Sound absorption coefficient measurement: Re-examining the relationship between impedance tube and reverberant room methods

Mathew McGrory (1, 2), Daniel Castro Cirac (1), Olivier Gaussen (1), Densil Cabrera (2)

(1) Wood & Grieve Engineers, Sydney, Australia
(2) Faculty of Architecture, Design and Planning, The University of Sydney, Sydney, Australia

ABSTRACT

Absorption is one of the most commonly used parameters in linear acoustics. It is well known that the absorption for any material will differ when the properties of the material change. These properties include: thickness, density, flow resistivity, method of mounting, etc. Previous studies have shown that the results for an absorption coefficient test are dependent on the testing method, that is, the absorption coefficients of the same material with the same properties will vary depending on the testing method. Two techniques commonly used to perform such measurements are: 1) Reverberant room method and 2) Impedance tube transfer function method. Intuitively a relationship between the results of the two measurement methods for the same material should exist. This paper aims to develop a methodology to establish and define a clear relationship between the two resulting absorption coefficients measured from samples of the same type of material. To do this, 28 polyester samples have been tested using the two aforementioned methods. A set of variables has been considered for each sample such as thickness, density, and flow resistivity. This paper presents the results of the multivariate linear regression study of the absorption coefficients and provides a new model to convert the normal incidence sound absorption coefficient measured in an impedance tube into a random incidence sound absorption coefficient.

INTRODUCTION

The absorption coefficient could be defined as the relationship between the acoustic energy that is absorbed by a material and the total incident energy impinging upon it. This coefficient should be limited between 0 (not absorbent at all, i.e. reflective) and 1 (totally absorbent). However, one can find absorption coefficient values greater than one due to several reasons later discussed in this paper.

Various methods exist for obtaining absorption coefficient values but we have focused over the course of this study on measurements in a reverberant chamber following ISO 354:2006, and measurements using an impedance tube following ISO 10534-2:1998. In fact, the objective of this study was to find a relationship between these two measurement methods based on a set of experimental data, i.e. trying to derive an empirical transfer function that allows us to convert the results of one method to the other while minimising the error. To do so, we have tested 28 samples of polyester in both reverberation room and impedance tube following the respective standards and then compared the results.

Previous similar work has been reported dealing with this subject with two clearly different paths: a theoretical approach and an empirical one. In both cases, a combination of the two paths is used but there is clear distinction in the intent of the two. Makita and Hidaka (1987) tried to solve the problem of translating from free field to random incidence coefficients for homogeneous and isotropic porous materials using Paris' formula (Kuttruff, 1991). With a more empirical focus Olynyk and Northwood (1964) and Vér and Beranek (2005) compared results of measurements conducted in both impedance tube and reverberation room reporting significant disparity in values. However, neither study conducted a statistical analysis of the problem where several variables were analysed simultaneously.

Quite often engineers tend to round down to 1 any absorption coefficient result higher than 1 in order to represent a physical reality. However, values lower but close to unity remain untouched. The proposed methodology could be useful in these situations as it could provide a transfer function that will convert the absorption coefficients measured in a reverberation room (with sometimes values greater than one) to values capped to unity.

The remainder of the paper is divided in four parts including the description of the two ISO standard methods, a brief description of the statistical analysis used to achieve the results and a conclusion section where we present the proposed methodology, its application and limitations. As expected, a statistical approach has been taken in order to minimise the error of the prediction, however due to the nature of the experiments it is inherent in the process that small errors will exist. The key issue is to be able to quantify and narrow these errors as much as possible.

ISO STANDARD 354:2006

The reverberation room (or random incidence) method is the most commonly used method for determining the absorption coefficient of a material.

ISO 354:2006 promotes the use of Sabine's (1922) formula (1) for determining absorption coefficients within a reverberant room.

$$RT_{60} = \frac{0.161V}{A} \tag{1}$$

Here V is the volume of the room (m^3) and A is the total area of absorption in the room calculated from (2).

$$A = S\bar{a} \tag{2}$$

S is the total surface area of the room and $\bar{a}$ is the average absorption coefficient of the room given by

$$\bar{a} = \frac{S_1 a_1 + S_2 a_2 + \cdots + S_n a_n}{S} \quad (3)$$

$$A_T = 55.3\, V \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_1 - m_2) \quad (4)$$

In equation 4, A_T is the equivalent sound absorption area of only the test specimen (m^2); c_1 and c_2 are the propagation speeds of the sound in air (m/s) for empty and full room conditions and T_1 and T_2 are the reverberation times, in seconds, of the room under empty and full conditions respectively. The power attenuation coefficients m_1 and m_2 are calculated according to ISO 9613-1 using the atmospheric conditions of the empty and full room correspondingly. The random incidence absorption coefficient can be then calculated using Equation (5).

$$a_s = \frac{A_T}{S} \quad (5)$$

Testing details

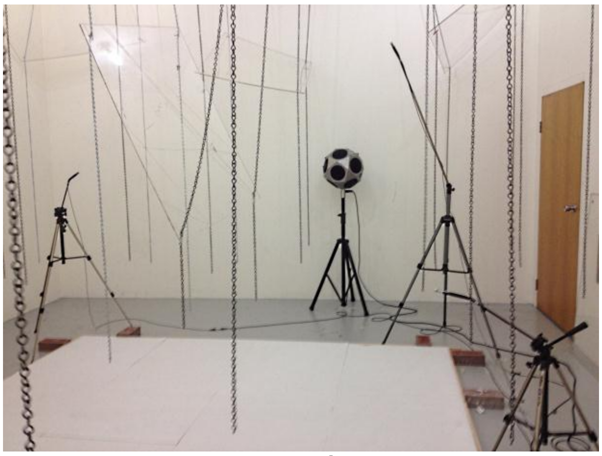
The measurements were conducted adhering to ISO354:2006 with some exceptions later described. While this standard has been criticised for ensuing inaccuracies (Sauro, 2009) the method was followed where possible due to the fact it is recognised as the standard way to test.

