Influence of Sound-Absorbing Ceiling on the Reverberation Time. Comparison Between Software and Calculation Method EN 12354-6

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Abstract

The correct acoustic design of rooms such as classrooms, conference rooms and offices is of fundamental importance to ensure high speech intelligibility and to contain internal noise levels. The use of sound-absorbing ceilings alone is not always sufficient to guarantee adequate comfort, as the reflections between parallel walls could introduce unwanted phenomena such as flutter echo or the accentuation of modal resonances. One more issue is related to the use of Sabine or Eyring models, which could lead to an underestimation of the reverberation times. This article compares the reverberation time measured and simulated in two small rooms with (i) Sabine and Eyring models, (ii) two commercial simulation software and (iii) the EN 12354-6 standard method valid for rooms, with absorption not homogeneously distributed between the surfaces.

1. Introduction

Correct room acoustic design is of fundamental importance to increase comfort and speech intelligibility.

Many studies have been carried out regarding room acoustics optimization (Farina et al., 1998; Meissner, 2017; Nowoświat et al., 2016 and 2022; Prato et al., 2016; Tronchin et al., 2016, 2021a, 2021b, 2021c and 2022) and regarding acoustic building materials (Fabbri et al., 2021). The tools available to designers are simple equations, such as those of Sabine and Eyring or the EN 12354-6 standard or dedicated calculation software.

The Sabine and Eyring formulations are reliable under the following conditions:

1) diffuse sound field;
2) average absorption coefficient of the room less than 0.2;
3) homogeneous absorption.

Often in rooms such as offices, only the sound-absorbing ceiling is used both for cost and positioning reasons. In this case, the absorption is not homogeneous, since it is concentrated in just one part of the room. Thus, the Sabine and Eyring models may not provide reliable results.

To design rooms with non-homogeneous absorption, the calculation method described in EN 12354-6 Annex D can be used.

A further problem concerns the input data in the calculation software. The measurement of the absorption coefficient in the reverberation room, according to the ISO 354 standard, assumes a perfectly diffused sound field and the use of the Sabine formulation. Unfortunately, this is not possible in real laboratories, since these conditions are only ideal. Another problem of the measurement in a reverberant room is the presence of diffusers, which make the volume of the room lower than that actually used in the Sabine formula, with a consequent overestimation of the results (Scrosati et al., 2019).

On the other hand, methods such as normal incidence measurements according to ISO 10534-2 cannot be directly correlated with measurements carried out in a diffuse field in a reverberation room (Di Bella et al., 2019). The uncertainty of measurement of the absorption coefficient according to ISO 354 standard is also high (Scrosati et al., 2019 and 2020).

This paper presents measurements made on two small, unfurnished offices with sound-absorbing ceilings and simulations carried out with simplified

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formulations (Sabine, Eyring), EN 12354-6 calculation method and two dedicated room acoustic software packages.

2. Calculation Models

For the acoustic simulations the following models were compared:

1) equations of Sabine and Eyring;
2) calculation method EN 12354-6;
3) two different room acoustic simulation software.

The Sabine formula is:

$$T_{Sabine} = \frac{55.3}{c_0}\frac{V}{A} \qquad (1)$$

The equivalent absorption area A, considering only flat surfaces and not objects, is calculated with Eq. (2):

$$A = \sum_i \alpha_i S_i \qquad (2)$$

Eyring equation is:

$$T_{Eyring} = \frac{55.3}{c_0}\frac{V}{-S\ln(1-\alpha_m)} \qquad (3)$$

The calculation method of EN 12354-6 (Annex D) for rooms with non-homogeneous absorption considers the following reverberation time (without the absorption of objects):

$$T_{est} = \frac{55.3V}{4c_0}\left(\frac{1}{A_x^*}+\frac{1}{A_y^*}+\frac{1}{A_z^*}+\frac{1}{A}\right) \geq T_{Sabine} \qquad f \geq f_t = \frac{8.7c_0}{V^{1/3}} \qquad (4)$$

$$T_{est} = \frac{55.3}{c_0}\frac{V}{A_{xyzd}^*} \qquad f < f_t = \frac{8.7c_0}{V^{1/3}} \qquad (5)$$

A^*_x, A^*_y, A^*_z, A^*_d are the effective sound absorption area for each sound field, while A^*_{xyzd} is the effective sound absorption area for the total field for low frequency ($f < f_t$).

