New ratings in ISO 11654 of plane sound absorbers made for speech communication in classrooms and meeting rooms

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ABSTRACT

A computer-based study of a typical furnished classroom has been made, where reverberation times, sound pressure levels, signal-to-noise ratios, speech intelligibilities and auralization files have been computed for five common types of ceiling. The sound absorption of those ceilings vary significantly in the octave bands 125-4000 Hz, of which one is an almost completely reflecting surface and the other four represent common tile products intended for suspended ceilings. The results show that the speech intelligibility indices (STI) are almost the same for the four absorptive materials applied in this analysis, the STI:s range from 0,77-0,80 with realistic background noise. The reflecting ceiling has a lower value. It seems most important to absorb mid frequency energy.

These findings support a proposal for a voice weighted average sound absorption coefficient 'α_v'. It differs from the 'α_w' defined in ISO 11654, where the rating curve puts more weight on the absorption at higher frequencies. The voice weighted α_v stresses the mid frequency absorption and rates resonator types of products more equally to porous types, which can be justified by similar STI results in the classroom. This new α_v should be relatively easy to explain to architects, contractors and occupants of work premises.

Keywords: Sound absorber, ratings, ISO standards 35.3 81.2.1

1. INTRODUCTION

A working group within ISO (TC 43/SC 2/WG 30) is currently working on a revision of the ISO 11654. This standard is used to rate and classify plane sound absorbers, e.g. ceiling tiles of mineral wool or perforated plasterboards. As a part of this work, it has been studied whether other types of rating principles could be adopted to summarize the octave band values into a single number, as an alternative to the current reference curve weighting method. The basis for the comparison between different rating principles has been a computer-based evaluation of various types of sound absorbing ceiling in a furnished classroom. The results show the influence of various sound absorption in the ceiling on the speech intelligibility and the ease of hearing in furnished rooms intended for speech communication, e.g. in classrooms and conference premises.

2. METHOD

2.1 Calculation of reverberation times, speech intelligibility and impulse responses

The analyses have been made with the widely used computer aided acoustical design software ”CATT-Acoustic”[1], intended for mapping of sound fields in enclosed spaces, e.g. for performing musical arts. Its basic principles are explained in a short paper presented at the conference B-NAM in Bergen 2010[2] and detailed in a doctoral thesis in 1995[3] and a scientifical paper in 1996[4].

In brief, room acoustics predictions are based on geometrical acoustics, where room impulse responses (squared RIR:s may be referred to as echograms or energy-time curves) are predicted from sound rays that radiate from a sound source, reflect at the boundaries and reach the listening positions. A three dimensional mathematical model of an enclosed space is used to calculate the reflections. Frequency dependent material properties (absorption, scattering and transmission coefficients) are assigned to all room surfaces and furnitures, e.g. the ceiling, walls, floor, chairs, tables and bookshelves. Frequency dependent source directivities are assigned to sound sources, in this case a teacher at the front of the classroom and a ventilation outlet on a sidewall.

The room impulse responses are filtered in octave bands and use to calculate sound pressure levels, speech intelligibility indices[5], and reverberation times where the ”listeners” are seated. In this study, more detailed room impulse responses are calculated as well, for the purpose of creating audible sound files, a so-called auralization process. Thus, both objective numbers and subjective impressions of various ceiling materials can be created and compared. The purpose of these calculations are to establish a group of examples, being realistic enough, and then compare how the octave band values might be converted into various single numbers.

2.2 Classroom design

A rather typical Swedish classroom has been modeled for the purpose of this study, c.f. Figure 1:

