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Acoustic absorption increase by placing absorbent material in pieces with and without back air layer.

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ABSTRACT

The reverberation time of a reverberation room with an absorbent material is proved against different layouts of the material and with and without a combination of different back air layers, compared to those results where the same material is placed as a single piece. With the analysis of the obtained data, a regression model is established in order to predict, for certain frequencies, the improvement produced in the reverberation time of a room, using the same amount of material by placing it in pieces separated from each other, instead of in one piece, and including different distances from the wall as a variable. It becomes a simple on work predictive tool which allows to estimate the alteration in the reverberation time due to the separation of the patches. The model is validated and proven to be robust and it is shown to be applicable to a variety of materials.

Keywords: Absorption, Sound-absorbent material, Materials in patches.
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

The extra absorption of a sound absorbent material when it is placed in patches rather than in one piece has been considered since long [1,2,3,4] as well as recently [5,6] This effect has been attributed to lack of diffusion and to the so called edge effect. Likewise, some research studies [7,8] quantify the diffusion based on the dispersion and absorption coefficient of the walls. Other researchers [9,10,11] have studied how the edge effect increases the measured absorption in a reverberation chamber due to the extra surface area that is present because of the thickness of the sample under test. Yet other studies concentrate on absorbers based on the passive destructive interference principle (PDI) [12] or based on metamaterials [13,14]. However, none of these studies has found a simple method that allows to predict the improvement produced in the reverberation time of a dwelling, using the same amount of absorbent material but placing it in separated pieces. This is the goal of this manuscript: to find a simple method that allows an in situ

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estimation of the improved response of an absorbent material upon being placed in separated patches in a building work, instead of the usual theoretical models with many parameters [15] which are more difficult to apply in situ.

2. MATERIALS AND METHOD

We have chosen to measure the reverberation time under the same conditions specified by the ISO 354 standard [16] for the measurement of the absorption coefficient of an absorbent material. The method described in this standard measures the mean reverberation time in the reverberation room with and without the test sample. The equivalent sound absorption area is calculated from these reverberation time periods through Sabine's equation, and then the absorption coefficient. The testing conditions prescribe a specific reverberation room size and shape, with controlled temperature and humidity. The testing sample must have an area between 10 m^2 and 12 m^2 and must be rectangular in shape with a width-to-length ratio between 0.7 and 1.

The reverberation time has been measured in third octave bands with three different materials of similar thickness (3 cm, a thickness that is usually found in work sites for this type of materials), with and without different layouts of the material pieces and different thickness of the back air layer. The three materials have been chosen on the basis of the following criteria:

1. Be used regularly in work sites.

2. That their absorbent properties were very different. Therefore, two fibrous materials are chosen, one of them with low density (30 kg/m3) and another with high density (100 kg/m3) and one porous with very low density (10 kg/m3). So that different flow resistivity values could be guaranteed [17].

The tested materials have the following properties:

- Material 1 (M1): non-woven polyester fiber 30 mm. thick, in rigid planks with dimensions 1000x500x30 mm. and 30kg/m^3 density.
- Material 2 (M2): 30 mm. thick rock wool, in rigid planks with dimensions 1000x600 x30 mm. and 100 kg/m^3 density.
- Material 3 (M3): melamine foam 30 mm. thick, in rigid planks with dimensions 1000x500x30 mm and 10 kg/m^3 density.

For each material, the reverberation time was measured with three different thickness of the back air layer (0 cm, 5 cm and 15 cm) and five layouts of the planks of the absorbent material. The samples have a net area of 10 m^2 (in one piece), but the gross area has been increased through the separation of the planks in the different positions tested. As the patches are separated, the ratio between the net area of the patches (10 m^2) and the gross area they occupy diminishes from 1 (all patches together in a single piece) to 0.86, 0.75, 0.51 and 0.37. This ratio of net to gross area is the variable that is referred to as “O”, occupation, throughout this manuscript. Thus, each material has been tested in 15 different arrangements.

As was explained previously, we are searching for a simple in situ prediction method useful for technicians on an on site work or in a designer's office. Since the separation of the absorbent material in patches do not usually involve the covering of the sides of the patches. We have diverted here from the standard and we have not covered them, our aim being to stay close to the real application procedures.

The separators are made of extruded polystyrene foam, a material without any acoustic absorption capabilities. For reference, the reverberation time in the empty chamber with and without the separators in their positions was also measured, (see image 1).

Image 1: Empty reverberation chamber, with separators of 5 cm.

