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Acoustic absorption prediction by placing absorbent material in separate pieces with or without back air layer

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Abstract: the reverberation time was tested in a reverberation chamber with three acoustic absorbent materials commonly used in construction. The tests were performed with different materials, setups, and back air layers. Results have been compared with those where this material is placed as a single piece. Analyzing obtained data, a linear regression model is established to predict, for certain frequencies, the alteration produced in the reverberation time. So, knowing the absorption coefficient of an amount of material, it is possible to predict the different absorption coefficients placing the same material in separated pieces and different distances from room walls. The model has been validated and tested, which demonstrates its accuracy, it has also been proved to be applicable to a wide variety of materials. It becomes a simple predictive tool that allows to estimate in situ the alteration in the reverberation time due to the separation of the absorbent material in patches.

Keywords: acoustic absorption, building materials, materials in patches, sound-absorbent material, air layer.

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1. Introduction

The world of construction requires quick responses to problems that arise when carrying out projects and even more when building them. On the other hand, the calculation of acoustic absorption in a space is subject to various variables. The material placement, related to wall on which it is set and its pattern, changes the reverberation times of the space (Garay & Pino, 2019). For these two reasons, the need for quick responses and the fact of the variability in terms of the reverberation times of a space when changing the arrangement of materials, made clear the necessity to create a tool with which to quickly calculate the alteration in the reverberation time for different materials settings.

Absorption increase of an absorbent acoustic construction material has been studied for years, when placed in separated pieces from each other rather than together (Chrisler, 1934; Cook, 1957; Feshbach & Harris, 1946; Garay & Pino, 2019) also recently (Lanoye, Vermeir, Lauriks, Sgard, & Desmet, 2008; Thomasson, 1982). This effect has been attributed to diffusion increase due to recesses and projections exist and also the edge effect. Thus, several research (Cox & D'Antonio, 2016; Hanyu, 2010)-for these kind of cases- quantify acoustic diffusion as a function of dispersion and wall absorption coefficient. Other research (de Bruijn, 1967; Guicking, 1990; Hanyu, Hoshi, & Nakakita, 2016)have studied how edge effect increases absorption measured in a reverberation chamber, mainly due to additional absorbent surface that appears in the thickness of sample analyzed. Other studies are focus on investigate absorbent materials basing on passive destructive interference principles (Kawakami, 1998)or metamaterials (Setaki, Tenpierik, Turrin, & van Timmeren, 2014).

However, none of these studies has found a simple method that allows predicting decrease reverberation time in a room, when the same amount of material is placed in separate pieces, that is, the same amount but different setup. The main aim of this research is to find a simple method that allows an in situ estimation of acoustic absorption increase when the material is placed in separate pieces instead together. Because, usual theoretical models, with many parameters (Ju Kim et al., 2017), are more difficult to apply on construction works.

Previously, we have carried out two researchs that study similar issues (Caballol & Raposo, 2016; Ouisse, Ichchou, & Chedly, 2012) but in a different way and focused on another audience. The present study works directly with reverberation time, without needing to transform obtained values in tests by the equivalent sound absorption area. This new model allows offering an actual practical formulation, straightly applicable and useful. The main advantage is giving as a result just what the technician usually needs on work site.

2. Materials and methods

Conditions specified in ISO 354 (AENOR, 2004) have been chosen to measure reverberation time, because is the standard regulation for measuring the acoustic absorption of building materials in a reverberation chamber. The methodology described -in that ISO- measures the average reverberation time in the reverberation chamber with and without the test samples inside. The equivalent absorption area is calculated from the reverberation times through the Sabine's equation and next the absorption coefficient of the tested material is obtained.

Test conditions establish a specific size and shape of the reverberation chamber, also temperature and humidity are controlled. Test sample should have a surface between 10 m^2 and 12 m^2 and be rectangular, width / length ratio must be between 0.7 to 1. Reverberation time has been measured in one third octave frequency bands, that are refereed by their central frequency. Three different materials of similar thickness -3 cm- have been taken since this kind of materials are usually found and used with that thickness. Two together setups have been tested: different gaps between pieces of material and different thickness of back distances to the solid base –different thicknesses of the back air layer-. This set up was the closest possible to how the material is usually placed in the building.