The commercial software used are based on ray-tracing (A) and pyramid-tracing (B) techniques.

3. Case Studies

Two unfurnished rooms with an access floor with plan surfaces of 16.3 m² (Room 1) and 32.9 m² (Room 2) were examined. The walls are made of gypsum board and plastered concrete, the ceiling is made with square rock wool panels, with dimensions of 600 mm x 600 mm. The windows equal in length to the façade are positioned 108 cm from the floor and have a height of 118 cm. The dimensions of the rooms are shown in Figs. 1, 2, 3 and 4.

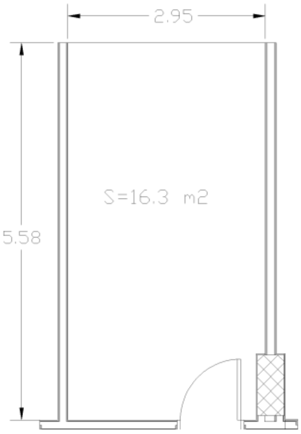

Fig. 1 – Room 1 plan

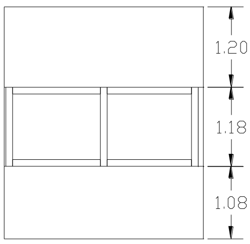

Fig. 2 – Room 1 Façade

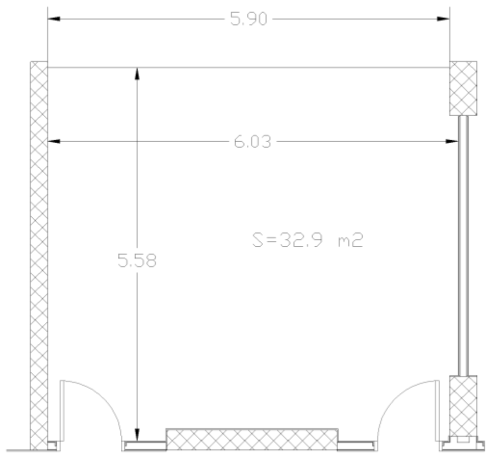

Fig. 3 – Room 2 plan

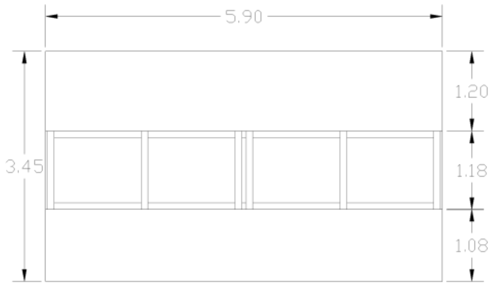

Fig. 4 – Room 2 Façade

The geometric characteristics of the rooms are shown in Table 1. The mean free path (MFP) calculated as Sabine, or obtained with the software, is also reported. It can be noted that the MFP obtained with the software is very similar to the ones obtained using the Sabine model.

Table 1 – Mean free path

	Room 1	**Room 2**
V	56.2	113.5
S	91.5	147.2
MFP=4V/S	2.460	3.084
MFP-Software A	2.480	3.100
MFP-Software B	2.470	3.090

4. Reverberation Time Measurements

Reverberation time measurements T_{20} on the two offices (Room 1 and Room 2) were carried out to verify the reliability of the different calculation methods. Measurements were made with the interrupted noise method according to ISO 3382-2 standard.
In Room 1, one sound source position and three microphone positions were used, while in Room 2, two source positions and three microphone positions were used. Omnidirectional sound source was placed at 1.7 m height and a microphone was placed at 1.5 m height. Measurements were repeated twice for each source-microphone combination.
The results obtained are shown in Fig. 5.

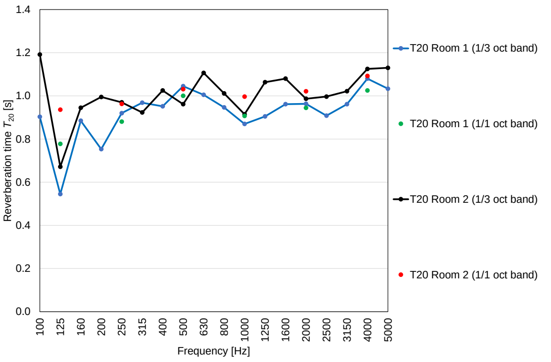

Fig. 5 – Measured reverberation time T_{20} for Room 1 and Room 2 in 1/3 and 1/1 octave bands

It can be noted that the volume of room 1 is about half of the one of room 2, but the reverberation time is only slightly lower.

