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CONSOLIDATED GRANULAR MEDIA FOR SOUND INSULATION: PERFORMANCE EVALUATION THROUGH DIFFERENT METHODS

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Abstract

Recent studies indicates that loose granulated samples of recycled materials can be mixed with a binder and pressed into consolidated, elastic, porous media combining good mechanical and acoustical properties. Four different samples of these types of materials have been measured in a standing wave tube employing the four-microphone technique to determine the normal incidence transmission loss. Different acoustic terminations and methods of data analysis have been used and compared in terms of accuracy and repeatability. It has been shown that the accuracy of some techniques depends on the type and quality of the acoustic termination and on the acoustic properties of the tested samples. The experimental results have been compared favourably with numerical predictions based on a simple model for poroelastic plates. A high insulation performance has been observed in the case of low-density, high-flow resistivity consolidated recycled foams. These materials offer good absorbing and insulating performances, relatively low density and high structural strength.

INTRODUCTION

Transmission loss measurements by means of coupled reverberation rooms are not the best solution for material testing, as they require large samples and long time.

Measurements by means of an impedance tube demonstrated to be useful provided that the chosen analysis method is able to give reliable results.

Recent research indicates that loose granulated samples of recycled materials can be mixed with a binder and pressed into consolidated, elastic, porous media combining good mechanical and acoustical properties [1].

Recently Song *et al.* [2] determined, through the four-microphone transfer function technique, the normal incidence transmission loss of samples of fibrous materials by means of an impedance tube and a dissipative (approximately anechoic) termination. The experimental setup has been reproduced at the University of Bradford to carry out tests on porous granular samples of different materials, e.g. consolidated flint, recycled foam and recycled rubber. Different methods of data analysis have been used: one-load and two-load methods, employing dissipative, open boundary and hard acoustic terminations. The experimental results indicate that, depending on the material under test, considerable difference can be expected between the methods and that care must be taken handling the recorded signals.

THEORETICAL BACKGROUND

The experimental apparatus (Figure 1) consists of a stainless steel standing wave tube (inner diameter 82.5 mm) divided in two sections: an upstream section terminated at one side by the sound source and a downstream section with an acoustic termination. Each section has three 1/4" microphone holders. Between the two sections a sample holder allows mounting samples of different thickness and sealing the tube allows to reduce the amount of acoustic energy exchanged via the flanking transmission pass. A microphone spacing of 50 mm was used to ensure accuracy at the medium frequencies (around 2 kHz). The expected working frequency range of the apparatus is between 100 and 2000 Hz. A single roving microphone was used to detect signals in four different positions along the tube: this approach avoided the need of an accurate calibration procedure for compensating channels' responses.

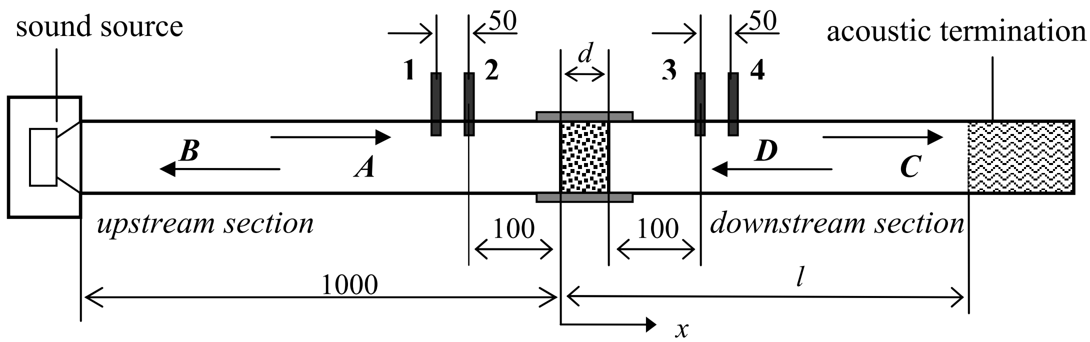

Figure 1 – Standing wave tube geometry for the plane wave decomposition procedure. Dimensions are in mm.

The MLS technique was used for impulse response acquisition (sampling frequency 22050 Hz, order 16, 8 averages). Appropriate Matlab® subroutines were developed to carry out post-processing of the signal.