2.1. *Materials*

Three materials have been chosen to be tested. Criteria were the following ones:

- To be materials usually used in building works.
- To have very different acoustic absorbent properties. So, two fibrous materials and one porous have been proposed.
- Speaking in terms of density, among the fibrous ones, one of two was low density (30 kg/m^3) and the other was high density (100 kg/m^3). The porous one was very low density (10 kg/m^3).

In this way, it is possible to guarantee different values of flow resistivity (Sabine, 1923)
These are the materials and properties:

- Material 1 (M1): non-woven polyester fiber. Rigid planks. Dimension: 1,000x500x30 mm. Density: 30 kg/m^3.
- Material 2 (M2): rock wool. Rigid planks. Dimension: 1,000x600x30 mm. Density: 100 kg/m^3.
- Material 3 (M3): thick of melamine foam. Rigid planks. Dimension: 1,000x500x30 mm. Density: 10 kg/m^3.

2.2. *Methodology*

For each material reverberation time was obtained: from three different thicknesses of back air layer (0 cm, 5 cm and 15 cm) and five gaps between material pieces, therefore, each material has been tested in 15 different arrangements. Sample's net area was 10 m^2 (every pieces together), but the area has been increasing by placing pieces into the tested different sites. As pieces are away, the ratio between the net area of the together patches (10 m^2) and the final area occupied is decrease from 1 (case that represents all the material joined in one surface) to 0.86, 0.75, 0.51 and 0.37 (where pieces are farthest). This relation between net area and total area is the variable named as “O” (occupancy) in this study.

Analyzing the pieces’ thickness is necessary to take account what happen with them. The regulation says this part of the piece need to be covered, so at this point this study have not consciously followed the rule and thicknesses have stayed uncovered, because in most of the normal cases in building works these are not covered. The aim is staying as near as possible to the real on-site procedures. As explained above, this work pretends to find out a simple and useful prediction method so that technicians can draw it on in building works or designers in technical office work.

Figure 1. Material 3 ready to be tested. Occupancy 0.75.

The dividers used to build the behind air layer were made from extruded polystyrene foam, it was chosen because is a reflective material. The reverberation time obtained in empty reverberation chamber with and without dividers -in place- was the same at all frequencies studied. Test samples had a rectangular shape, and the ratio width/length is 0.7. These were placed such way that piece edges stayed more than one meter from reverberation chamber’s walls. This distance changes as the gap between pieces increases, however, even in the most unfavorable case (O=0.37) at least the distance was 0.75 m.

As a rule, before starting the test, samples got to equilibrium with the reverberation chamber temperature and relative humidity. The relative humidity during the test stayed between 38 to 39 % and temperature between 19.9 to 20.6 degrees Celsius. For the measurement of reverberation time, the interrupted noise signal method was used, the sound decay curves were measured from equivalent levels (using the linear average) having integration times ranging between 20 milliseconds for third octave bands at frequencies 100, 125 and 160 Hz and 10 milliseconds for the others frequency bands. The whole data were carried out in third octave bands of frequency, as specified in ISO 266 (AENOR, 1998). Eighteen measurements of each material were made for each arrangement, that mean, six positions of the microphone for three positions of the noise source. It has been done six more measurements than the twelve specified as minimum by regulations.

3. Experimental results and analysis

This data forms a complete factorial design taking on account four items: frequency -18 levels, from 100 Hz to 5000 Hz in thirds octave bands-, material -3 levels, called M1, M2 and M3-, back air layer thickness -3 levels: 0 cm, 5 cm and 15 cm- and, finally, variable occupancy -5 levels: 0.37, 0.51, 0.75, 0.86 and 1.00-, which amounts to 18 x 3 x 3 x 5 = 810 data. The variables were: time named "T" in seconds, air layer thickness named "B" in centimeters and occupancy named "O" in one percent. The purpose is to quantify the effect of the variables "B" and, mainly, "O" on reverberation time by a simple model. This model must take into account their possible interaction. In addition, it is necessary to find out if the dependency of reverberation time in relation to these variables is significantly different in the three materials tested.