The testing was performed at the University of Sydney, which houses a rectangular reverberation room made up of painted concrete and painted rendered masonry. The reverberation room measures 6.36m (L) x 5.12m (W) x 3.98m (H), yielding a total volume of 130m^3, which is 20m^3 below the minimum size according to the ISO354:2006. The ASTM C423 - 09a, however, specifies a minimum volume of 125m^3.

The dimensions of the samples used for the testing were 3.4m (L) by 3m (W), which results in a surface area of 10.2m^2. The ISO 354:2006 details the minimum and maximum sample sizes as 10m^2 – 12m^2 respectively, which must follow a length to width ratio of 1:0.7 – 1:1. In this instance, the length to width ratio is 1:0.9. The samples were cut into 8 pieces due to manufacturing limitations, and mounted side-by-side with frames corresponding to the method outlined in the ISO354:2006 Annex B.

The equipment used to perform the measurements included: Brüel and Kjær omnisource loudspeaker, 4 x Brüel and Kjær 4189 microphones, Brüel and Kjær 2716C amplifier, Brüel and Kjær front end with signal generator and Brüel and Kjær Pulse software using Labshop template.

Since the reverberation room used for the conducted tests contains parallel walls, adequate diffusion was imperative to obtain accurate measurements. The diffusivity of a room's sound field is the foundation of acoustic measurements such as reverberation time and absorption. For a room to be considered as diffuse it must produce a uniform local energy density and have uniform incident energy onto a surface from all directions. ISO354:2006 proposes the reverberant room diffuseness be measured prior to testing. Bassett *et al* (2010) assessed the diffusivity of the utilised reverberation room, and concluded there were negligible differences in absorption when 10 or more diffusers were deployed. For this reason 10 panels were suspended throughout the room. These reflecting panels were made of Perspex of dimensions:1220mm x 915mm x 5mm (1.1163m^2) per panel.



Source: Authors

Figure 1. Photograph of the reverberation room.

ISO 354:2006 Results discussion

A topic that generates much confusion in acoustics is why one can obtain absorption coefficients greater than one when measured in a reverberant chamber. Given the absorption coefficient is a ratio between the total incident energy and the absorbed energy it is difficult to understand why an absorption coefficient can be greater than unity as it implies that the sample under test is generating energy, which goes against the laws of physics.

Cox and D'Antonio (2004) summarised the reasons why the absorption coefficient can exceed unity, and these reasons include: 1) Edge diffraction, 2) Non-diffuseness 3) Sabine formulation.

Edge diffraction: The diffraction from the edges at low frequencies causes the reflected wave to no longer be planar, and so diffraction produces the edge effect whereby substantially more absorption happens near the edges of an absorber than at its centre.

Non-diffuseness: In order to apply the Sabine formulation a statistical approach is assumed to define the sound field in the room. Therefore it can be assumed that the time and space distribution of the sound pressure level is even across the room, which is typically not the case in real situations. In fact, the ISO 354:2006 requires the room to be diffuse which usually demands the installation of stationary suspended diffusers. With all, the reverberation time needs to be measured at several locations with different positions of microphones and loudspeakers in order to later average the reverberation time of the room.

Sabine formulation: It is well understood that the Sabine (1922) formulation should not be applied when the mean absorption value is higher than 0.4. Various authors propose the use of the Norris-Eyring or Millington formulae to compensate for this (Cox and D'Antonio, 2004).

ISO STANDARD 10534-2:1998

Background Theory

This ISO standard is based on the theory of transfer function method for sound propagating in a tube. Chung and Blaser (1980) introduced a variation for the already known two-microphone method where the acoustic transfer function H_{12} is calculated as a substitute of the spectral densities.

This method requires a two-channel FFT analyser and two spaced microphones.

In summary, instead of working with the convolution integrals and their Fourier transforms, Chung and Blaser's expression for the reflection coefficient can be derived as follows (assuming we are working with plane waves in an inviscid moving medium):

$$p_1(\omega) = A(\omega)e^{jk+z_1} + B(\omega)e^{-jk-z_1}$$

$$p_2(\omega) = A(\omega)e^{jk+z_2} + B(\omega)e^{-jk-z_2} \quad (6)$$

where $k^{\pm} = \frac{k_0}{1 \pm M} = \frac{\omega}{a_0 \pm U}$ and the transfer function

$$H_{12}(\omega) = \frac{p_2(\omega)}{p_1(\omega)} \quad (7)$$

This can be rearranged to obtain the reflection coefficient as:

$$R(\omega) = \frac{B(\omega)}{A(\omega)} \frac{H_{21}(\omega) - e^{-jk^{+}(z_2 - z1)}}{e^{+jk^{-}(z_1 - z_2)} - H_{21}(\omega)} e^{+j(k^{+} + k^{-})z_1} \quad (8)$$