From the four frequency responses recorded mounting the microphone in positions 1 - 4, it is possible to calculate the complex amplitudes *A-D* [2] of the forward and backward propagating plane wave components in the up- and downstream tube sections (see Figure 1). The complex wave amplitudes can be correlated in a matrix equation, where the matrix coefficients depend just on the properties of the sample:

$$\begin{Bmatrix} A \\ B \end{Bmatrix} = \begin{pmatrix} \tau & \beta \\ \gamma & \delta \end{pmatrix} \begin{Bmatrix} C \\ D \end{Bmatrix}, \tag{1}$$

The latter is a very general formula: indeed, physical meaning can be given to the matrix coefficients, as it will be shown afterwards. In particular, the normal incidence transmission coefficient is $T = \tau^{-1}$. The so-called transmission loss can then be calculated in dB using its usual definition $TL = 10\log_{10}\left(\left|T^{-1}\right|^2\right)$.

An approximately anechoic termination was created stacking layers of natural wool and progressively more dense glass fibres. Its normal incidence absorption coefficient was independently determined (Figure 2). Following Chung and Blaser [3], a perfectly anechoic termination assumption has firstly been used to carry out *TL* calculations. Using the mentioned hypothesis (D = 0, see Figure 1), the transmission coefficient T_a can be determined from a single measurement session as follows:

$$T_a = \frac{1}{\tau_a} = \frac{C}{A}, \tag{2}$$

where the suffix *a* stands for the anechoic termination method.

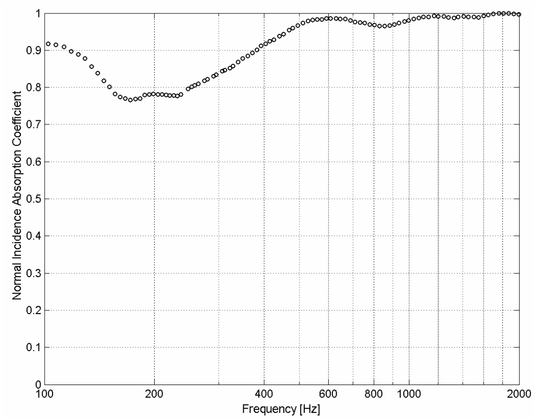

Figure 2 - Normal incidence absorption coefficient (with no backing) of the dissipative termination used in the experiment.

Then the two-load method [4] has been investigated. This method involves measuring in sequence the frequency responses with a modified tube termination. The only requirement is that the chosen terminations are sufficiently different, e.g. an open-end boundary condition and a hard one (heavy steel screwed plug in Figure 3 (a)) can be used in this case. It is then possible to solve the matrix Eq. (1) as follows:

$$T_{tl} = \frac{1}{\tau_{tl}} = \frac{C_I D_{II} - C_{II} D_I}{A_I D_{II} - A_{II} D_I}, \tag{3}$$

where suffices *I* and *II* denote the different terminations and *tl* stands for the two-load method.

The relationship between the above-mentioned methods can be found considering the case of a termination of known impedance or, that is equivalent, of known reflection coefficient R_t. It has been shown by the authors [5] that T_a as calculated in Eq. (2) depends not just on the transmission coefficient of the sample T, but even on the downstream section geometry (l, see Figure 1), the termination reflection coefficient (R_t) and the sample acoustical properties (β). Even if $|R_t|$ is small throughout the considered frequency range of 100-2000 Hz, a significant error could occur while evaluating the transmission loss if the perfectly anechoic termination were assumed. In particular, employing Eq. (2) for the tested materials resulted in the instabilities in the predictions. Such an effect is not evident in the results obtained for low-density glass fibres by Song *et al.* [2], probably because of the characteristics of the materials they tested. Indeed, this effect is likely to be more pronounced in case of materials with low to medium porosity and high flow resistivity [5] which are characteristic to the tested materials.

