each room configuration. In addition, extra measurements were carried out to possibly highlight the contribution (and the usefulness) of the different variations introduced by the Draft:2019. Three samples were used in the test. The first, also assumed as the "reference" sample, was made by two layers of a 10 cm-thick stone wool mat. The second was made of a single layer of the same material, and the third was a 2-cm thick polyester fibre mat, to take into account the implication of the use of γ correction for less absorbing materials (even if the polyester fibre has a high absorption coefficient at high frequencies, even with only 2 cm thickness).

With reference to the main innovation introduced by Draft:2019, the analysis of the results allow to highlight the following points:

- the use of T30 instead of T20 contributed to reduce in several cases both the repeatability and reproducibility standard deviations, but in some cases an increase was observed;
- the introduction of room damping resulted in a general reduction of both the within- and inter- laboratory variance at frequencies below 500 Hz. At higher frequencies the effect of damping was negligible and, in some cases it resulted in a slightly worsened performance;
- damping elements needed to be carefully located because in some cases, particularly in rooms with less-than-ideal diffusion, their addition resulted in a general worsening of the room performance;
- the use of the reference absorber to qualify the reverberation room might be a valid, although challenging, test to understand the room behaviour. However, the proposed use of the f_d coefficient (i.e. the ratio of measured to theoretical spatial variance), as a measure of room diffusiveness with the reference absorber returned inconsistent results. In fact, some of the labs with a large number of diffusers performed well, but the addition of extra diffusers in the others had little or no effect on f_d. Such conclusions support Davy's statement [48] against the use of this index as a room qualifier;
- the use of γ factor to "correct" the absorption coefficient values proved to be very questionable for a number of reasons:
  - the equivalent absorption area to be assigned to the reference sample, which is essential to calculate γ, should not be assigned arbitrarily but should result from several measurements under different conditions and provided with its measurement uncertainty (rather than in terms of

"minimum" and "maximum" values). Comparison with theoretical values calculated assuming a finite difference sample showed large, and sometimes hard to be measured/observed/trusted variations, so this topic needs a much deeper investigation before it can be proposed for a standard;
- even assuming the reference equivalent absorption area values to be trustworthy, application of the γ correction proved to be effective in reducing the inter-laboratory variances only when the absorption coefficient of the sample was sufficiently similar to that of the reference one. In the other cases its application resulted in an odd modification of the absorption curves, reduction of the single number values, and no significant improvement (if not the contrary) of the reproducibility standard deviation.

Further analyses of collected data are under way in order to better understand the complex phenomena taking place in reverberation rooms. At this stage, it seems possible to conclude that some of the proposed modifications of the standard may contribute to improve measurement accuracy. However, it appears clear that introducing "γ-corrected" absorption coefficients, without a firm scientific background to support them, might only contribute to increase the confusion in the final user, without any guarantee that such values might return more accurate results when used in practice (e.g. in acoustical simulations). Conversely, the use of the "reference absorber" might certainly be recommended as a convenient tool to test and improve reverberant rooms under very demanding (non-diffuse) conditions. However, the values of the reference absorber used for this purpose must be very carefully chosen and, at the current level of knowledge, the only practicable (scientific based) choice is the use of the average coming from an ILT, like the one described in the paper or others (e.g. [49]).

Acknowledgments

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Authors' contributions

All authors provided feedback on all steps, especially critical feedback on the paper, and performed measurements. C. Scrosati conceived of the idea and organized the project. C. Scrosati, F. Martellotta, F. Pompoli, A. Schiavi, A. Prato, D. D'Orazio, N. Granzotto and A. Di Bella, wrote the protocol. F. Martellotta performed the first measurements on the basis of which the protocol was improved. F. Pompoli, A. Prato, N. Granzotto and F. Martellotta performed impedance tube measurements. A. Schiavi performed airflow resistivity measurements. F. Pompoli performed calculation of predicted diffuse field values for finite dimension samples. C. Scrosati acquired data, analyzed and interpreted data, supervised the ILT and performed the statistical analysis. F. Martellotta and C. Scrosati drafted the manuscript with contribution of F. Pompoli, A. Schiavi and N. Granzotto for paragraph 3.2 and contribution of M. Garai for paragraph 2.