From (8) we can then readily obtain:

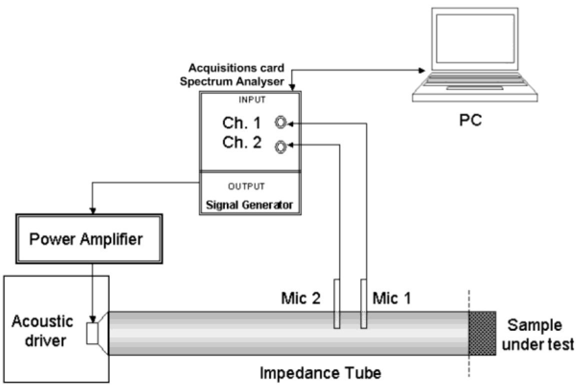
The absorption coefficient $\alpha_N(\omega) = 1 - |R(\omega)|^2$ (9)

The acoustic impedance $Z(\omega) = \rho_0 c_0 - \left(\frac{1+R(\omega)}{1-R(\omega)}\right)$ (10)

The acoustic admittance (ω)=1/ $Z(\omega)$ (11)

Procedure

In the two-microphone method the test starts by placing the sample at one end of the tube and calculating the first transfer function H_{12}. Then, and in order to compensate for the possible gain and phase mismatch of the two microphones, the measurement is repeated interchanging the two channels. The modulus of the equalised transfer function of the measurement is then obtained and equations (7) and (8) are used to find the absorption coefficient. Figure 2 displays the experimental setup to conduct such tests.



Source: Authors

Figure 2. Experimental setup for evaluation of acoustic properties of materials by means of the two-microphone method.

One of the main constraints of this method is the valid frequency range. Due to the fact that we are working with plane waves inside the tube, the working frequencies are defined by a range of frequencies set by the accuracy of the signal processing equipment for the lower limit, and by the diameter of the tube for the higher one. For the conducted measurements two Brüel and Kjær impedance tubes of 29mm and 100mm diameter have been used, allowing the measurement of a combined absorption coefficient between 100Hz and 5000Hz as required by the ISO standard.

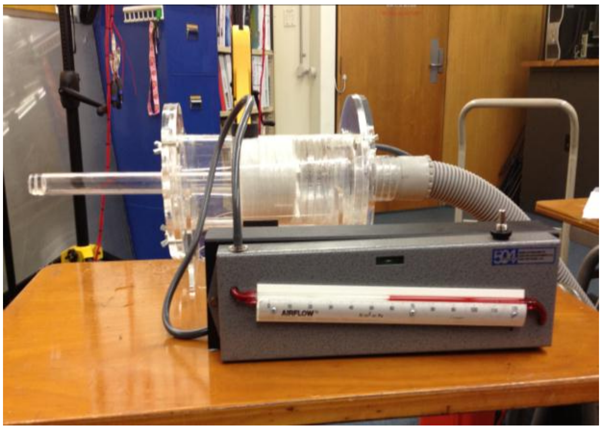
Rife & Vanderkoy (1989) and Farina (2000) proposed a more efficient method to conduct the test by using a deterministic signal such as a maximum length sequence or swept sine wave instead of broad-band noise referred in the standard. However, due to the fact that we are comparing two ISO standards we have decided to follow the standards as closely as possible.

Flow resistivity Measurements

The sound absorption of porous materials is related to airflow resistance due to an increase in friction and viscosity within the material. This increase typically leads to a higher absorption coefficient (Seddeq, 2009). Lee & Jou (2003) investigated the sound absorption properties for polyester and concluded an increase in absorption coefficient for a fine denier blend compared to a coarser denier blend.

In our case, two different denier fibre blends were tested with the same configurations of thickness and density (with the exception of the 100mm, see Figure 4). The flow resistivity measurements were conducted in accordance with ASTMC522-3 "Standard Test Method for Airflow Resistance of Acoustical Materials".

The equipment used to conduct the airflow resistivity tests included: airflow sample apparatus, TSI Series 4000/4100 flow meter, Mi TF2151 power supply and an airflow developments manometer type 504. The airflow resistivity apparatus used for the measurements is demonstrated in Figure 3.



Source: Authors

Figure 3. Airflow resistivity apparatus.

MULTIVARIATE LINEAR MODEL

The main goal of this study was to evaluate the relationship between two sets of absorption measurement data obtained by two different methods while taking into consideration the influence of the main variables in the problem. Among several possible ways of achieving this, we opted for using what is commonly known in statistics as Multivariate Linear Models (MLM). Timm (1975) describes the MLM as:

$$\mathbf{Y} = \mathbf{X}\,\mathbf{B} + \mathbf{E} \quad (12)$$

Wherein our case, $\mathbf{Y}$ is an $n \times m$ matrix of responses; $\mathbf{X}$ is an $n \times p$ design matrix with intercepts $x_{i0} = 1$ for all i; $\mathbf{B}$ is a $p \times m$

matrix of regression coefficients, one column for each response variable and **E** is an $n \times m$ matrix of errors.