As a result, a single measurement with a non-perfectly anechoic termination is likely to yield errors, unless further hypothesis are assumed. Many authors [6] in the past noticed that it is possible to presume that the transmission coefficient of the sample is identical in both directions (condition of reciprocity). This means to assume that $D = \tau B + \beta A$ (see Figure 1). Such hypothesis has recently been employed by Liu *et al.* [7] to develop a revision of Chung and Blaser's formula [3] for *TL*. It can be shown that, using such method, the matrix Eq. (1) gains a straightforward physical value and can be rewritten as follows:

$$\begin{Bmatrix} A \\ B \end{Bmatrix} = \begin{pmatrix} \tau & \beta \\ -\beta & \left(1-\beta^2\right)/\tau \end{pmatrix} \begin{Bmatrix} C \\ D \end{Bmatrix} = \begin{pmatrix} T^{-1} & -R/T \\ R/T & (T^2 - R^2)/T \end{pmatrix} \begin{Bmatrix} C \\ D \end{Bmatrix}, \tag{4}$$

$$T_r = \frac{1}{\tau_r} = \frac{AC - BD}{A^2 - D^2}, \tag{5}$$

where R is the normal incidence reflection coefficient of the sample and the suffix r stands for the reciprocity method. Eq. (4) can be directly solved using the results of a single measurement, avoiding any assumption on the nature of the termination. A similar approach is the so-called transfer-matrix method developed by Song *et al.* [6].

EXPERIMENTAL SETUP AND RESULTS

Figure 3 shows the photographs of the transmission loss tube used in the experiments (a) and the tested samples of four different porous materials (b). The materials were made from flint particles (sample C), recycled automotive foam particles (samples F1 and F2) and recycled tyre rubber particles (sample R) consolidated with an epoxy-rubber or polyurethane binders.

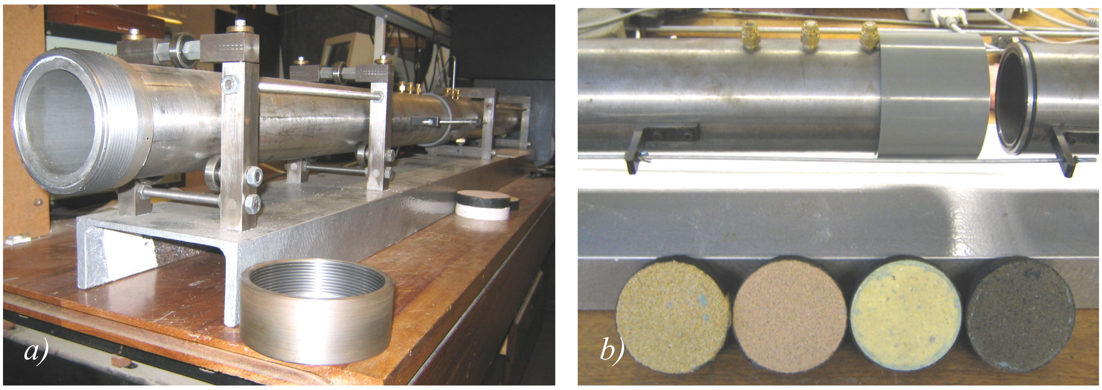

Figure 3 - Experimental setup used for the measurements: a) view of the standing wave tube from the downstream section side, b) the four tested samples and the tube sample holder.

Padé approximation model was used to predict the acoustic response of the samples and then their *TL*, according to Horoshenkov *et al.* [8]. Table 1 presents a summary of the non-acoustical properties of the tested materials which were used as input data for the model.

Table 1 – Non-acoustical properties of the tested samples.

	R	**C**	**F1**	**F2**
Material	**recycled rubber**	**consolidated flint**	**recycled foam**	**recycled foam**
Flow resistivity σ [kPa s m^{-2}]	18.3	46	190	1 358
Open porosity Ω	0.36	0.40	0.8	0.8
Tortuosity q	1.36	1.34	2.52	2.6
Pore size standard deviation [ϕ units]	0.35	0.31	0.31	0.3
Young's elastic modulus E [MPa]	1.7	62	23	20
Poisson ratio ν	0.35	0.3	0.35	0.35
Bulk density [kg m^{-3}]	1050	1455	418	400
Plate thickness d [m]	0.02	0.02	0.021	0.02

The *TL* experimental results for the four samples are provided in Figure 4 (a), both for the two-load method and for the anechoic termination method. Significant differences between the two (more than 5 dB) can be observed for samples F1 and F2. Figure 4 (b) presents the measured transmission loss data which is obtained using the two-load method and compared against the prediction. The predicted and experimental data match well for samples R and C. The agreement between the measurement and prediction in the case of samples F1 is less close, particularly in the medium frequency range. Such phenomenon may be attributed to the edge constraint's effect investigated by Song *et al.* [2]. This effect is not included in the adopted theoretical model. Measured data for sample F1 shows a minimum around 600 Hz, below which the *TL* increases to a finite limit that can be predicted using the theory detailed in [2]. According to this work a low frequency *TL* limit of 15 dB can be predicted in the case of sample F1, consistently with the experimental data.