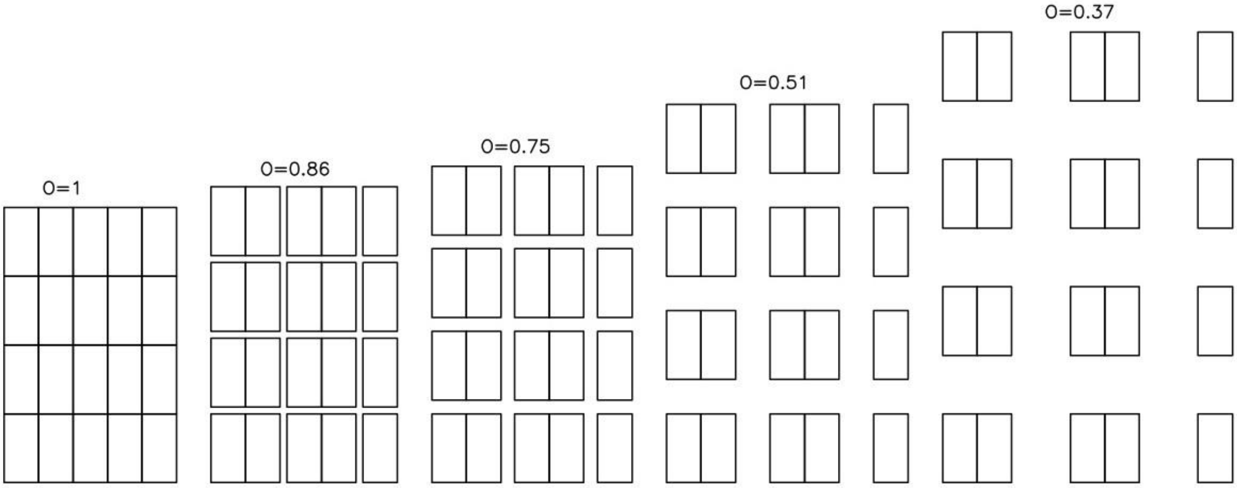

Figure 2. Explanatory diagram of different occupancy "O". Five different gaps between pieces, from shortest to largest distance.

From a theoretical point of view, results expected would be very different in every frequency band. Since the space between pieces had a very wide range -from 10 cm to 1 m- and also air layer thickness -from 0 cm to 15 cm-. It expected that low frequency waves barely notice material separations because their long wavelengths, rather the effect should be visible in high frequency bands. The area effect was another possible consequence to consider for frequencies less than 500 Hz since patches size -more or less 1 m- is like wavelengths of those frequencies. However, Kawai and Meotoiwa (Kawai & Meotoiwa, 2005) have proved that area effect of absorbent pieces placed separated by a pattern hardly differs from that when pieces are all together. Therefore, the main amount of results obtained in this research were expected to be consequence of edge effect and not of the area affect.

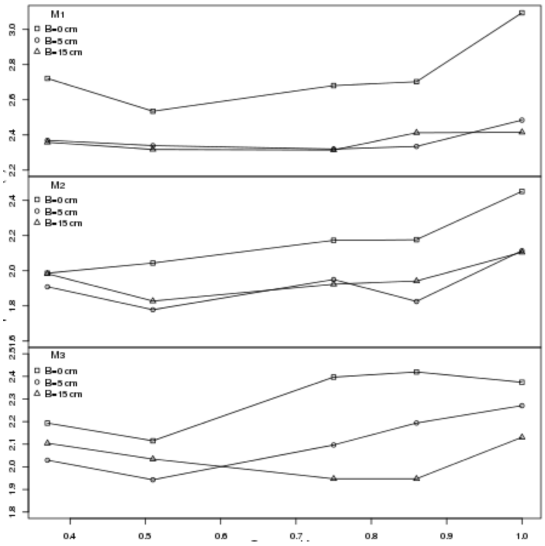

Figure 3. Reverberation time (s) (Y axis), occupancy (X axis) for three materials and air layer thickness. Frequency 800 Hz.

Figure 3 shows the dependency of occupancy variable for different back air layer thickness, for the three materials tested and for one frequency -800 Hz-. In that case it has been able to see a few decreases of reverberation time as occupancy decrease. Also, it has been able to notice a decrease of reverberation time when air layer thickness increase, but in the chart -figure 3- material dependency is not clear, neither if there is or is not interaction between occupancy and air layer thickness. So, it has been clarified that a serious and complete statistical analysis is needed to confirm or reject the first ideas and theoretical intuitions, with the porpoise to apply to every frequency, materials, air layer thickness and occupancy cases. Also, if it is possible, to quantify dependency between variables. This statistical analysis has been carried out step by step in the following sections.

3.1. *Variance analysis at each frequency*

Table 1 shows variance analysis results for the 45 data of each frequency.