In our model, each observation corresponds to the measurement at a particular frequency in third octave bands from 100Hz to 5000Hz with the corresponding values for thickness, density and flow resistivity. If we assume each **E** component in (12) is independent and that each row is multivariately normally distributed with zero expectation and common covariance matrix $\varepsilon_i^T \sim \mathbf{N_n(0,\Sigma)}$ where Σ is a non-singular error-covariance matrix and $\mathbf{N_n}$ denotes the multivariate-normal distribution for *n* variables, then we can write the least square estimator as follows

$$\hat{\mathbf{B}} = (\mathbf{X^T X})^{-1}\mathbf{X^T Y} \tag{13}$$

Where (13) describes the maximum likelihood estimator of **B**, i.e. the matrix of coefficients that will minimise the error of our prediction while taking into consideration all the variables of the model. Further extensive information about multivariate models can be found in Everitt (2005) and Fox &Weisberg (2011).

Sampled population

The polyester fibre material used in this study has been manufactured in blankets with different densities, thicknesses, and fibre blends. Generally, the samples are formed by a combination of several deniers achieving significant different coarse fibres depending on the type of product. All samples are made of polyethylene terephthalate recycled up to 80% from plastic bottles. Although in some cases the blended samples can be compressed in order to obtain blankets of different thicknesses and densities, the samples used for this study were not compressed. Figure 4 below shows the matrix measurements used in this study; in summary, there are four densities, four thicknesses and two types of denier blends: Blend 1 and Blend 2.

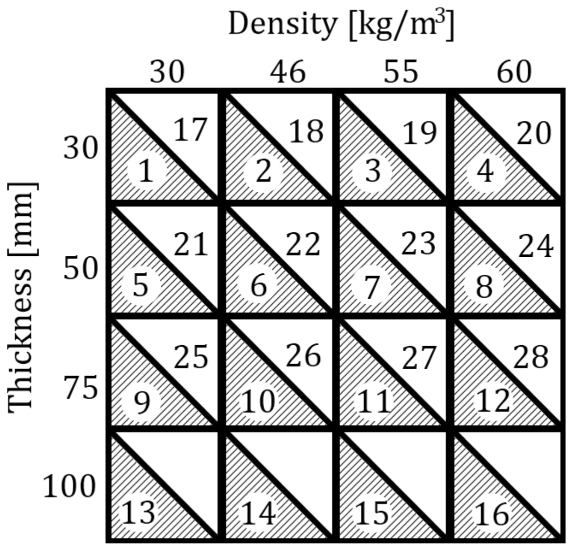


Figure 4. Variables summary of the samples used in this study. Tests #1 to #16 correspond to Blend 1, and tests #17 to #28 correspond to Blend 2.

Table 1 shows the differences of the nominal flow resistivity for the two types of fiber blends.

Table 1. Nominal flow resistivity comparison for the two types of fiber blends used in this study.

Density (kg/m^3)	*Thickness (mm)*	*Blend 1 (mksrayls/m)*	*Blend 2 (mksrayls/m)*
30	30	4931	7152
30	50	4963	6379
30	75	5044	7459
30	100	5041	n/a
46	30	7341	12841
46	50	7417	11188
46	75	7790	10567
46	100	7559	n/a
55	30	9922	19309
55	50	9881	18953
55	75	10061	18685
55	100	10103	n/a
60	30	11419	21941
60	50	11133	20221
60	75	11339	20861
60	100	11014	n/a

RESULTS

This section presents a summary of the variables that have been taken into account in this study: thickness, density, and flow resistivity and that are likely to influence the acoustic performance of sound absorptive materials.

Thickness: Previous studies from Ginn (1978) and Coates and Kierzkowski (2002) reported a clear correlation between the thickness of a material and its absorption coefficient values. Figure 5 shows a similar trend for both methods. We can observe how the improvement of the absorption at low frequencies is directly proportional to the increase in thickness of the material.

Density: The density of the absorption material is often used as a parameter to define its acoustic efficiency. For instance, when defining the insulation within a double wall system the density is usually specified to ensure the partition will achieve the required performance. In a previous study Koizumi *et al.* (2002) showed the increase of sound absorption value in the middle and higher frequency as the density of the sample increased. From the results obtained in our study we have observed that generally, an increase of density will result in a better absorption performance. However, as it can be seen in Figure 6, although the difference in kg/m^3 is almost the same, it is noticeable that the differences between the $46kg/m^3$and $60kg/m^3$are less apparent than those between the $30kg/m^3$ and $46kg/m^3$.

Flow resistivity: Another important quality of the sound absorbing characteristics of a fibrous material is the specific flow resistance per unit thickness of the material. Figure 7 shows the combination effect of the thickness, density and flow resistivity in function of the sound absorption coefficient SAA (as defined in ASTMC423-9a). It is interesting to see how the SAA increases with thickness and density, however, the differences between ~10,000 mksrayls/m and ~11,000 mksrayls/m are negligible.

In addition to the information provided by the graphs we have also developed several multivariate models to assess the accuracy of each of the models. Different combinations of variables have been used to test the robustness of each case. This process has been used to ensure that all the variables that have been taken into consideration are the necessary ones to achieve the best fit. So in summary, the thickness, density and flow resistivity were necessary to achieve the best correlation between the two sets of data.