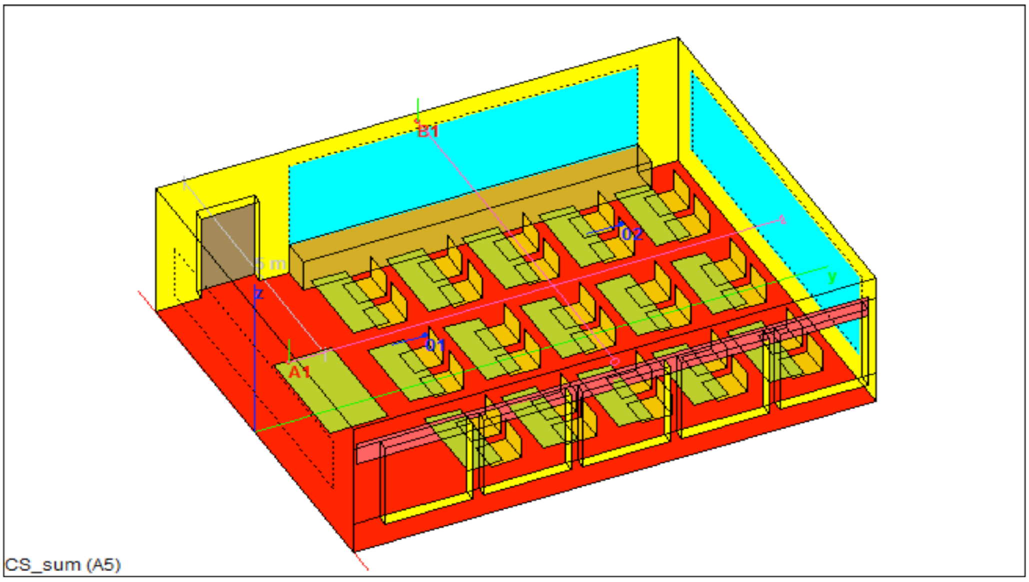

Figure 1. A model of a typical classroom layout. Length 9 m, width 7 m, height 3,1 m.

Table 1. Sound absorption of surfaces of the classroom model.

Surface	Area (m^2)	Absorption coefficients α	Octave band (Hz)	125	250	500	1000	2000	4000
Façade	20,9	Concrete, plastered masonry		0,01	0,01	0,01	0,02	0,02	0,03
Corridor, wall	25,9	Masonry		0,02	0,02	0,03	0,04	0,05	0,07
Back wall	21,7	2x13 gypsum, 70 stud, 45 min-wool (mm)		0,12	0,1	0,08	0,06	0,06	0,06
Front wall	21,7	2x13 gypsum, 70 stud, 45 min-wool (mm)		0,12	0,1	0,08	0,06	0,06	0,06
Ceiling	63	Concrete, plastered masonry		0,01	0,01	0,01	0,02	0,02	0,03
Doors	2	Doorset, light weight		0,25	0,2	0,15	0,1	0,08	0,07
Windows	7	Windows, double glazed		0,12	0,08	0,05	0,04	0,03	0,02
Curtains	7	Curtains, <0,2 kg/m^2, 200 mm distance		0,05	0,06	0,09	0,12	0,18	0,22
Floor	63	Linoleum on concrete, glued		0,02	0,03	0,04	0,05	0,05	0,06
Chairs, tables	30	Chair+table for 1 person, not polstered, (A_{obj} =$0,3^{2/3}$ per 1 m^2 floor area)		0,1	0,2	0,25	0,25	0,25	0,25
Cupboards	7	Cupboard 30 cm (A_{obj} =0,32/3, per m^2		0,28	0,37	0,45	0,45	0,45	0,45
		EN 12354-6 reverberation time T_{30} (s):		*2,24*	*1,89*	*1,71*	*1,63*	*1,58*	*1,42*

The corridor wall and the back wall are made diffusing, as well as the chairs and tables. This choice may be justified for two reasons. The first is to make the sound absorbing ceiling hit by many diffuse sound rays and to avoid standing waves between the walls to determine the reverberation time T_{30}. The second reason is that empirical comparisons between measurements in 23 densely furnished classrooms in the Nordic countries showed a good agreement between the measured and calculated T_{30}:s, whereas longer T_{30} than expected were found in 21 rooms with less diffusing furniture or with complicated geometries[6]. Thus, it seemed reasonable to assign high diffusivity to the walls and furniture, for the focused purpose of studying the influence of the ceiling absorptions.