Table 1. Variance analysis results by frequency. P-values are associated with F-test.

Frequency (Hz)	Sum of squares				p-values		
	Material	Air layer	Occupancy	Residual	Material	Air layer	Occupancy
100	0.574	0.252	0.483	4.662	0.1240	0.3880	0.4570
125	2.071	1.879	0.281	4.239	0.0008	0.0014	0.6674
160	2.448	1.181	0.472	3.461	0.0000	0.0051	0.3169
200	3.115	3.850	0.393	3.367	0.0000	0.0000	0.3940
250	0.753	7.371	0.946	4.221	0.0521	0.0000	0.1127
315	2.309	4.135	0.372	1.641	0.0000	0.0000	0.1090
400	1.445	2.430	0.039	1.521	0.0000	0.0000	0.9200
500	1.582	1.269	0.086	0.620	0.0000	0.0000	0.3070
630	1.771	0.801	0.071	0.681	0.0000	0.0000	0.4540
800	1.848	0.786	0.373	0.302	0.0000	0.0000	0.0000
1000	1.661	0.395	0.233	0.308	0.0000	0.0000	0.0003
1250	1.353	0.276	0.266	0.283	0.0000	0.0000	0.0000
1600	1.065	0.182	0.188	0.096	0.0000	0.0000	0.0000
2000	0.779	0.079	0.125	0.002	0.0000	0.0000	0.0000
2500	0.616	0.065	0.079	0.065	0.0000	0.0000	0.0000
3150	0.545	0.027	0.036	0.086	0.0000	0.0077	0.0113
4000	0.464	0.008	0.008	0.108	0.0000	0.2600	0.6310
5000	0.369	0.002	0.005	0.155	0.0000	0.7720	0.8760

Only results of sum of squares and p-values of F-test are presented for each case. On the table it can be seen material is the dominant factor in each frequency, except in the irregular item of 250 Hz, in which air layer is the main issue to explain variability. So, excepting 250 Hz and 100 Hz, material is the main influence to explain reverberation time variability. The second influence about that is air layer, and it seems to be significant at all frequencies above 100 Hz and below 4,000 Hz. Finally, occupancy effect is the least important of three of them and only, it is relevant from 800 Hz to 4,000 Hz. For more than 4,000 Hz it has stopped been an explanatory variable of the reverberation time variability.

Considering that the aim is to study the occupancy variable effect using a simple model, above results would have forced to consider only the middle frequencies -from 800 Hz to 3150 Hz-, Nevertheless, the irregularity found in air layer and occupancy as explanatory variables from very high frequencies -4,000 Hz to 5,000 Hz- deserves a deeper study, therefore, these frequencies have been taking into account in the following discussions.

3.2. *Different models study*

In this section model series are showed to explain that reverberation time as a function of thickness, air layer and occupancy variables, for each frequency band in the range 800 Hz to 5,000 Hz to choose the best. A statistical model including many parameters will predictably right better than a reduced one, however, the simplest possible model will be considered better choice to be implemented on work site. To carry out the propose, data have been organized in four models and compared with each other doing the following test: supposing that A and B are two models with parameters P_A and P_B, respectively, and model B contains model A, for some combination of their parameters. Therefore, $P_B > P_A$ so model A residuals sum of squares must be greater than this addition in model B. The question to be answered in this situation is if to add more parameters to model A is worth it. Consequently, the follow statistic has been used (Weisberg, 1985; Yan & Su, 2009):

$$\boldsymbol{F} = \frac{n-p_B}{p_B-p_A} . \frac{S_A-S_B}{S_B} \qquad (1)$$

Where S_A and S_B are sums of squares residuals of each model and "n" is the sample size. This statistic follows an F distribution with P_B-P_A and n-P_B freedom degrees, under the null hypothesis that model B does not improve model A. This test allows comparing the four models and, thus, accepting or discarding more complex models compared to simplest ones.