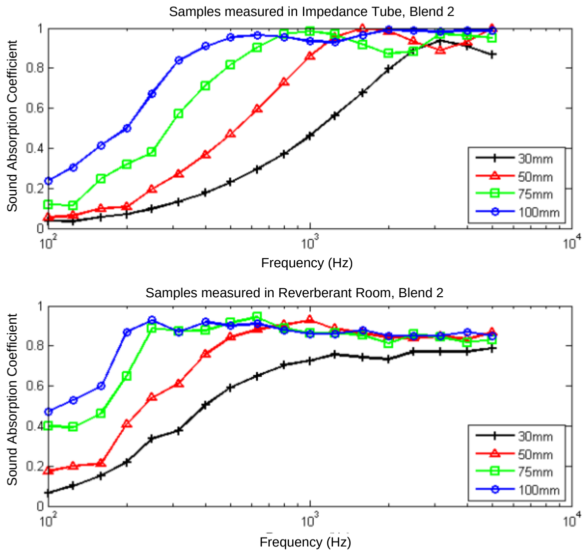


Figure 5. Dependence of the absorption coefficient on thickness. Constant density 55Kg/m^3, Blend2.

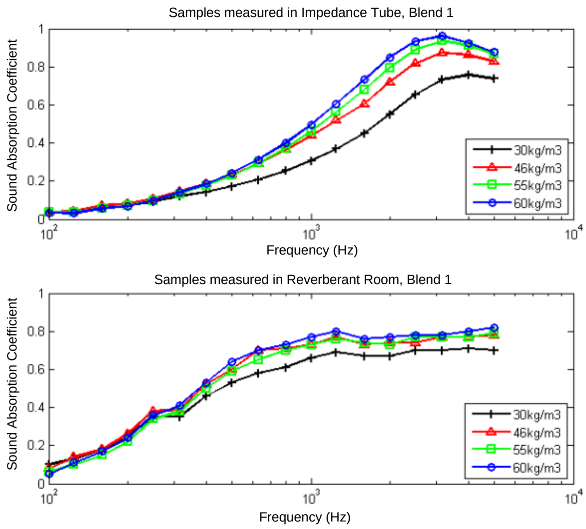


Figure 6. Dependence of the absorption coefficient on density. Constant thickness 50mm, Blend 1.

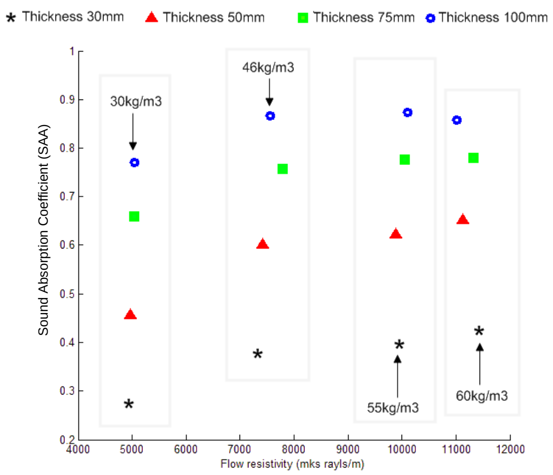


Figure 7. Dependence of the absorption coefficient on flow resistivity, Blend 1.

Note on the divergence of the measurements

The laboratory repeatability is one of the main critiques to the ISO standard methodologies. A number of round robins have taken place to identify the weaknesses and strengths of both methods.

Haines (1989) and Horoshenkov (2007) have reported significant differences between impedance tube measurements made at different laboratories. It is complex to strictly attribute the differences to the methodology without noticing the possible differences between samples characteristics, i.e. any physical property of a material (thickness, density, etc.) which is based on a nominal value but it is expected that tolerances up to 10% may exist due to production processes. It is easy to envisage that a 10% increment in thickness in a sample that is 29mm thick could have a significant impact on its acoustic performance in the impedance tube.

Similarly, significant differences have also been reported by the round robins conducted on the reverberation room method. Kath (1983), ASTM Internal report (1990) and Vercammen (2010) have showed results of tests conducted within different laboratories.

With all, these differences/measurement errors have not yet been incorporated in the statistical model and this subject remains open to further investigations.

The model

Our model has been implemented using the “R package” software. The first step for building the statistical model is to evaluate the level of linearity of the input data. Since the algorithm we are proposing to use is linear, we need to ensure that the relationship between our variables is also linear. To do so we have plotted the main input and output variables of our model, i.e. all the results obtained in the impedance tube against all the results from the reverberation room. This result is shown in Figure 8 below. As it can be seen the relationship between the two variables is far from linear, in fact it looks more like a logarithmic relation. Notwithstanding that, we know we can make use of mathematical transformations to linearise the data. Thus, we proceeded to transform the impedance tube absorption values into the natural logarithm of the input data. The results can be seen in Figure 9. We can observe how this transformation will achieve its purpose of converting the relationship between the two methods in a linear one.

Once the main input/output variables have been determined we can proceed to evaluate the remaining variables of the problem, i.e. frequency, density, thickness and flow resistivity. One of the important steps when defining a multivariate model is to correctly categorise the variables according to its weighting in the output results. This means that in an iterative process we have gauged the effect of any individual variables in order to evaluate their impact. In order to achieve this we have looked at the R-squared values of the fitting model to establish the “robustness” of each individual model.

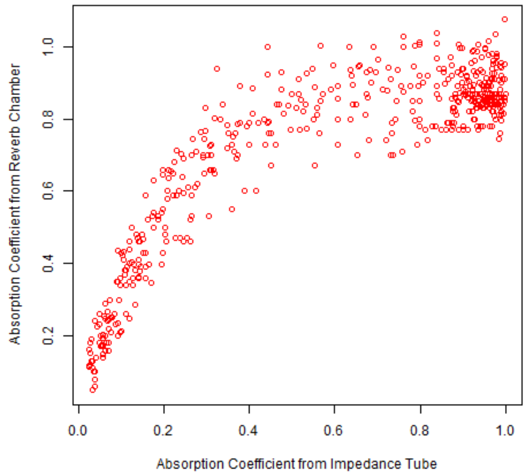


Figure 8. Scatter plot of raw input and output variables.