Image 2: Two different arrangements of material M1:in the left side the material is laid in one piece (occupation 1) and with an air layer thickness of 15 cm; in the right side the material is laid in separated pieces, with an occupation of 0.86 and separated 5 cm from the floor.

The test samples are initially rectangular in shape, with a width/length ratio of 0.7 and are placed in such a way that every part is more than 1 m. away from the edges of the reverberation room. This condition varies as the separation distance between the pieces increases, nevertheless a separation of at least 0.75 m. was maintained, (see image 2).

In all cases, test sample pieces were allowed to reach a balance with the temperature and the relative humidity of the reverberation room before the tests were performed. The relative humidity of the chamber ranged from 38\% to 39\% during the tests, and the temperature between 19.9 and 20.6 degrees Celsius.

The interrupted noise signal method was used for measuring the reverberation time and the sound fall curves were measured from equivalent levels (using linear average) with integration times that vary between 20 milliseconds for the third octave bands of frequency 100, 125 and 160 Hz and 10 milliseconds for the rest of frequency bands. Readings were made in all cases in third octave bands, as specified in the ISO 266 standard [18]. As it is also specified in this standard, for each arrangement of each material eighteen measurements are made, corresponding to six positions of the microphone and three positions of the noise source in the chamber.

3. DATA ANALYSIS

Our data form a complete factorial design with four factors: the frequency (with 18 levels, from 100 Hz to 5000 Hz in thirds octave bands), the material (with 3 levels, denoted M1, M2 and M3), the thickness of the back air layer (with 3 levels, 0 cm, 5 cm and 15 cm) and, finally, the occupation variable (with 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 are denoted “T”, for time in seconds, “B”, for the thickness of the air layer in centimetres, and “O” for the occupation. The goal is to quantify the effect of the variables “B” and, mainly, “O” on the reverberation time by means of a model, as simple as possible, but which takes into account the possible interaction between the variables. Moreover, we need to explore to what extent the dependence of the reverberation time on these variables is different for different materials.

From a theoretical viewpoint, one may expect very different results at different frequency bands. Since the gaps between patches of the material range from 10cm. to almost 1m., and the thickness of the air layer from 0 cm to 15 cm, low frequency waves are expected not to notice the different arrangements of the absorbent materials due to their long wavelengths. On the contrary, the effect should be noticeable in the high frequency bands. Another effect that should be bearded in mind is the area effect for frequencies of 500Hz or below, because the size of the patches (of the order of 1 m) is similar to the wavelengths of those frequencies. However, Kawai and Meotoiwa [19] have shown that, with regard to the area effect, the area effect of absorbent patches collocated like checked pattern does not much different from that of simple one. The main part of the results of this experiment are expected to be the consequence of the edge effect rather than the area effect.

In Figure 1 the dependence on the variable occupation is shown for different air layer thickness, different materials at a fixed frequency of 800 Hz. In this case we can see, in general terms, a slight diminution of the reverberation time as the occupation goes down, as well as when the thickness of the air layer is increased, but the dependence on the material is not clear and it is also not clear if there is interaction between occupation and thickness of the air layer.

It is clear, thus, that a rigorous statistical analysis is needed in order to confirm or reject the naive observations and the theoretical intuitions, to extend them to all the cases of frequencies, materials, air layer thickness and levels of occupation and, if possible, to quantify the observed dependencies. In the following subsections a series of steps performs such a statistical analysis.