All models studied take into account material effect as a qualitative variable, air layer thickness and occupancy as a continuous variable. Models are named as a, b, c and d. Model a is defined by equation (2):

$$\boldsymbol{T} = \alpha_i + \beta O + \gamma B + e \tag{2}$$

Where O and B represent occupancy and air layer variables, as explained above, while "e" is the stochastic term, what it is supposed that usually is distribute with average σ and variance R^2. The model parameters are α1, α2 y α3, which are material effect of M1, M2 and M3 materials, respectively. β is the O variable slope, and γ is the B variable slope. The model has $p_a = 5$ parameters. In this model the effect of one of each variable are obtained separately and does not take into account any interaction between them. Model b is defined by equation (3):

$$\boldsymbol{T} = \alpha_i + \beta O + \gamma B + \delta OB + e \tag{3}$$

In this equation variables are the same as before, but "b" model has a new parameter δ, which takes into account interaction between B and O, that means it has six parameters -pb=6-. Model B contains A model, if δ is equal to zero. Model c is defined by equation (4):

$$\boldsymbol{T} = \alpha_i + \beta_i O + \gamma_i B + e \tag{4}$$

Now, parameters are α_i, β_i y γ_i, where "i" is equal to 1, 2 and 3 for each material. This model has a constant term, a slope for O variable and a slope por B variable for each material. This is equivalent to considering interaction between material and occupancy and, also between material and air layer, but no interaction between occupancy and air layer. The model C sum of squares is obtained adjusting the model to each material data and adding the three models sum of squares with their corresponding data. The complete number of parameters in this model is 9 $-p_c = 9-$. Model C contains model a keeping $\beta_1=\beta_2=\beta_3$ and $\gamma_1=\gamma_2=\gamma_3$, but it does not contain model b, so these cases cannot be compared. Finally, model d is described by equation (5):

$$\boldsymbol{T} = \alpha_i + \beta_i O + \gamma_i B + \delta_i OB + e \tag{5}$$

Three more parameters are considering, δ_i (i=1, 2 and 3), which explains the possible B and O variables interaction and the material. The number of parameters is 12 $-p_d = 12-$. This model contains all the previous ones because of the same parameter's conditions, as already explained.

Table 2. Comparative F-test results of four models for each frequency.

Frequen.	Residuals sum of squares				p-values of F-test				
Hz	S_a	S_b	S_c	S_d	a-b	a-c	a-d	b-d	c-d
800	0.755	0.681	0.716	0.640	0.0461	0.7420	0.5548	0.9018	0.2871
1000	0.646	0.606	0.619	0.438	0.1176	0.8189	0.0559	0.0782	0.0088
1250	0.515	0.495	0.480	0.456	0.2238	0.6286	0.7503	0.8272	0.6425
1600	0.191	0.182	0.167	0.145	0.1775	0.2903	0.1980	0.2339	0.1866
2000	0.096	0.091	0.077	0.069	0.1088	0.0631	0.0964	0.1407	0.3336
2500	0.116	0.116	0.097	0.092	0.9541	0.1479	0.3173	0.2335	0.6611
3150	0.114	0.109	0.074	0.069	0.2177	0.0033	0.0139	0.0138	0.5050
4000	0.109	0.109	0.032	0.031	0.7070	0.0000	0.0000	0.0000	0.6576
5000	0.159	0.157	0.056	0.050	0.4847	0.0000	0.0000	0.0000	0.2734

The four models have been adapted to 45 data -n = 45- in central frequency of thirds octave and compare by the F-test, already said. Possible comparations are a-b, a-c, a-d, b-d y c-d. Table 2 shows the sum of squares of each model and their p-valor for F-test. Looking at comparations p-valor column between models a and b, it can be able to notice that, except for 800 Hz, the introduction of an extra parameter which explains the interaction between occupancy and air layer was not useful, so that model a is better than model b. Also model a is better than models c or d for thirds octave frequencies, between 800 to 2,500 Hz. For higher frequencies, 3150, 4000 and 5000 Hz, model c could be considered better than model a, while model d does not add any improvement that validates its use.

3.3. *Chosen model description and validation*

In this section it has been explained deeply models c and d, which are the ones that best explain the dependence on material reverberation time, occupancy and air layer. Their utility and diagnosis have been discussed to verify them. Table 3 shows model a parameters combined with: standard errors, residuals standard error, R^2 calculated and test of model adjust from p-valor. Residuals standard error is an estimate of σ (the standard stochastic term deviation of equation 3). Model set to 3150, 4000 and 5000 Hz is also shown because it helps to understand what happens in high frequencies.

On the table, high R values are noted, which indicates that model explains much of the variability detected in data, around 80%. P-values are remarkable, all of them are zero to four decimal places, that means that in all cases explanatory variables contribution is important, however that it could be possible due just the material. In fact, for the three highest frequencies occupancy slope and air layer slope are very small, in both variables, they become almost zero for 5000 Hz, that means result does not depend at all on these variables.