The ceilings are modeled as five alternatives A1-A5. The A1 case represents a 40 mm thick painted mineral wool tile backed with 200 mm air and filled with mineral wool in the plenum close to the walls. The A2 is the same 40 mm tile, but now glued to the concrete slab (without a plenum). The A3 is a widely used 20 mm painted tile, glued as with A2. The A4 represents a perforated 13 mm board with a dedicated cloth glued above the holes, 200 mm empty plenum. The A5 represents painted concrete, taken as the reference case (without any acoustic ceiling). Absorption factors are plotted in Figure 2:

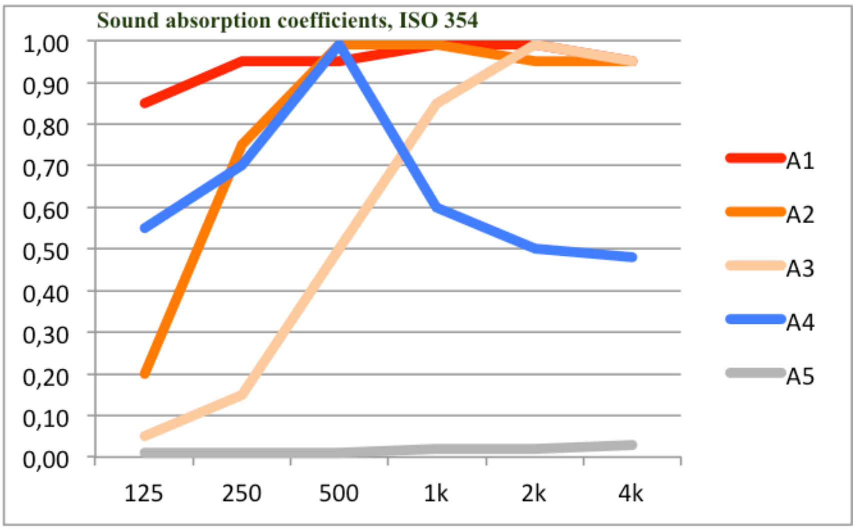

Figure 2. Sound absorption coefficients of the five types of ceiling.

The sound pressure level of the teacher is assigned to a ”comfortable” speech situation, with a level of about 55-60 dBA. The background sounds from ventilation, traffic, activities in other rooms and pupils inside the classroom is represented by pink noise at three levels: 1) a normal lecturing case according to the table below and is applied to the calculation of all single numbers, 2) with -10 dB attenuation (individual work case) and 3) with -20 dB attenuation (as during very quiet listening or reading activities). Cases 2 and 3 are used for auralization only. Researchers have reported a background noise level in classroom of 45-50 dBA[7,8] to be representative for normal presentations where the pupils are assumed to listen to the teacher. Noticeably, the sound from the pupils may be considerably higher from time to time, e.g. during free activities, but this is not a meaningful teaching situation and considered outside of the scope of this study.

Table 2. Sources: sound pressure levels at 1 m, in dB, without correction for room attenuation:

Octave band:	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
Speech @1m (A1)	58,5	62,2	53,6	60	54,1	54,8	48,8	31,4
Noise @1m (B1)	57,3	53,8	52,1	50	51,9	55,7	55,9	51,3
Talker directivity	1,1	1,9	3,0	0,7	2,3	5,1	7,6	9,7
Noise directivity	3,0	4,9	9,1	13,0	14,9	15,9	19,1	21,1

3. Results

The reverberation times in Figure 3 have been calculated from the echograms, i.e. not with a Sabine type of statistical calculation. They are in the range 0,4-0,5 seconds at medium and high frequencies, but longer at lower frequencies. To facilitate the analyses, only two listening positions and one source position have been used, where more positions may be added at a later stage.