Predicted data for sample F2 is not shown as it is believed that its mounting conditions have had a strong influence on the measured performance, in particular in the higher end of the frequency spectra. Similar behaviours (see Figure 4 (a)) have been observed and modelled by Bolton *et al.* [9] in foam-lined aluminium panels. Nonetheless, its non-acoustical properties could not be determined with adequate accuracy.

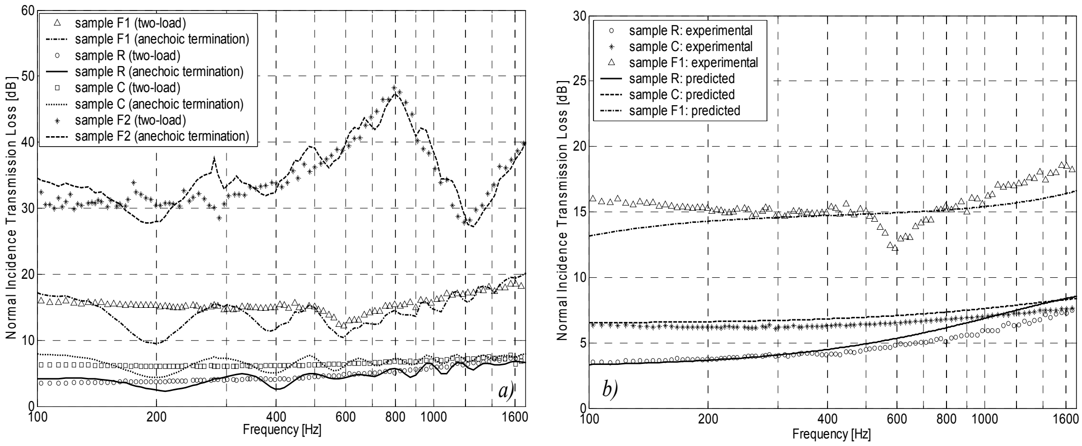

Figure 4 – a) Transmission loss measurements with the anechoic termination and the two-load method (open-end and hard terminations); b) Comparison between predicted and measured (two-load method) values of Transmission Loss for samples R, C and F1.

The two-load method shows a good repeatability for which the data is presented in Figure 5 (a) (samples R, C and F1). It is likely that the upper limit of this type of measurements is reached due to the flanking transmission along the tube for sample F2 (Figure 5 (b)). Further predictions show that the flanking transmission coefficient at the lower frequencies is around 0.03 which corresponds to a maximum measurable *TL* of 30 dB. This is likely to affect the repeatability of the experimental method.

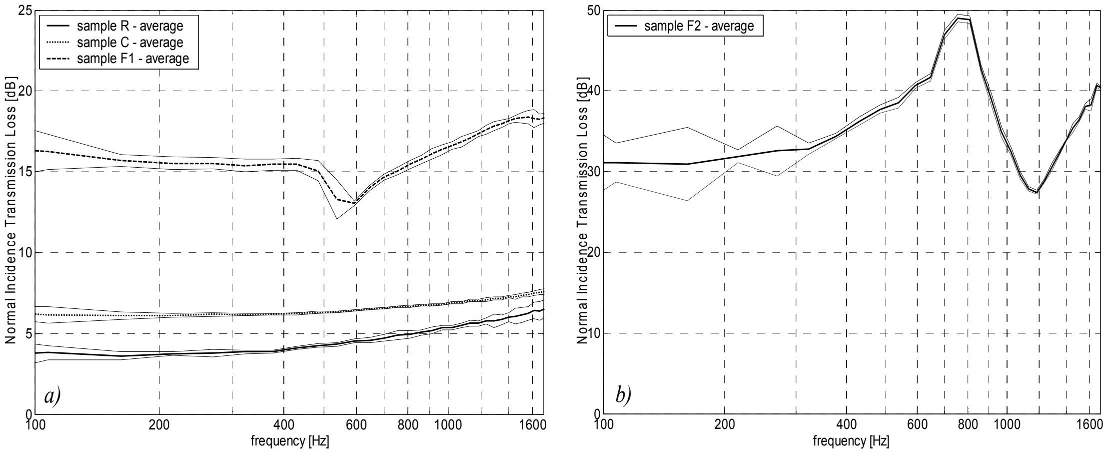

Figure 5 – Average TL data (two-load method with open-end and hard terminations) and 95%-confidence limits (thinner lines). a) sample R, C, and F1; b) sample F2.