Table 3: Model "a" parameters.

Frequ.	α1	$S_{\alpha 1}$	α2	$S_{\alpha 2}$	α3	$S_{\alpha 3}$	β	S_β	γ	S_γ	S_R	R_2	p-valor
800	2.39	0.07	1.91	0.05	2.06	0.05	0.31	0.09	-0.017	0.003	0.14	0.7718	0.0000
1000	2.28	0.07	1.82	0.05	1.96	0.05	0.27	0.08	-0.008	0.003	0.13	0.7513	0.0000
1250	2.23	0.06	1.82	0.04	1.91	0.04	0.31	0.07	-0.007	0.003	0.11	0.7638	0.0000
1600	2.22	0.04	1.86	0.03	1.96	0.03	0.23	0.04	-0.009	0.002	0.07	0.8754	0.0000
2000	2.15	0.03	1.83	0.02	1.95	0.02	0.21	0.03	-0.007	0.001	0.05	0.9078	0.0000
2500	2.07	0.03	1.79	0.02	1.90	0.02	0.15	0.04	-0.005	0.001	0.05	0.8590	0.0000
3150	1.94	0.03	1.68	0.02	1.73	0.02	0.09	0.03	-0.003	0.001	0.05	0.8361	0.0000
4000	1.73	0.03	1.50	0.02	1.53	0.02	0.05	0.03	-0.002	0.001	0.05	0.8144	0.0000
5000	1.46	0.03	1.26	0.02	1.28	0.02	0.03	0.04	0.001	0.002	0.06	0.7016	0.0000

For other frecuencies, 800 Hz to 2500 Hz, occupancy slope and air layer slope are clearly non-zero and they have a standard error cosidered as a allowable data. Focus on each slope sign: occupancy is positive and air layer is negative. Positive occupancy slope means that reverberation time is reduced as occupancy is reduced too when material pieces are separated. On other side, when air layer is thicker, reverberation time is shorter, as figure 3 have suggested.

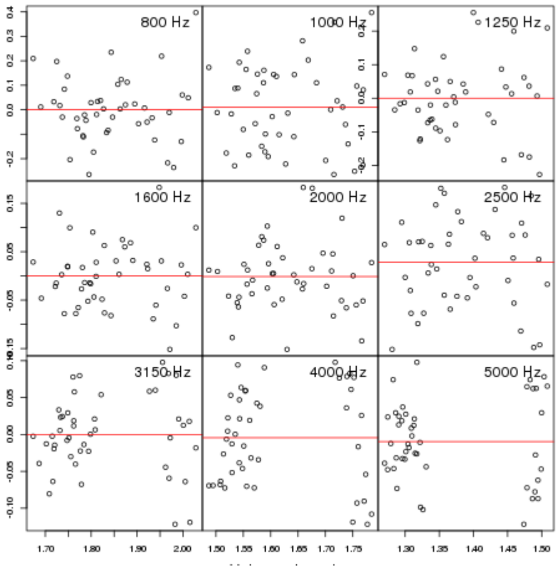

Figure 4. Model residuals versus adjusted values. Horizontal line sets 0. Residuals (Y axis), Adjusted values (X axis).

Model a must be checked before accepting it is right. For those residuals are checked figure 4, which appear distributed above and below zero and there are not significant trends, so residuals agree with the hypothesis of a linear correlation of variables and independence. Residuals are divided into two groups at the 3150, 4000 and 5000 Hz frequencies, that are defined by the material, but this division does not invalidate the previous deductions. The homoscedasticity hypothesis is also approved by these graphs, as we can see because it is observed dispersions in the similar residuals at all points. The normality hypothesis of the residuals is also confirmed, as shown in figure 5, as points are sufficiently aligned along the theoretical quantiles line.