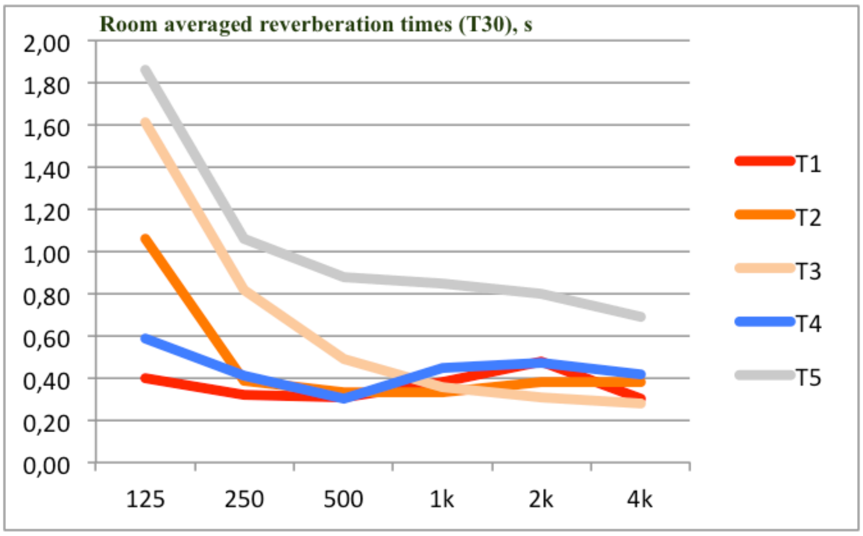

Figure 3. Calculated room average reverberation timed (T_{30}), seconds.

Table 3. The sound pressure levels from two types of source, in the listening position (02), ceilings A1-A5

Octave band	125	250	500	1000	2000	4000	dBA
A1, teacher	54,7	54,0	44,7	50,2	46,3	44,6	54,0
A2, teacher	60,6	55,8	44,4	50,9	46,8	44,7	55,0
A3, teacher	62,8	60,1	47,3	52,3	46,5	44,4	56,8
A4, teacher	58,4	56,5	44,9	54,1	48,7	46,8	57,1
A5, teacher	64,0	62,1	51,7	58,9	52,3	49,3	61,7
A1, vent outlet	53,6	47,4	38,4	33,4	33,3	36,2	44,3
A2, vent outlet	57,9	49,9	38,9	32,8	33,8	36,2	46,3
A3, vent outlet	59,6	51,6	41,6	33,3	34,1	36,3	47,8
A4, vent outlet	55,9	50,3	38,8	34,4	36,0	37,4	46,3
A5, vent outlet	60,3	52,5	44,0	38,0	38,2	40,0	49,6

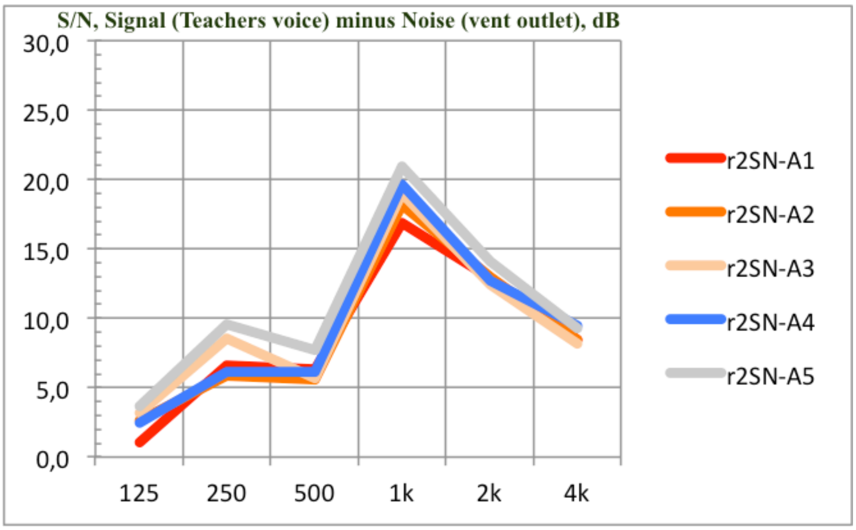

Figure 4. Signal to noise ratios in the listening position (02).

The resulting signal-to-noise ratio, e.g. the margin between the teachers voice to the background sound (without any attenuation) was then estimated for the ceiling types A1-A5, results in Figure 4:

As expected, the S/N is *lowest* for the A1 case (maximum absorption) and *highest* for the A5 case (lowest absorption). This may seem contradictory to what could be an intuitive idea of increasing the amount of absorption, but is in fact explained by the difference in distances from the sources to the listening position R2.

The ceiling attenuates reflections of speech more efficiently (teacher at 6 m distance) than reflections from the air terminal (at 3 m distance). The sound absorbers do not differ between useful sounds and disturbing sounds (noise), they absorb everything that hits them! If the variation of angle of incidence of sound could be taken into account, instead of applying the diffuse sound field absorption coefficients, the effect of long distances would most likely be even more pronounced since grazing incident sound would be less attenuated by the ceiling compared to sound incident at right angles (perpendicularly). Nilsson has investigated this problem in several papers.[9]

The speech transmission index (STI) for the five ceilings A1-A5 and the three levels of background noise (pink noise) is plotted in the figure below. It seems that the positive effect of increasing the strength of early reflections from the ceiling A4 is counterbalanced by the prolonged reverberation time caused by higher order reflections.