Figure 6 presents the results obtained through the two-load method using different combinations of the dissipative, open-end and hard acoustic terminations, in comparison with those given by the reciprocity method. Data for the sample C (a) shows a very similar behaviour for all the methods; small fluctuations appear for the reciprocity method employing the hard and open-end terminations. Similar notes can be made analysing the results for sample R. A different behaviour is evident from the data for sample F1 (b): in this case, the two-load method with the open-end and hard terminations gives the least data dispersion. This may confirm what has been already noticed by Bolton *et al.* [9] for foams: waves different from the longitudinal airborne wave can be supported by these materials and sometimes contribute significantly to their transmission properties. A reciprocity assumption could be not entirely correct in these cases and the choice of the most accurate techniques relies on the type and quality of the acoustic termination and on the acoustic properties of the samples.

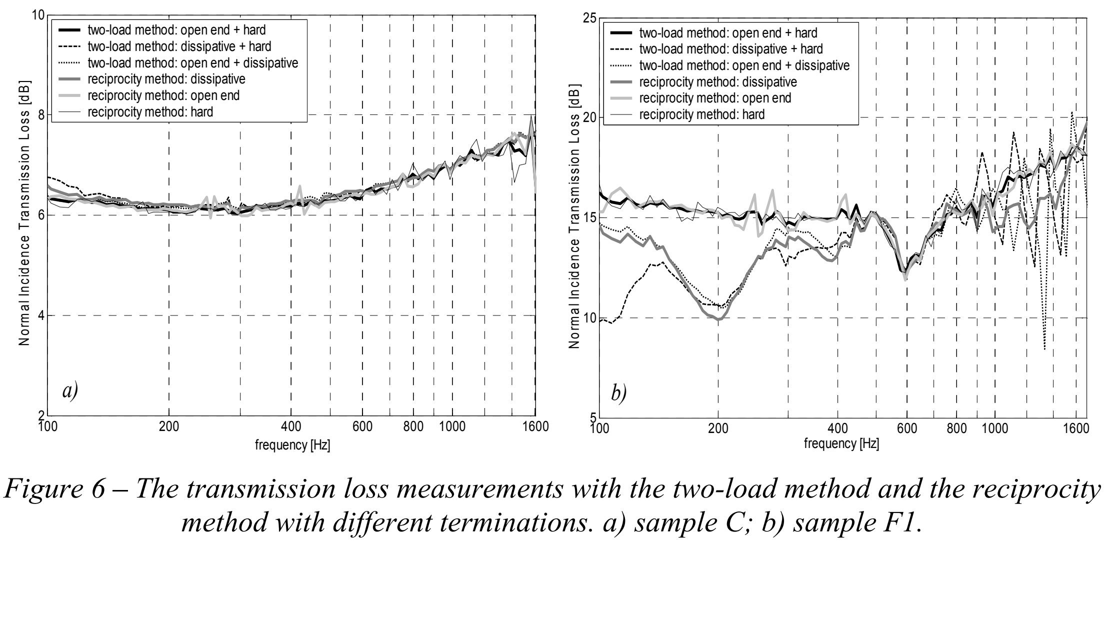

Figure 6 – The transmission loss measurements with the two-load method and the reciprocity method with different terminations. a) sample C; b) sample F1.

CONCLUSIONS

Utilization of recycled materials could represent a sustainable alternative to virgin insulating products. Normal incidence transmission loss data for consolidated granular samples of different materials shows good insulating performance, together with relatively low density and high structural strength. In this work, four samples of different consolidated granular media have been tested by means of the four-microphone technique in an impedance tube. Different analysis methods have been examined, finding a dependence of their accuracy on several parameters, such as the properties of the employed acoustic termination and of the tested sample. It is believed that one-load methods, as the anechoic termination method and the more accurate reciprocity method, lead to fast and reliable tests on low flow resistivity materials (e.g. fiber glass, consolidated rubber grains and flint). Two-load methods, on the other side, seem to be more suitable for high flow resistivity and more complex materials, such as consolidated granular foams.

ACKNOWLEDGEMENTS

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