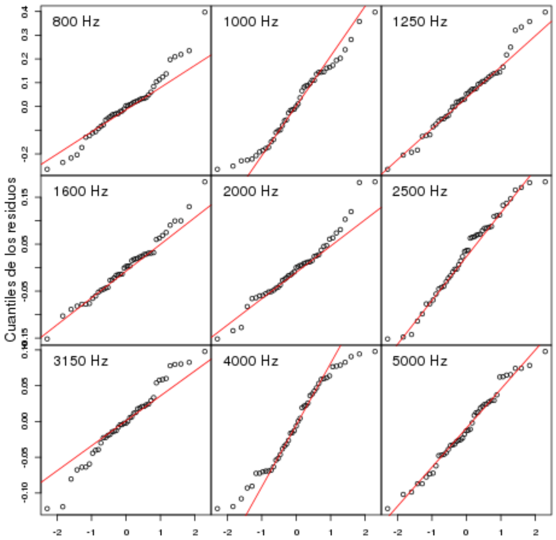

Figure 5. Quantile diagram of model residuals. Assuming normal distribution. Residual Quantiles (Y axis), Theoretical Quantiles (X axis).

Table 4 shows model c parameters adjust to the data for the high frequencies: 3150, 4000 and 5000 Hz. These frequencies data deserve a specific analysis. The main difference between model a and c is that model c represents an interaction of the material with variables O and B, the different values obtained for a specified central band of octave thirds -for different materials- establish that interaction. In two cases, M1 at 3150 Hz and M3 at 5000 Hz, the adjusted model cannot be acceptable due to the low value of R2 or high p-value. In addition, the values of the coefficient, that explains the occupancy effect, could be compare with zero in most of the M1 and M3 cases, that might indicate there is no effect of the occupancy variable in the reverberation time. However, for M2 the adjust models are all reliable, both in high R2 values and in small p-values, and all of them have non-zero in parameter values.

Table 4: Model "c" aligned parameters at high frequencies

Frequencies	Material	α	Sα	β	Sβ	γ	Sγ	S_R	R^2	p-valor
3150	M1	1.93	0.06	0.05	0.07	0.003	0.003	0.06	0.1287	0.4375
	M2	1.64	0.03	0.18	0.04	-0.006	0.002	0.04	0.7381	0.0003
	M3	1.78	0.03	0.05	0.03	-0.006	0.001	0.03	0.6889	0.0009
4000	M1	1.71	0.03	0.00	0.04	0.006	0.001	0.03	0.6261	0.0027
	M2	1.46	0.02	0.16	0.03	-0.007	0.001	0.02	0.8700	0.0000
	M3	1.59	0.03	0.01	0.03	-0.006	0.001	0.03	0.6771	0.0011
5000	M1	1.44	0.04	-0.03	0.05	0.011	0.002	0.05	0.7400	0.0003
	M2	1.22	0.02	0.13	0.03	-0.003	0.001	0.03	0.7037	0.0007
	M3	1.34	0.04	0.01	0.05	-0.005	0.002	0.04	0.4028	0.0454

When analyzing model c in the same way as model a, it is noted that M1 and M3 present a residues pattern, in where points are separated in three groups. This groups are related to the three air layer thickness values and there are an important deviation of each group at 4000 and 5000 Hz. In the case of model c normality of residuals hypothesis is also established. Consequently, this model c is highly dependent on material variable, it gives a very reliable result for M2 but weak result for M1 and M3. As the aim of this study were to obtain conclusions independent of the material, it is required to left the model c.

3.4. *Material independent results*

Finally, it is needed to emphasize the part of model that is independent of tested materials. Fortunately, model a has the slope of the occupancy and thickness air layer variables independent of material variable, so it is possible consider the reverberation time value, T_s, when B = 0 -without air layer behind- and O = 1 -all the pieces together-. On equation 2 in the deterministic part of the model there is $T_s = \alpha_i + \beta$, so α_i can be solved by the T_S and β terms. Therefore, the deterministic part of model a can be transcribe as expressed in equation 6:

$$\mathbf{T} = T_s + \beta(O - 1) + \gamma B \qquad (6)$$

Now β and γ parameters are given by the adjusted model and can be obtained from table 3. However, and to improve the usefully, only the exact data necessary to use the formula are shown in table 5. The material dependency is taken into account in the T_S value, what is the reverberation time under the conditions of the ISO 354 (Caballol & Raposo, 2019) for obtaining the material absorbent coefficient. Therefore, this value could be known by Sabine's equation using the data offered by the manufacturer on the technical specifications.

Equation 6 and table 5 have been the main results of this research. Equation 6 has been tested from 800 to 5000 Hz, higher frequencies could be defined more accurate by the model c, as it was shown previously. But also, model c from 4000 to 5000 Hz has been shown to be wrong for some materials, and furthermore, the occupancy effect and air layer thickness are irrelevant at high frequencies, so model c is not included in the final summary, only for the data of 3150 Hz which are within model a.