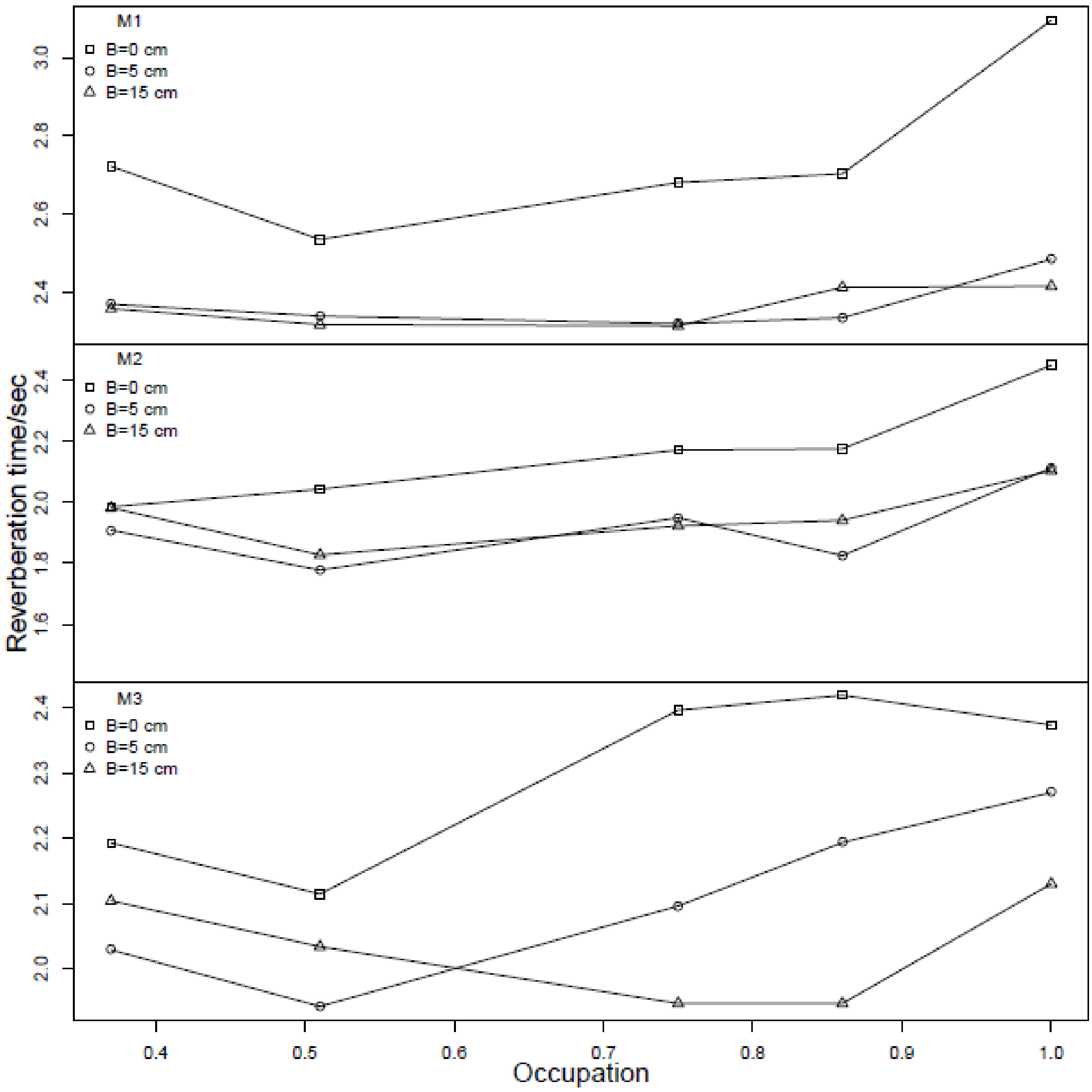

Figure 1: Reverberation time as a function of the occupation for the three different materials and the three levels of the air layer thickness, all of them for a fixed frequency of 800 Hz.

3.1 Analysis of variance in each frequency

Table 1 shows the results of the analysis of variance applied to the data in each frequency, which are 45 points. Only the sums of squares and the p$-values of the F test in each case are presented.

Factor	sum sq.	d.f.	F value	p-value
Frequency	370.2	17	312.99	0.0000
Material	12.3	2	88.2	0.0000
Air layer	13.0	2	93.4	0.0000
Occupation	0.3	4	1.0	0.4070
Residuals	54.5	784	–	–

Table 1: Results of the analysis of variance on the complete set of data, with the factors frequency, material, air layer thickness and occupation. Notice that all the variables are considered factors here. The sum of squares, the degrees of freedom, the value of the statistic F of the F-test and its associated p-value are shown.

In the table the material is seen to be the dominant factor in each frequency, except for the anomalous case of 250 Hz, where the air layer is the main factor in explaining the variability. Except at 100 Hz and the former case of 250 Hz, the material is a significant factor in the explanation of the variability of the reverberation time. Apart from the material, the air layer is the second main factor, appearing to be relevant at all frequencies above 100 Hz and below 4000 Hz. Finally, the effect of the occupation is the less important of the three, and is only significant starting from 800 Hz and above, until 4000 Hz, in which it ceases to be a satisfactory explanatory variable of the reverberation time variability.

Since the goal is to study the effect of the occupation variable by means of a simple model, the previous results bound us to consider only the medium frequencies, from 800 Hz to 3150 Hz. However, the failure of the air layer and the occupation as explanatory variables at very high frequencies (4000 and 5000 Hz) deserves further study so these frequencies are still considered in the following paragraphs.