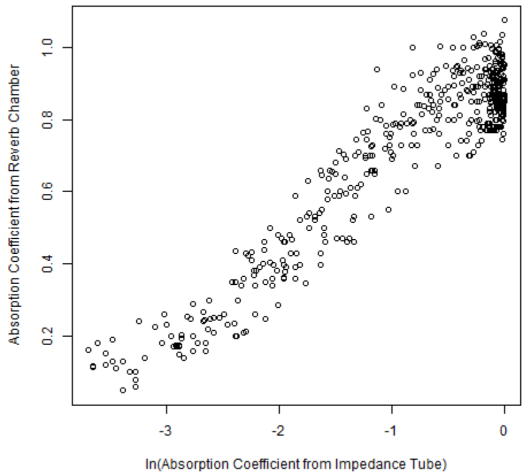


Figure 9. Scatter plot of natural logarithm transformation on input variables to linearise the model.

The result of this iterative process showed that we have to use frequency as a *factor* variable and density, thickness and flow resistivity as *continuous* variables. The main difference between these two types of variables is the impact on the prediction. *Factor* variables increase the number of degrees of freedom in our system and will not allow any interpolation during the prediction, i.e. any attempted forecast with our model will be based on the same values we used as a factor. Given we are working with third-octave band values we do not see this as a problem at all. However, the *continuous* variables will allow us to interpolate any value within the used range. For instance, we have used the following thicknesses: 30mm, 50mm, 75mm and 100mm, so in our estimates we will be able to predict any thickness between 30mm and 100mm.

Finally, after the model is linearised and the input variables have been defined, we can proceed to obtain our best fitting coefficients, i.e. the estimator $\hat{\mathbf{B}}$ from (13). These values are shown in equation (14) and Table 2.

$$\alpha_r(f) = 0.945 + 0.245\ln(\alpha_n) + \phi(f) - 0.002\,\delta + 0.0015\,\Theta + 7.52e^{-6}\rho \tag{14}$$

Where α_r is the predicted random incidence sound absorption coefficient; α_n is the measured normal incidence sound absorption coefficient; $\phi(f)$ are the frequency factor coefficients (shown in Table 2) and δ, Θ and ρ are the density, thickness and flow resistivity properties of the measured sample.

Table 2. Frequency *factor* coefficients, $\phi(f)$

Frequency (Hz)	$\phi(f)$
100	0.000000
125	0.006276
160	-0.082530
200	0.036260
250	0.110300
315	0.064040
400	0.098280
500	0.094280
630	0.078040
800	0.056560
1000	0.036920
1250	0.010380
1600	-0.025150
2000	-0.040960
2500	-0.047400
3150	-0.045580
4000	-0.048560
5000	-0.044970

Figure 10 shows two examples of the predicted values obtained using equation (14). As we can see, the correlation is reasonably good, achieving overall R-squared values of 0.9556 for the entire sampled population. R-squared makes reference to the squared values of the sample correlation coefficient between the measured response and their predicted values, so the closer to 1 the better.

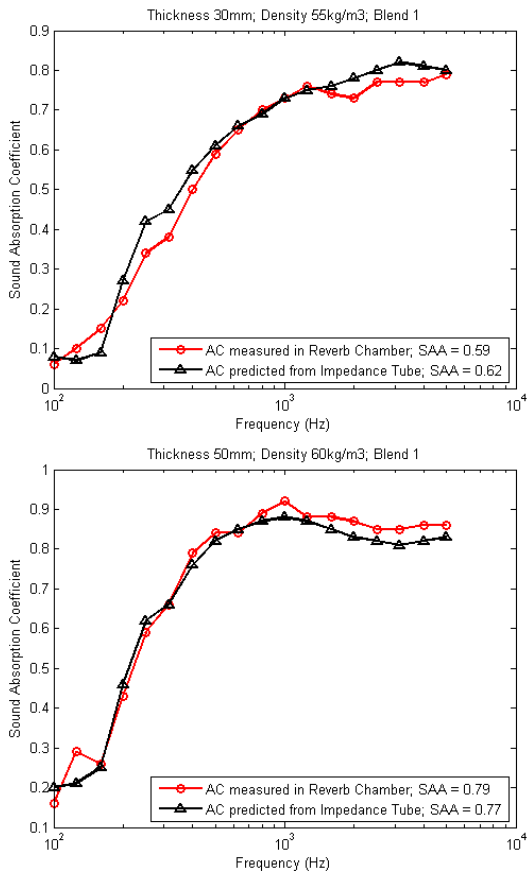


Figure 10. Comparison of the measured absorption values versus the predicted ones.

As a first step to evaluate how well the model predicts the measured data we have plotted the differences, in function of the frequency, of all the tested samples. Figure 11 shows these differences in a box-plot format. This graph aims at providing information about the errors between the two sets of data (measured and predicted). The data is organised in the following sets: the extremes, the upper and lower hinges (25% and 75% quartiles respectively) and the median. The first incorporates a measure of the group size (maximum difference between optimum value and the maximum error), the second incorporates an indication of rough significance between medians and the third combines the features of the first two. In addition, we can also see the outliers (red circles); Moore and McCabe (1999) defined the outliers as "observations that lie outside the overall pattern of a distribution".