Table 5. Model a: Slopes of occupancy (β) and air layer behind (γ) values and each standard errors.

Frequency	β	Sβ	γ	Sγ
800	0.31	0.09	-0.017	0.003
1000	0.27	0.08	-0.008	0.003
1250	0.31	0.07	-0.007	0.003
1600	0.23	0.04	-0.009	0.002
2000	0.21	0.03	-0.007	0.001
2500	0.15	0.04	-0.005	0.001
3150	0.09	0.03	-0.003	0.001

3.5 *Validation to test the robustness of the model*

In order to test the robustness of the model a check was carried out. Data has been obtained during an assay carried out in one of the classroom of the Escuela Técnica Superior de Edificación (UPM) in Madrid (Spain). The procedure was:

- In the chosen room (classroom P0T6), it was placed on the floor 10 m^2 of non-hydrophilic glass wool, below this a 75 g/m^2 Kraft paper was set, to act as a vapor barrier. Kraft paper was 80 mm thick and 14 Kg/m^3 density. It was chosen because it is different from the other three materials previously studied.
- Reverberation time of the room was obtained, named T1.
- The 10 m^2 of glass wool were divided into five equal pieces and placed on the floor separated 10 cm from each other, that means O=0.91.
- New reverberation time was obtained, named T2.
- Now glass wool pieces were separated 20 cm, occupancy was 0.95. This reverberation time was named T3.

Having this data, it was able to use equation 6 (β and γ values from table 5). Finally, values obtained when using the model were compared with those tested *in situ.*

Table 6. Summary of test values and calculated values for interest frequencies, included standard error.

Hz	T1	T2	Calc. T2	S_{T2}	T3	Calc T3	S_{T3}
800	0.49	0.45	0.47	0.02	0.45	0.46	0.01
1000	0.55	0.52	0.54	0.01	0.50	0.53	0.02
1250	0.59	0.60	0.57	0.02	0.58	0.56	0.01
1600	0.63	0.64	0.62	0.02	0.63	0.61	0.01
2000	0.62	0.62	0.61	0.01	0.61	0.60	0.01

2500	0.64	0.64	0.63	0.01	0.63	0.63	0.00
3150	0.62	0.61	0.62	0.00	0.60	0.61	0.01

4. Conclusions and comments

The reverberation time was measured according to standard test in reverberation chamber. The test was done in three different materials, with the following arrangements: three air layer back thickness and each of one of those with different placement of the material in separate pieces.

1. A statistically significant dependence on reverberation time has been found with the air layer thickness and the occupancy variables in the range of 800 to 2500 Hz. In this range, a linear regression model has been successfully adjusted to the data of each of the third's octave frequencies, and it has been verified that the dependencies of air layer thickness and occupancy are independent of the material studied. The model result is the equation 6 and the parameters presented on table 5;
2. Positive values of β parameter suggest a decrease of several hundredths of second of the reverberation time when pieces of material are placed separately. Negative values of γ parameter show that when air layer thickness increases the reverberation time decreases, the decrease is about a few milliseconds per centimeter;
3. The linear model for each frequency from 800 Hz to 2500 Hz has been proved in its hypothesis by the analysis of the model residuals and the result in all cases has been positive, verifying their reliability;
4. For frequencies below 800 Hz, the occupancy variable is not statistically significant to explain the variability of the data, mainly because the material factor and others uncontrolled factors do not allow distinguishing the occupancy effect. On the contrary, for higher frequencies, especially at 4000 Hz and 5000 Hz, there is a primarily result in air layer thickness and occupancy, as in these cases, its slopes are compatible with zero, that is, for these frequencies the reverberation time is completely independent of them;
5. These results are compatible with the previous results presented in (Caballol & Raposo, 2016), in where similar test were carried out, but without air layer. $\gamma = 0$ in equation 6, so it is without the air layer effect this equation is the same as equation 7 in the previous study, but the values of β parameter in both studies are compatibles. In this way, equation 6 achieves the purpose of formulate a simple predictive model that allows -if it is known the absorption coefficient- to calculate *in situ* the behavior improvement by placing the same surface but in pieces separated from each other and having different air layers;
6. Finally, data shown in table 6 support robustness of the model. The values calculated are similar to those tested in situ, also standard errors confirm, because they are minimum.

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