3.2 Description of the model and validation

The model is defined by the equation 1.

Equation 1: $$T = \alpha_i + \beta O + \gamma B + e$$

Where “T” is the reverberation time (seconds), “O” and “B” stand for the variables occupation ($^{o}/_{1}$) and air layer (centimeters) respectively as stated previously, while “e” is the stochastic term, which is assumed to be normally distributed with mean 0 and variance σ^2. The parameters of the model are α_1, α_2, α_3, which are the effect of the materials M1, M2 and M3 respectively, β the slope for the variable “O”, and γ, the slope for the variable “B”. The model has p_a=5 parameters to be estimated. Also the error variance, σ2, has to be estimated. In this model the effect of each of the variables is collected separately, and no interaction among them is accounted for.

Table 2 gives the parameters of the model, together with their standard errors, the standard error of the residuals, which is an estimation of σ (the standard deviation of the stochastic term in Equation 1, the computed R^2 and the p-value of the test of the fitting of the model. The fitted model at 3150, 4000 and 5000 Hz are also shown since it helps to understand the situation in this regime of high frequencies.

Freq.	α_1	s_{α_1}	α_2	s_{α_2}	α_3	s_{α_3}	β	s_β	γ	s_γ	s_R	R^2	p-value
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

Table 2: Fitted parameters of the model, as given by Equation 1. Each parameter is given with its standard error. In addition the standard error of the residuals, s_R, is the estimation of σ. Also the R^2 and p-value of each fitting is given.

In the table 2 it is noticeable the high values of the computed R^2 which indicates that the model explain a great part of the variability observed in the data, around 80\%. Also the p-values are noticeable, all of them zero up to four decimal places, which tells us that in all cases the contribution of the explanatory variables is significant. However, the latter may be possibly accounted for only because of the material. In fact, for the three highest frequencies the slopes of the occupation and the air layer are very small becoming compatible with zero in the case of 5000 Hz in both variables, which means no dependence at all on these variables. For the other frequencies, 800 to 2500 Hz, the slopes of the occupation as well as the air layer are sound numbers with a standard error which is an admissible figure. Notice the sign of each slope: the parameter β.

The model must be validated against the hypothesis of model fitting prior to assume it correct. This is done in Figure 2.

In Figure 2 the residuals appear randomly distributed above and below the zero and no significant trends are visible, therefore supporting the hypothesis of linear correlation of the variables and independence. At 3150, 4000 and 5000 Hz the residues show a splitting into two groups, which are defined by the material as it is discussed below, but this splitting does not invalidate the previous conclusions. Also the hypothesis of homoscedasticity is confirmed by these graphs, as the dispersions of the residuals look similar at all points. The Figure 3 confirms the hypothesis of normality of the residuals, as all the quantile-quantile plots show the points sufficiently aligned along the theoretical line of quantiles.

To end up with the model description we want to emphasize the part of the model which is independent of the materials tested. Fortunately, our model gives the slopes of the variables occupation and air layer thickness independent of the material, so we can consider the value of the reverberation time with B=0, that is, with no back air layer, and O=1, i.e. all the patches of the material together in a single piece. Let us name this time T_s after standard. By Equation 1 in the deterministic part of the model we have $T_s = \alpha_i + \beta$ so we can solve for α_i in terms of T_s and β. Therefore we can write the deterministic part of the model in the following form (Equation 2):