5. Acoustic Simulations

To verify the reliability of the different calculation methods, simulations of the reverberation time T_{20} were performed. 3D models were realized with two different types of room acoustic software, one based on ray-tracing and the other based on pyramid tracing. Models are reported in Figs. 6 - 9.

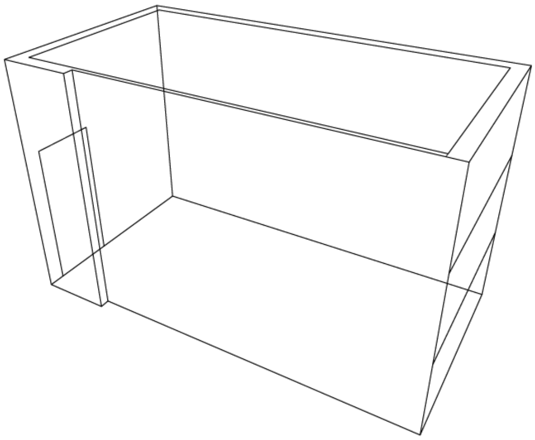

Fig. 6 – Room 1 - 3D simulation model - Software A

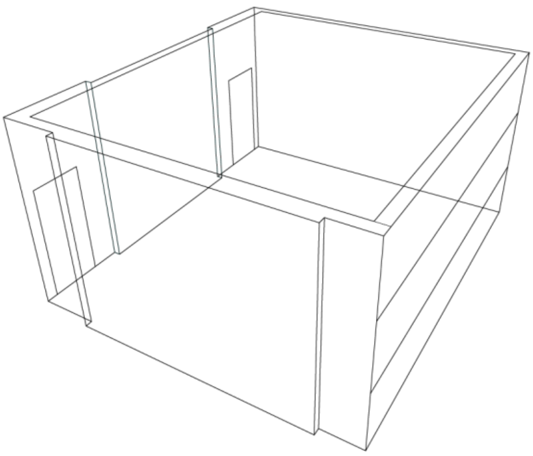

Fig. 7 – Room 2 - 3D simulation model - Software A

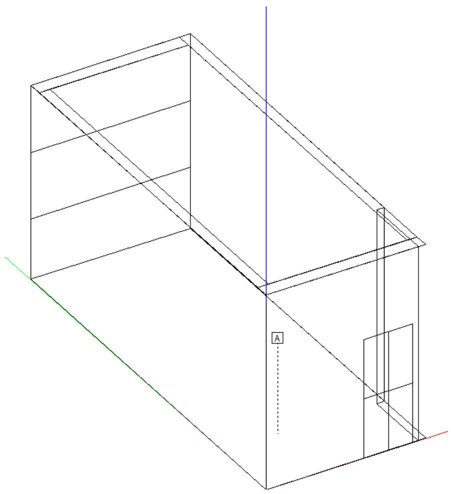

Fig. 8 – Room 1 - 3D simulation model - Software B

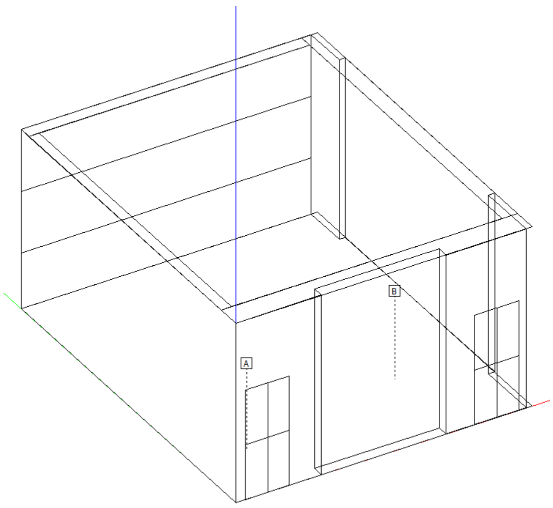

Fig. 9 – Room 2 - 3D simulation model - Software B

The acoustic absorption coefficients used are reported in Table 2.