Appendix

Table A.1 – Summary of results for 20cm sample - average (avg), repeatability standard deviation s_r and reproducibility standard deviation s_R - referred to ISO 354:2003 in force expressed as a function of T20 reverberation times, and to Draft:2019 including the effect of room damping and the use of different γ corrections, ILT and TMM.

	alpha_s/-											
	ISO354-T20			Draft-Damped-T30			Draft-γ-ILT-T30			Draft-γ-TMM-T30		
f /Hz	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R
100	0.665	0.079	0.187	0.723	0.034	0.129	0.706	0.033	0.030	0.548	0.026	0.023
125	0.721	0.043	0.216	0.780	0.030	0.191	0.744	0.029	0.026	0.638	0.025	0.022
160	0.908	0.036	0.122	0.904	0.018	0.116	0.883	0.019	0.017	0.739	0.016	0.014
200	0.937	0.038	0.106	0.946	0.027	0.100	0.918	0.027	0.024	0.814	0.024	0.021
250	0.946	0.036	0.126	0.937	0.020	0.065	0.926	0.021	0.019	0.885	0.020	0.018
315	1.005	0.033	0.068	1.008	0.023	0.059	1.012	0.025	0.022	0.935	0.023	0.020
400	1.046	0.031	0.065	1.014	0.018	0.058	1.009	0.019	0.017	0.960	0.018	0.016
500	1.056	0.023	0.063	1.051	0.011	0.061	1.047	0.011	0.010	0.967	0.010	0.009
630	1.069	0.024	0.049	1.036	0.009	0.063	1.032	0.009	0.008	0.964	0.008	0.008
800	1.052	0.021	0.049	1.034	0.010	0.069	1.028	0.010	0.009	0.958	0.010	0.009
1000	1.031	0.019	0.057	1.019	0.012	0.068	1.014	0.012	0.011	0.953	0.011	0.010
1250	1.010	0.017	0.052	0.987	0.009	0.075	0.985	0.010	0.009	0.949	0.009	0.008
1600	0.987	0.014	0.055	0.972	0.010	0.074	0.973	0.010	0.009	0.948	0.010	0.009
2000	0.971	0.017	0.060	0.963	0.017	0.078	0.968	0.018	0.016	0.947	0.018	0.016
2500	0.961	0.020	0.068	0.945	0.011	0.077	0.953	0.011	0.010	0.947	0.011	0.010
3150	0.959	0.029	0.080	0.938	0.014	0.085	0.945	0.015	0.013	0.948	0.015	0.013
4000	0.945	0.034	0.093	0.935	0.021	0.099	0.942	0.020	0.018	0.949	0.021	0.018
5000	0.940	0.046	0.108	0.924	0.034	0.116	0.932	0.038	0.034	0.950	0.039	0.035

Table A.2 – Summary of results for 10cm sample - average (avg), repeatability standard deviation s_r and reproducibility standard deviation s_R - referred to ISO 354:2003 in force expressed as a function of T20 reverberation times, and to Draft:2019 including the effect of room damping and the use of different γ corrections, ILT and TMM.

	alpha_s/-											
	ISO354-T20			Draft-Damped-T30			Draft-γ-ILT-T30			Draft-γ-TMM-T30		
f /Hz	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R
100	0.545	0.050	0.294	0.556	0.046	0.223	0.540	0.040	0.168	0.419	0.031	0.130
125	0.656	0.045	0.212	0.739	0.028	0.160	0.721	0.027	0.140	0.618	0.023	0.120
160	0.931	0.036	0.098	0.991	0.019	0.121	0.973	0.019	0.113	0.815	0.016	0.095
200	0.957	0.034	0.083	1.004	0.016	0.044	0.982	0.016	0.095	0.872	0.014	0.084
250	0.971	0.031	0.103	1.012	0.022	0.070	1.003	0.021	0.074	0.959	0.020	0.071
315	1.020	0.021	0.080	1.043	0.014	0.082	1.047	0.014	0.063	0.967	0.013	0.058
400	1.059	0.020	0.062	1.057	0.027	0.050	1.054	0.025	0.067	1.003	0.024	0.064
500	1.075	0.013	0.042	1.070	0.019	0.046	1.068	0.020	0.051	0.986	0.018	0.047
630	1.068	0.023	0.046	1.062	0.012	0.049	1.059	0.013	0.039	0.990	0.012	0.036
800	1.042	0.017	0.050	1.056	0.010	0.040	1.051	0.010	0.037	0.980	0.009	0.034
1000	1.027	0.016	0.052	1.022	0.012	0.059	1.018	0.012	0.023	0.957	0.011	0.022
1250	0.998	0.015	0.054	1.000	0.009	0.063	0.999	0.009	0.022	0.963	0.009	0.021
1600	0.982	0.013	0.058	0.977	0.012	0.074	0.979	0.013	0.028	0.953	0.012	0.027
2000	0.968	0.015	0.064	0.959	0.014	0.089	0.964	0.015	0.028	0.943	0.015	0.028
2500	0.950	0.011	0.071	0.940	0.009	0.086	0.947	0.009	0.024	0.941	0.009	0.024
3150	0.944	0.021	0.080	0.937	0.011	0.088	0.944	0.011	0.017	0.947	0.011	0.017
4000	0.940	0.029	0.092	0.928	0.019	0.092	0.935	0.021	0.025	0.942	0.021	0.025
5000	0.929	0.043	0.110	0.937	0.045	0.091	0.951	0.058	0.071	0.968	0.059	0.073