Also, the noise from the vent outlet is higher in case A4 than A1 because the noise reverberates longer. The resulting similarity of STI is surprising, especially when compared to what could be expected bearing in mind the large variation of the α_w of the ceiling A1 (α_w 1,0) to ceiling A5 (α_w 0,55). Bradley found similar effects and explains the reasons for those.[13]

It seems reasonable that a single number for the speech situation should be more equal between the cases A1-A4, but clearly distinguish the A5 ceiling from the others. The small difference in STI does not support the single number α_w according to the present ISO 11654 to differ by a factor of almost two.

All ceilings A1-A4 meet the strict STI requirements in Finland, where STI $\geq$ 0,7 is prescribed for the minimum requirements (sound class C according to Finnish standard SFS 5907) and $\geq$ 0,8 in the higher sound classes A and B. STI-values higher than 0,75 are classified as ”excellent” in the SFS 5907. The requirements should be tested without influence of background noise. With a higher background noise of about 45-50 dB, slightly lower STI:s may be encountered, but they are still above 0,75 and thus satisfying in most cases.

These results agree reasonably with findings by Seidel et al[10], where the STI was highly correlated to the early decay time and T_{15} (with a correlation factor R^2 of 0.98).

Mikulski et al found similar results in a study of 110 classrooms in Warsaw[11]. It can be concluded, that one parameter (out of several defined in ISO 3382-2 or EN 60268-16) seems to be enough to state in regulations and standards, to ensure satisfying speech intelligibility.

It can be noted that T_{15} or T_{30} are considerably easier to calculate during design and measure *in situ* than the more advanced parameters based on full impulse responses (U50, STI etcetera). T_{15} can be assumed to agree with T_{30} in the classroom studied in this project, since the diffusion properties have been set to create diffuse sound fields in the room. For moderately diffusive room boundaries, e.g. in rooms without furniture close to the walls, the T_{30} may be somewhat longer than T_{15}, but the differences are typically small.

Five acoustic consultants judged the subjective listening impression of the auralized sounds from the teacher, with the ceilings A1-A5 and for maximum, typical and minimum background noise from the ventilation outlet. The procedure is explained in clause 5. They came to similar judgments, showing that low frequency sound absorption is important and should be stressed more in the single number rating, whereas the high frequency sound absorption seemed less important.

The A1 and A4 were judged to perform equally well in this aspect, even if the character of the sound differ between the cases. It was mentioned, that general noise in the room may be handled somewhat more efficiently by ceiling A1, but ceiling A4 will be better in case the teacher is remote or faces another direction than to the listener while talking, because of stronger early reflections that compensate for the attenuated direct sound.

Also, it was noticed that the S/N was better with A4 which eases the listening effort, in particular for people with some hearing loss in the high frequency domain (1000 Hz and higher), where the consonants bearing speech information are located (vowels typically reside in the lower bands 125-500 Hz). These findings are broadly speaking in line with findings by Rychtarikova[12] and Bradley[13], even if their studies and results are designed differently and difficult to compare in detail.

Figure 5. Speech transmission indices (STI) in the listening position (02), ceilings A1-A5.

These listening tests were only pre-tests, not at a scientific level. They should be amended with a larger group of trained listeners and evaluated with a questionnaire or paired comparison type of test.

The ease of talking, from the teacher's point of view, has not been addressed in this study, but may be another factor influencing the rating of sound absorbing products intended for ceilings or walls. Support of early reflections might support the teacher as well, where the room "responds".