Table 2 – Acoustic absorption coefficient

	125	250	500	1000	2000	4000
Ceiling	0.45	0.90	1.00	0.85	0.95	0.95
Plastered wall	0.02	0.03	0.03	0.04	0.05	0.07
Access floor	0.20	0.15	0.10	0.10	0.05	0.10
Gypsum board wall	0.15	0.10	0.06	0.04	0.04	0.05
Window	0.18	0.06	0.04	0.03	0.02	0.02
Door	0.14	0.10	0.06	0.08	0.10	0.10

6. Results and Discussion

The reverberation times obtained are shown in Fig. 10 (Room 1) and in Fig. 11 (Room 2). Some noise maps are shown in Fig. 12 (Room 1 - software B) and Fig. 13 (Room 2 - software B).

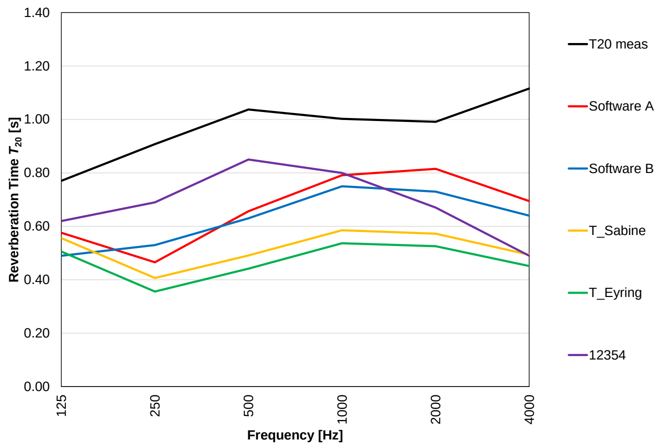

Fig. 10 – Measured and simulated reverberation time T_{20} (Room 1)

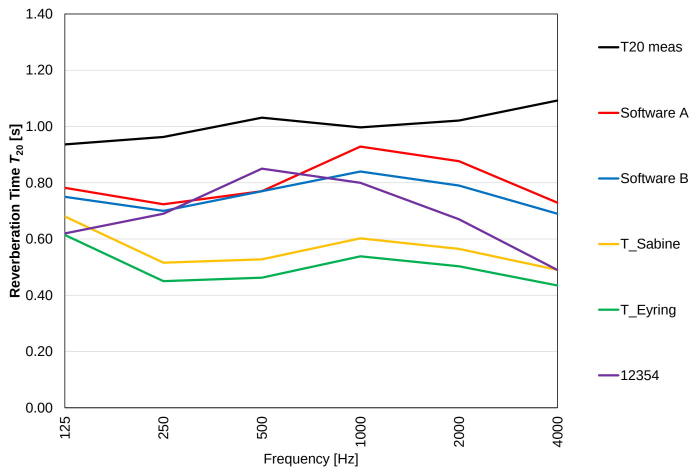

Fig. 11 – Measured and simulated reverberation time T_{20} (Room 2)

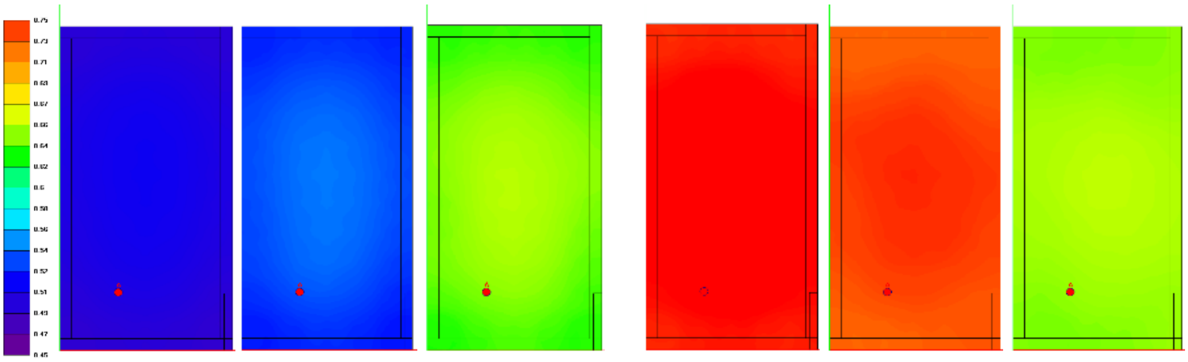

Fig. 12 – Reverberation time T_{20} simulation software B – Room 1 (125 Hz - 4000 Hz)