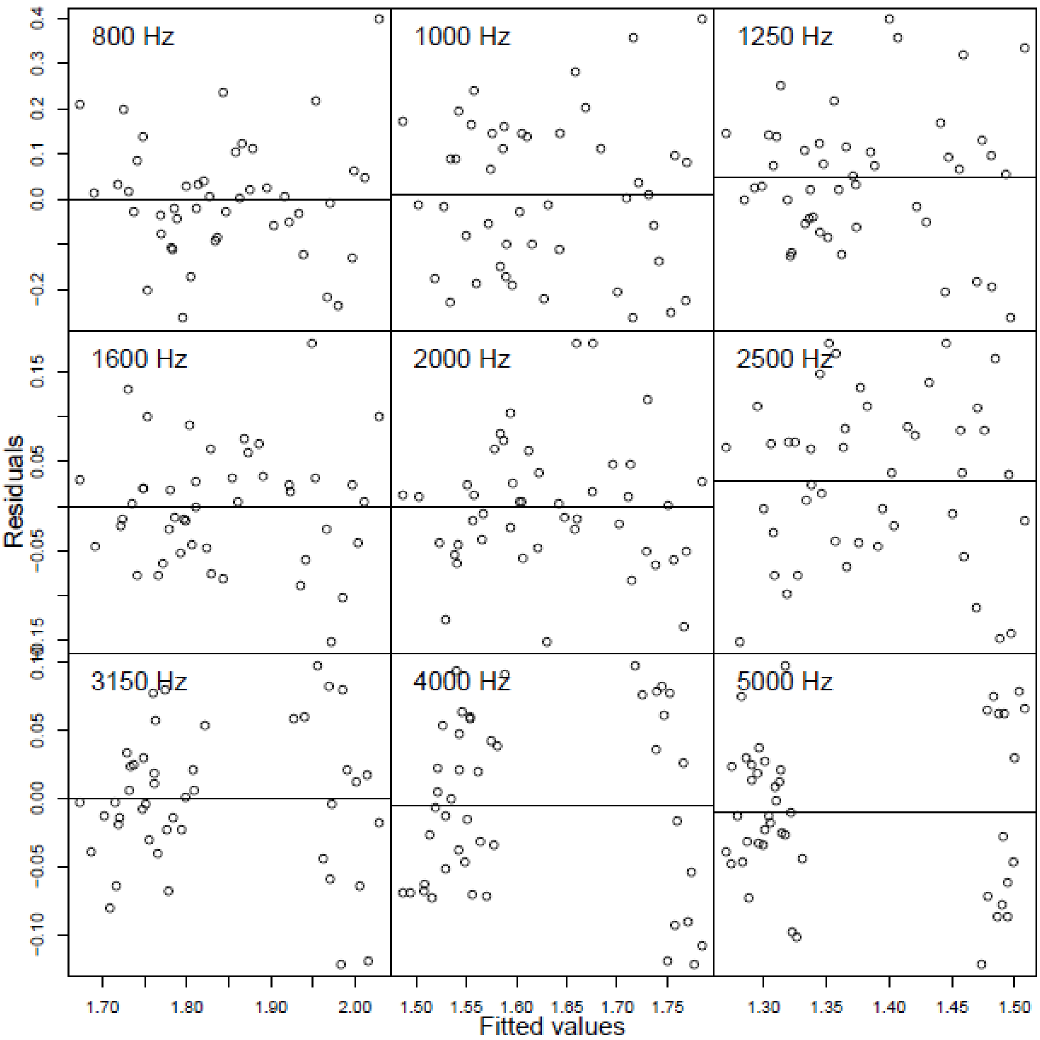

Figure 2: Residuals of the model versus fitted values for each frequency. The horizontal line sets the zero in each graph.

Equation 2: $$T = T_s + \beta(O - 1) + \gamma B$$

Now the parameters β and γ are given by the fitted model, in Table 2, which we have extracted again in Table 3.

Freq.	β	s_β	γ	s_γ
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

Table 3: Slopes of the variables occupation (β) and air layer thickness (γ) of the model with their respective standard error.