4. Suggestion of a new single number for sound absorbing ceilings in rooms intended for speech communication, e.g. classrooms and conference rooms

4.1 Calculation of the voice weighted average sound absorption coefficient α_v

The suggested calculation procedure for the α_v is:

- The practical sound coefficient $\alpha_p(f)$ is tabulated for the octave bands 125 Hz – 4000 Hz.
- Each $\alpha_p(f)$ is multiplied with a speech weight $\omega_p(f)$ ranging from 0 to 1, where each $\omega_p(f)$ represents the relative energy of standardized speech in the octave band *f*, taken as an average of male and female speakers according to EN ISO 3382-3. The sum of weights $\omega_p(f)$, in all octave bands is 1,00 (i.e. 100%).
- The sum of all products $[\omega_p(f) * \alpha_p(f)]$ for the octave bands 125 Hz – 4000 Hz is the final result, the *voice weighted average sound absorption coefficient* α_v

An example of a calculation is demonstrated in Table 4:

Table 4. Calculation of the voice weighted average sound absorption coefficient α_v

Octave band, Hz	125	250	500	1k	2k	4k	Sum
Speech weights $\omega_p(f)$	0,082	0,225	0,528	0,133	0,025	0,006	1,00
	*	*	*	*	*	*	
Sample abs coeff $\alpha_p(f)$	0,55	0,70	0,99	0,60	0,50	0,48	
	=	=	=	=	=	=	
Products [$\omega_p(f) * \alpha_p(f)$	0,0450	0,1578	0,5231	0,0796	0,0126	0,0030	=0,82

4.2 Resulting single numbers for ceilings A1-A5

The resulting α_w and α_v single numbers for the ceilings A1-A5 are calculated according to Table 5:

Table 5. Resulting average weighted α_w and α_v

Ceilings 1-5 (α_p)	125	250	500	1000	2000	4000	α_v	α_w	α_v–α_w
A1	0,85	0,95	0,95	0,99	0,99	0,95	0,95	1,00	*-0,05*
A2	0,20	0,75	0,99	0,99	0,95	0,95	0,87	0,95	*-0,08*
A3	0,05	0,15	0,50	0,85	0,99	0,95	0,45	0,45	*0,00*
A4	0,55	0,70	0,99	0,60	0,50	0,48	0,82	0,55	*+0,27*
A5	0,01	0,01	0,01	0,02	0,02	0,03	0,01	0,00	*+0,01*

Ceilings similar to the cases A1-A3 and A5 may thus be rated about 0,05 or 0,10 lower by the α_v than by α_w. The A4 type of ceiling may be rated 0,25 higher by α_v than by α_w, thus making ceilings with voice shaped absorption coefficients more equally rated by their α_v than by their α_w. For the reasons discussed above, this seems to be a reasonable amendment of the ISO 11654.

5. Auralization procedure

Speech conditions were auralized for the five classroom cases. The auralization refers to a method where anechoically recorded speech is convolved with the impulse response (room reflections) of each case, and then filtered. The consultants reported similar subjective impressions on clarity and ease of listening. They noticed the importance of sound absorption at low and medium frequencies as well as the positive influence of early reflections. Some also noticed that an increased reverberation at higher frequencies might be acceptable and even desirable. However, this test was merely a kind of pilot test, a more thorough and systematic listening test should be undertaken in course of the work.

Anyone interested in listening to these files may contact the author. The headphones and sound card system must be of high quality and the background levels low, to give a realistic impression of the auralization examples.

6. CONCLUSIONS

The findings discussed above support the proposal of a *voice weighted average sound absorption coefficient* denoted α_v (alpha voice), as is defined above. This single number α_v differs from the single number α_w defined in the present version of ISO 11654, where a rating curve puts more weight on absorption at higher frequencies in the determination of α_w. A comparison of some typical mineral wool based products results in 0,00-0.10 lower α_v:s compared to their α_w:s. However, a resonant absorber with its maximum absorption in the 500 Hz octave band and lower absorption at high frequencies may achieve a 0,25 higher α_v compared to its α_w. This would occur when the low and mid frequency sound absorption is efficient but the high frequency absorption is in the order of 0,5.

The new single number α_v should be relatively easy to explain to architects, contractors and occupants of work premises. The α_v is the *voice weighted average sound absorption coefficient*. It is defined by a weighted sum of absorption coefficients in octave band, where the weights are taken as the sound power levels of an average of typical male and female voices, in a similar manner as with the spectrum adaptation terms used in ISO 717 for single numbers of sound insulation. The present α_w (in ISO 11654) is also a kind of weighted average, but it is based on a rating curve that is not specifically related to any speech intelligibility property, but more related to its broad band noise reduction. The α_v is probably a more intuitive type of single number than α_w.

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