Table A.3 – Summary of results for 2cm sample - average (avg), repeatability standard deviation s_r and reproducibility standard deviation s_R - referred to ISO 354:2003 in force expressed as a function of T20 reverberation times, and to Draft:2019 including the effect of room damping and the use of different γ corrections, ILT and TMM.

	alpha_s/-											
	ISO354-T20			Draft-Damped-T30			Draft-γ-ILT-T30			Draft-γ-TMM-T30		
f /Hz	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R	avg	s_r	s_R
100	0.046	0.021	0.026	0.043	0.010	0.014	0.042	0.009	0.011	0.032	0.007	0.008
125	0.065	0.013	0.022	0.063	0.026	0.035	0.065	0.021	0.039	0.056	0.018	0.034
160	0.080	0.011	0.020	0.099	0.015	0.023	0.099	0.012	0.030	0.083	0.010	0.025
200	0.108	0.009	0.018	0.114	0.006	0.013	0.111	0.005	0.015	0.098	0.005	0.013
250	0.167	0.006	0.021	0.170	0.006	0.025	0.168	0.006	0.021	0.161	0.005	0.020
315	0.223	0.006	0.017	0.234	0.004	0.018	0.235	0.004	0.022	0.217	0.004	0.020
400	0.320	0.006	0.026	0.324	0.005	0.023	0.323	0.005	0.031	0.307	0.005	0.030
500	0.419	0.007	0.029	0.425	0.005	0.028	0.425	0.005	0.034	0.392	0.005	0.032
630	0.519	0.007	0.047	0.527	0.007	0.036	0.525	0.007	0.039	0.491	0.007	0.037
800	0.614	0.006	0.054	0.616	0.006	0.038	0.614	0.006	0.044	0.572	0.005	0.041
1000	0.680	0.010	0.047	0.678	0.006	0.042	0.677	0.006	0.046	0.636	0.006	0.043
1250	0.745	0.011	0.045	0.743	0.010	0.042	0.745	0.010	0.055	0.717	0.009	0.053
1600	0.791	0.013	0.037	0.794	0.010	0.046	0.798	0.010	0.051	0.777	0.010	0.050
2000	0.824	0.012	0.049	0.836	0.008	0.050	0.843	0.009	0.050	0.825	0.008	0.049
2500	0.858	0.014	0.057	0.865	0.009	0.064	0.873	0.009	0.050	0.868	0.009	0.049
3150	0.887	0.020	0.067	0.894	0.010	0.070	0.903	0.011	0.052	0.906	0.011	0.052
4000	0.901	0.036	0.071	0.902	0.010	0.089	0.910	0.011	0.051	0.917	0.011	0.051
5000	0.919	0.062	0.080	0.918	0.014	0.079	0.932	0.014	0.064	0.950	0.015	0.066

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Declaration of interests

 The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Authors' contributions

All authors provided feedback on all steps, especially critical feedback on the paper, and performed measurements. C. Scrosati conceived of the idea and organized the project. C. Scrosati, F. Martellotta, F. Pompoli, A. Schiavi, A. Prato, D. D'Orazio, N. Granzotto and A. Di Bella, wrote the protocol. F. Martellotta performed the first measurements on the basis of which the protocol was improved. F. Pompoli, A. Prato, N. Granzotto and F. Martellotta performed impedance tube measurements. A. Schiavi performed airflow resistivity measurements. F. Pompoli performed calculation of predicted diffuse field values for finite dimension samples. C. Scrosati acquired data, analyzed and interpreted data, supervised the ILT and performed the statistical analysis. F. Martellotta and C. Scrosati drafted the manuscript with contribution of F. Pompoli, A. Schiavi and N. Granzotto for paragraph 3.2 and contribution of M. Garai for paragraph 2.