As it can be seen in Figure 11, the median error for most frequencies is close to 0, having the biggest deviations at 200Hz, 250Hz and 315Hz. This is not surprising as we are aware, based on our measurements, that the reported 95% interval confidence at these frequencies is generally higher than for other frequencies.

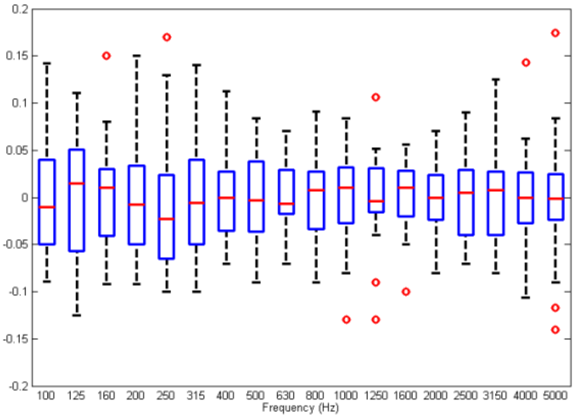


Figure 11. Error difference of the absorption coefficient measured in reverberation room vs. the predicted absorption coefficient obtained from the impedance tube measurements.

In order to further ascertain the level of accuracy that our prediction method achieves, we proceeded to conduct a cross-validation analysis, which is a methodology to evaluate how well the results of our model will respond to another set of measurements. In other words, how well the model is expected to work when predicting data that have not been taken into consideration in the generation of the model. Thus, cross validation techniques tend to focus on not using the entire data set when building a model so few cases are removed before the model is built. These removed cases are called the testing set. The remaining set of measurements is called the training set, i.e. the fitting coefficients will be obtained only with the training set and then the robustness of the model is tested against the testing set. The used algorithm is based on the partition of the original sample data into k subsamples. Of the total k subsamples, k-1 are used for the training set and 1 is left for the testing. The validation process is then repeated k-fold times. Figure 12 presents the summary of the cross-validation exercise. Note we have arbitrarily chosen to show the graph with 10 k-folds, but it could be slightly increased or decreased without any major significant deviation of the results.

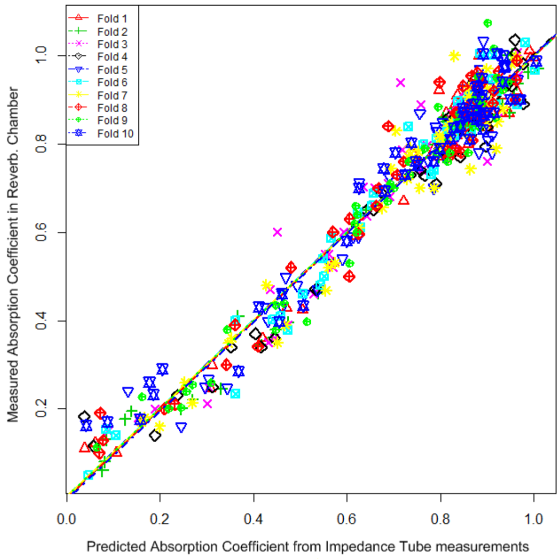


Figure12. Cross validation plot of each subgroup predicted values against the actual outcome variable for all 10 folds.

In addition, the algorithm also provides us with the cross validation residual sums of squares (overall *ms*), which is a corrected measure of prediction error averaged across all folds. Note this value is in the range of 1 (low correlation) to 0 (high correlation). The resulting overall *ms* in our model was 0.00306.

CONCLUSIONS

A new method relating the absorption coefficient measured in impedance tube and reverberation room has been developed in order to provide a better understanding of the relations between the two methods. 28 samples have been tested in 56 tests according to ISO 354:2006 and ISO 12354:1998 standards. The results of these tests have been compared with existing information and, in general, good agreement has been found between the absorption coefficients and density, thickness and flow resistivity values.

Moreover, a multivariate linear model has been implemented to analyse all the test data. This model has allowed us to obtain a number of regression coefficients in function of the frequency that can be used to predict the behaviour of a polyester blanket in the reverberation room based on the measurement of the same sample in an impedance tube.

A reasonably high correlation between the predicted and measured absorption coefficients has been found not only from the samples that were part of the experiment but also predicting results of samples that were not part of the model. This was achieved by means of the cross-validation process. Thus, we can conclude that the objective of the study has been achieved as we are in a position of being able to predict the random incidence sound absorption coefficient of a given polyester sample (within a range of thicknesses, densities and flow resistivities) with a good degree of accuracy based on the measurement in an impedance tube.

One of the main outcomes of this methodology is the cost efficiency and time reduction expected during the product development of a new type of material by manufacturers. Insulation producers could potentially use this method to target a specific product that achieves the best performance in function of its properties and maybe even including the manufacturing cost as a variable of the model.