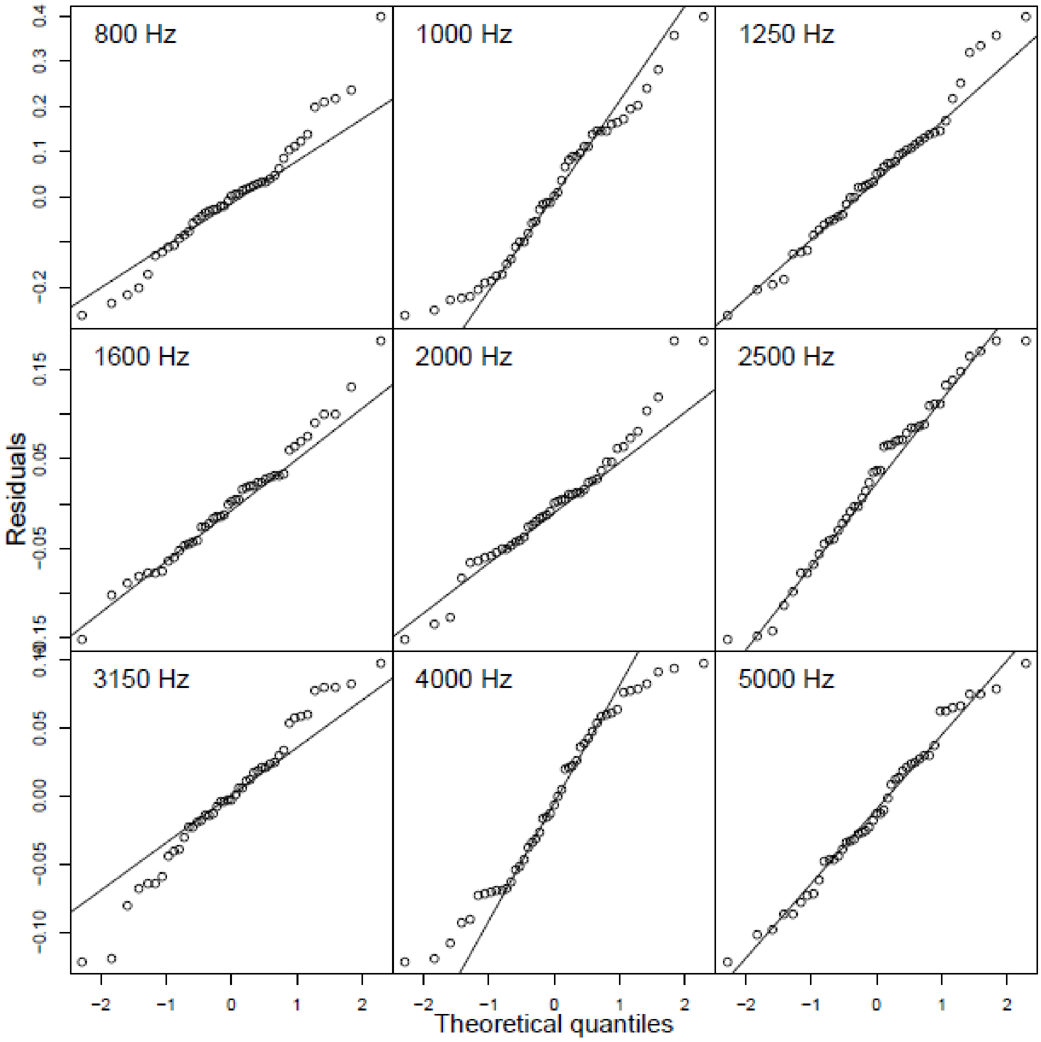

Figure 3: Quantile-quantile plot of the residuals of the model under the assumption of normal distribution.

The dependence on the material is collected in T_S but, since this number is the reverberation time in the conditions described by the standard for the determination of the coefficient of absorption of the material, it can be obtained from the technical specifications of the manufacturer and the Sabine´s equation. Equation 2 together with Table 3 is the main result of this work. Equation 2 has been proved right from 800 to 5000 Hz.

4. CONCLUSIONS

The reverberation time is measured following the standard test in the reverberation room with three absorbent materials and with different arrangements. With and without the thickness of a back air layer and the splitting of the material in several separated pieces. A statistically significant dependence has been found of the reverberation time on the air layer thickness and the occupation variable in the range of 800 to 2500 Hz. In this range a linear regression model has been successfully fitted to the data in each frequency, and the dependencies on the air layer thickness and the occupation have been found to be independent of the material under study. The output of the models is Equation 2 together with the parameters gathered in Table 3. The positive values of the parameter β inform of the reduction in the reverberation time as the patches of the material are placed separately, by an amount of several hundreds of second. The negative values of the parameter γ say that as the air layer thickness increases, the reverberation time is reduced by an amount of some milliseconds per centimetre.

The linear model for each frequency in the range 800 to 2500 Hz has been validated in its departing hypothesis by the analysis of the residuals of the model, and the result in each case has been positive making all the models reliable.

For frequencies less than 800 Hz the occupation variable is not statistically significant in explaining the variability of data because the dispersion due to other factors, mainly the material and uncontrolled factors, do not allow the effect of the occupation to be distinguishable. On the contrary, for higher frequencies, particularly 4000 and 5000 Hz, there is a significant result on the role of the air layer thickness and the occupation: their slopes are compatible with zero, that is, the reverberation time is completely independent of them at these frequencies.

Finally, these results are compatible with previous results presented in [20] where similar experiments were considered, but without any back air layer.

In this way, Equation 2 fulfills the purpose of enunciating a simple predictive model which allows, for absorbent materials in planks of 3 cm thickness, with the use of the coefficient of absorption of the material, to estimate in situ the improvement in its behaviour by placing it in separated pieces and with back air layer..

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