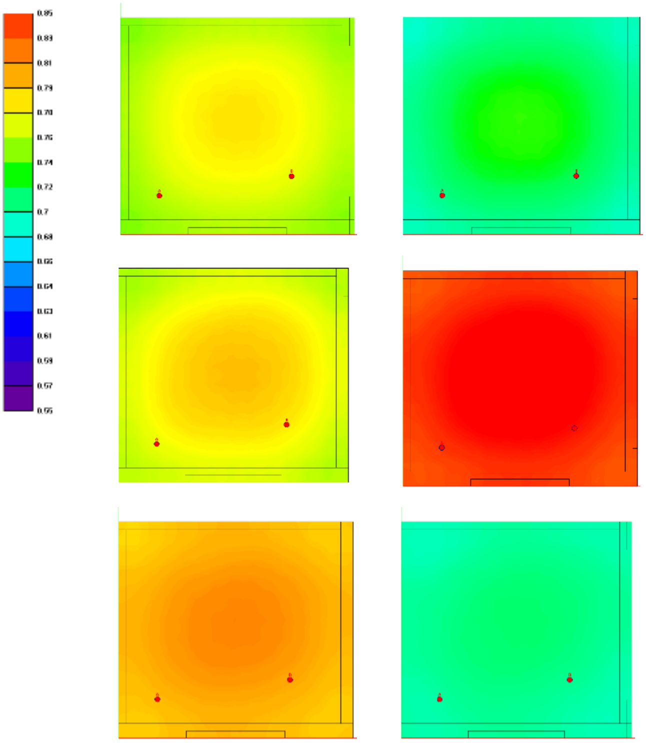

Fig. 13 – Reverberation time T_{20} simulation software B – Room 2 (125 Hz - 4000 Hz)

An underestimation of the simulated reverberation time compared to the measured one can be noted. In particular, the Sabine and Eyring formulas are not usable for rooms of this type. Accordingly, the simulated values obtained are about half of those measured (Farina, 1998). The results obtained with the EN 12354-6 model and with the calculation software are also lower than those measured, in particular, for room 1, the best estimate is represented by EN 12354-6 up to 1000 Hz and by software A over 1000 Hz. For room 2, the best estimate is represented by software A, as reported in Figs. 14 and 15.

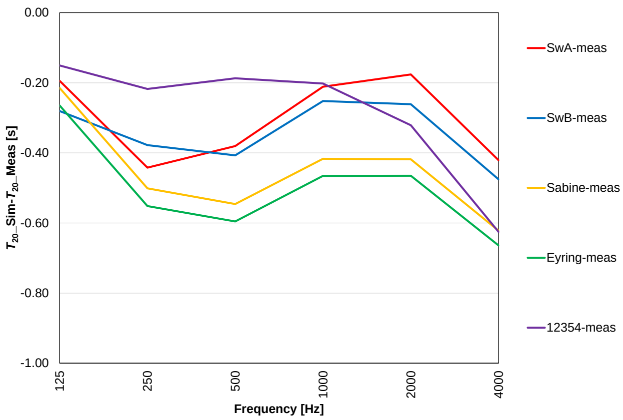

Fig. 14 – Difference between simulated and measured reverberation time T_{20} (Room 1)

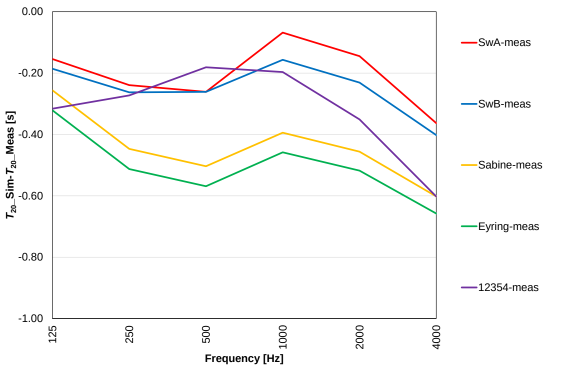

Fig. 15 – Difference between simulated and measured reverberation time T20 (Room 2)