Future works

We believe that this new method has a lot of potential for product development of absorption materials. At the same time there are a number of issues that should be further investigated in order to improve its prediction capabilities:

- Extrapolation of the results to other types of materials. We are quite confident that we can predict the random incident absorption coefficient of a polyester type material based on its measurement in the impedance tube. However, further analysis needs to be conducted to assess the similitudes and differences with other types of material such as glass wool or rockwool.
- Besides density, thickness and flow resistivity, there are other variables / material properties that could be included in the study to allow us refine the prediction method, e.g. tortuosity, porosity, compression, surface lamination, position of samples, air cavity, etc. All these other variables could be included within a single model.
- More analysis is required in relation to error management. Both ISO standards and the statistical model carry significant errors that could be further analysed.
- With the collected data it may be worth trying to find the inverse of the correction factor found, i.e. a correction that allows us to convert any random incidence absorption coefficient values greater than one into a capped version of the same material that could easily be used in the day-to-day calculation methods.
- The manufacturing cost/difficulty of the product could be incorporated as a continuous variable in the statistical model so the prediction of a new material will take into consideration these variables when designing a new product.

Acknowledgements

The authors wish to thank *Polymax Insulation by Martini Industries Pty Ltd.* for their financial support and permission to publish data, to Ken Stewart and Manuj Yadav for their testing support and to F.X. Magrans for his original idea about this paper.

REFERENCES

ASTM International, 1990, *European Sound Absorption Round Robin Test*, Internal Report.

ASTM International, 2003, *Standard Test Method for Airflow Resistance of Acoustical Materials*, ASTM C522-03.

ASTM International, 2009, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, ASTM C423 - 09a.

Bassett J, Spargo D & Cabrera D, 2010 'Using an ambisonic microphone for measurement of the diffuse state in a reverberant room', *Proceedings of 20th International Congress on Acoustics*, ICA 23-27 August 2010, Sydney, Australia.

Chung, JY, Blaser, DA, 1980, 'Transfer Function Method of Measuring In-Duct Acoustic Properties I & II', *Journal of the Acoustic Society of America*, Volume 68, No. 3, Sept.

Coates M, Kierzkowski, M, 2002. '*Acoustic Textiles - Lighter, Thinner and More Absorbent*', Technical-Textiles-International.

Cox, TJ, D'Antonio, P, 2004, *Acoustic Absorbers and Diffusers*, Taylor& Francis, New York.

Everitt,BS, 2005, *An R and S-plus companion for multivariate analysis*, Springer, London.

Farina, A, 2000, 'Simultaneous measurement of impulse response and distortion with a swept-sine technique', *Proceedings 108th Convention Audio Engineering Society*, Paris 18–22 February.

Fox J, Weinberg, S, 2011 '*Multivariate Linear Models in R'* An Appendix to An R Companion to Applied Regression, Sage, Thousand Oaks, CA, Second edition.

Ginn, KB, 1978, *Architectural Acoustics*, B&K Instruments.

Haines, J, 1989, *'Standing wave and two-microphone impedance tube round-robin test program'*, ASTM Research Report RR:E33-1006.

Horoshenkov K V et al., 2007, 'Reproducibility experiments on measuring acoustical properties of rigid-frame porous media (round-robin tests)', *Journal of Acoustical Society of America*, 122(1), 345–53.

International Organization for Standardization, 1993, *Acoustics –Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere*, ISO9613-1:1993, International Organization for Standardization, Geneva.

International Organization for Standardization, 1998, *Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method*, ISO10534-2:1998, International Organization for Standardization, Geneva.

International Organization for Standardization, 2006, *Acoustics - Measurement of sound absorption in a reverberation room*, ISO354:2006. International Organization for Standardization, Geneva.

Kath U, 1983, 'A reverberation room round robin on the determination of absorption coefficients', *Acustica*, 52 (4): 211-215.

Kuttruff, H,1991,*Room Acoustics*. 3rd ed. Elsevier Applied Science, London.

Maindonald, J. Braun, J. 2011, Package 'DAAG' [online], Available from: http://cran.rproject.org/web/packages/DAAG/index.html

Makita Y, Hidaka, T, 1987, 'Comparison between reverberant and random incident sound absorption coefficients of a homogeneous and isotropic sound absorbing porous material– experimental examination of the validity of the revised cos θ law', *Acustica*, 66, 214–20.

Olynyk, D, Northwood, TD, 1964, 'Comparison of Reverberation-room and Impedance-tube Absorption Measurements' The *Journal of Acoustical Society of America*, Vol. 36, No. 11, 2171 – 2174, November.

R Development Core Team, 2012,'R: A language and environment for statistical computing. R Foundation for Statistical Computing', Vienna, Austria. ISBN 3900051070

Rife, DD,Vanderkooy J, 1989 'Transfer function measurement with maximum-length sequences', *Journal of the Audio Engineering Society*, 37(6), 419–43.

Sabine WC,1922, *Collected Papers on Acoustics*, Cambridge (MA), Harvard University Press.

Sauro R, 'Absorption coefficients-part 2: is "edge effect" more important than expected?' *Internoise*, Ottawa, 23-26 August.

Seddeq, 2009 'Factors Influencing Acoustic Performance of Sound Absorptive Materials'. *Australian Journal of Basic and Applied Sciences*, 3(4): 4610-4617.

Timm, NH, 1975, *Multivariate Analysis and applications in education and psychology*, Brookes/Cole, Belmont CA.

Vér, IL, Beranek, LL, 2005, *Noise and Vibration Control Engineering*, Wiley & Sons, New Jersey.

Vercammen, MLS, 2010, 'Improving the accuracy of sound absorption measurement according to ISO 354', *Proceedings of the International Symposium on Room Acoustics, ISRA 2010*, 29-31 August 2010, Melbourne, Australia.