This underestimation is due to an overestimation of the absorption coefficients obtained in the reverberation room according to ISO 354 standard. This is due to the not-perfectly-diffuse sound field and to the modification of the MFP, due to the diffusers hanging to the ceiling of the reverberation room, compared with the one predicted by the Sabine formula contained in the measurement method.
According to Scrosati et al. (2019), the MFP of their empty reverberation room changes from 3.853 m (without diffusers) to 3.377 m (with diffusers), while with specimen MFP varies from 3.750 m (without diffusers) to 3.295 m (with diffusers). The statistical value calculated for this reverberation room was 3.810 m. By modifying the Sabine formula of ISO 354 standard with the correct MFP specific for this reverberation room, the authors found an absorption coefficient about 20-23 % lower than the one measured according to ISO 354.
To better understand the phenomenon, the best fit acoustic absorption coefficients which best approximate the measured reverberation times were calculated both with software A and B. The results are shown in Fig. 16.

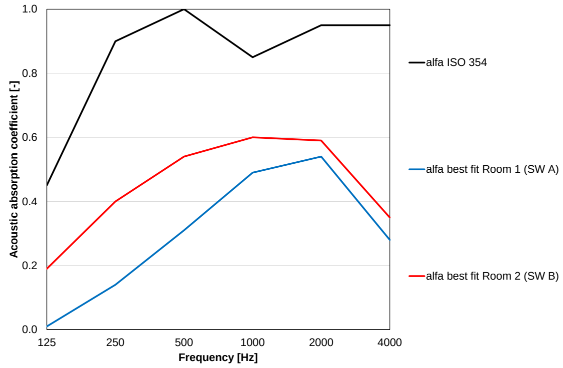

Fig. 16 – Best fit acoustic absorption coefficient

It can be noted that the best fit acoustic absorption coefficient is lower for room 1 than for room 2. This could be due to the different ceiling surface-to-total surface ratio (17.8 % for Room 1 and 22.8 % for Room 2). Furthermore, the celling angle of view concerning the sound source is 78° for Room 1 compared with 101° for Room 2 (Figs. 17 and 18) and differences could actually affect the real sound absorption.

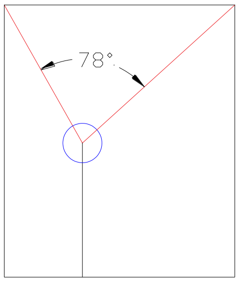

Fig. 17– Celling angle of view (Room 1)

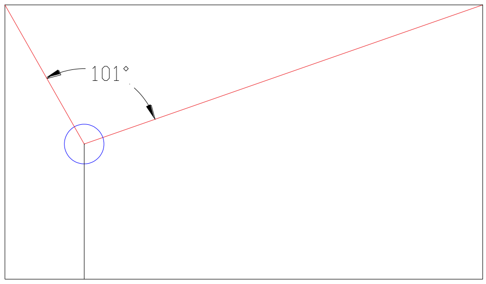

Fig. 18 – Celling angle of view (Room 2)

7. Conclusion

In this work, the acoustic simulation of the reverberation time of two small rooms with volumes of 56.2 m³ and 113.5 m³ was considered. These rooms feature sound-absorbing panels only on the ceiling. Therefore, they do not have a homogeneous surfaces absorption.
Simple equations such the Sabine and Eyring formulas, the EN 12354-6 standard model, and two dedicated calculation software were considered.
It was possible to note how all the computational models examined led to an underestimation of the reverberation time. In particular, since reverberation time values obtained with these methods are about half of those measured, the Sabine and Eyring models are not suitable for this type of room.
Better results were obtained using software based

on ray-tracing and pyramid-tracing and on the calculation model based on the EN 12354-6 standard. However, even in this case the reverberation time is underestimated.

A possible explanation of this phenomenon is the overestimation of the absorption coefficients obtained in the reverberation room, according to the ISO 354 standard, due to the not-perfectly-diffuse sound field and to the presence of the diffusers hanging from the ceiling. These do modify the effective volume of the reverberation room and the MFP compared with the one predicted by the Sabine formula.

It is therefore advisable to reduce the values of the acoustic absorption coefficients in the acoustic design.

Nomenclature

Symbols

T_{60}	Reverberation time (s)
V	Volume of the room (m^3)
A	Equivalent absorption area (m^2)
α	Acoustic absorption coefficient (m)
α_m	Mean acoustic absorption coefficient (m)
S	Surface (m^2)

Subscripts/Superscripts

i	i-th surface

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