Forum Acusticum 2011 - Aalborg - Denmark

Relating manufacturing parameters and material microstructure to acoustic properties of recycled polymers

François-Xavier Bécot, Luc Jaouen, Fabien Chevillotte
MATELYS - Acoustique & Vibrations, 20/24 rue Robert Desnos, F-69120 Vaulx-en-Velin, France

Amir Khan, Kirill V. Horoshenkov
School of Engineering, Design and Technology, University of Bradford, BD7 1DP, United Kingdom

Summary
Recycling polymers is attractive to reduce the amount of industrial waste and to limit the traditional dependence on virgin petro-chemical products. In order to produce competitive acoustic products it is important to understand the relationships between the material microstructure and the manufacturing process parameters. This paper presents results of experimental tests of materials produced at ambient room temperatures using an energy efficient extrusion process. This process does not require any additional heat and can be applied to a mix of grain and fibers recovered from carpet waste. The tests carried out comprise the direct measurement of the static air flow resistivity and the open porosity together with measurements of the sound absorption coefficient in impedance tube. In addition, a complete characterisation of the acoustic, elastic and damping parameters are performed on a sample having optimised properties. Simulations are also realised to compare the efficiency of this type of material in typical multi-layer system used in buildings.

PACS no. 43.55.Ev,43.50.Gf

1. Introduction

Acoustical porous materials are widely used for sound absorption or sound insulation in buildings, transport and machinery industries. These materials are mainly made up of fibers (e.g. glass-wools, rock-wools, felts...) or made up of tree-dimensional networks of struts (e.g. polymer foams...).

Industries which uses these acoustical materials also consume a large amount of polymeric materials (e.g. tires, carpets, automotive dashboards....). At end-of-life these materials are partly recycled (shredded tires can be used in road surfacing) but the main part is still land-filled or incinerated.

In the mean time, governments are publishing a growing number of recommendations to recycle wastes and in particular polymeric materials. (cf. for example European directives 75/442/EEC - 2006/12/EC: Waste Framework Directive or EU Directive 2000/53/EC on end-of-life vehicles).

In this context, we present the use of recycled carpet wastes (found inside buildings or vehicles) as sound absorption materials. These hard backed carpet tiles are made up of nylon fibres and PVC granules, the ratio of carpet fibres to grains is 40%:60% respectively by weight. Residues from the shredding of the underlay, they will be used in the form of grains and fibers.

Unlike previous works offering a second life to polymer materials as sound absorption materials [1, 2], a mix of two components with various properties, grains and fibers, are used in this study. Moreover, a cold extrusion process [3] is used to manufacture the final acoustical materials which does not required heating of the components.

Firstly, the preparation of the components, grains and fibers from the carpet wastes, and the cold extrusion process technique are briefly presented.

Secondly, the influence of manufacturing variables (fiber length, grain size, binder level, water level and grain to fiber ratio) on the acoustic absorption performances of extruded materials are presented and discussed. From these results, optimal parameters to manufacture a valuable sound absorption material are identified.

Finally, the optimum material is manufactured and to go further in the understanding of the dissipation phenomena occurring within this material, an acoustical characterization is investigated.

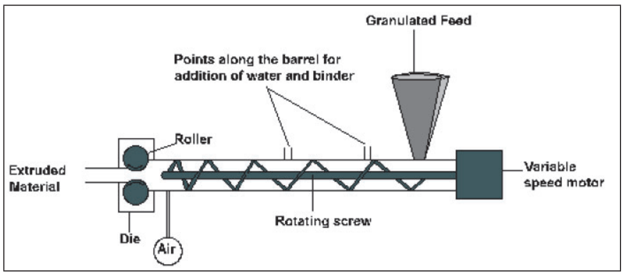

Figure 1. Principle of the extrusion process.

2. Material manufacturating using extrusion

2.1. Raw matter preparation

The matter preparation is composed of two steps which provide grains on one side and fibers on the other one. Wastes of a given chemical composition are fed into a triple blade, vertical granulator. The granulated output are then conveyed into a cyclone system that separated the raw mix into granular and fibrous components.

2.2. Extrusion process

A schematic view of the extruder used to manufature the studied materials is presented in Figure 1.

Grains and fibers, of controlled sizes and in controlled ratio, are fed from two distinct hoppers into a barrel containing a rotating screw. The barrel used for the experiments was 460 mm in length and the screw was 50 mm in diameter. Binder and water are added to the mixture while travelling through the barrel. At the end of the extruder the material resulting from the previous mixture passes through a die and is collected in a container.

Binder and water additions allow chemical reactions to take place with the matter components (see Khan et al. [4] for more information about these chemical reactions). These reactions are responsible for the apparition of bonds between grains and fibers and the release of carbon dioxide gas. This gas release produces pores inside the material. During a curing operation of the material (around one hour at room temperature) liquid evaporates and pores continue to open under the gas pressure.

This technology presents advantages over usual recycled material production techniques such as the “batch technology” mixing of solid granules with a liquid binder in an agitated vessel followed by compaction and drying [5]). First, the whole manufaturing process is realized at room temperature, there is no need to heat up components. Second, the cold extrusion process is continuous, which is compatible with large production volumes.

Examples of extruded samples are shown in Figure 2. As observed on the right hand side picture, the resulting material morpholgy may be intricate, comprising small pores between the grains and the fibers and larger pores, the dimensions of which are at least an order of magnitude greater. This type of morphology may thus require adapted models accounting for the different scale of porosities, as discussed for instance in [6].

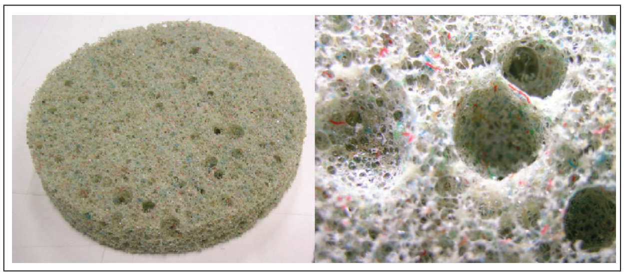

Figure 2. Samples of extruded material. Left : 100 mm diameter sample. Right : close-up on the structure morphology.

Table I. Reference values of extrusion process parameters.

Parameter	*Default value*
Screw speed	10 rpm
Flow rate	8 kg/hour
Ratio of water to binder	1:6 (16.7 %)
Grain size	3 mm
fiber length	2 mm
fiber to grain ratio	40-60 %

2.3. Influence of extruder variables on sound absorption

Changes in process parameters will change the overall chemical composition of manufatured materials and consequently modify vibro-acoustic properties of materials. To analyze these changes and provide information in order to obtain an optimized sound absorbing material, the influence of the following five process parameters will be studied: fiber length, grain size, water level, binder concentration, grain to fiber ratio.

From preliminary experiments, it has been chosen to keep the screw speed constant to 10 rotation per minute (rpm) to give the material sufficient residence time in the barrel, along with a corresponding reduction in the hopper feed rate to maintain an equivalent channel fill fraction. The target output was maintained to 8 kg/hour.

2.4. Experimental procedure

As a preambule, it should be underlined that the experiments are carried out at a laboratory scale. In other words, only small quantity of materials were produced. Thus no statistical analysis is reported in the present work. Work is in progress to discuss for

Table II. Material sample ID, mass density ρ, open porosity ϕ, static air flow resistivity σ and varying manufacturing parameter.

Sample	ρ	ϕ	σ	Parameter
				Binder (%)
ES30	198	0.89	60 400	10
ES31	110	0.92	35 500	20
ES32	105	0.93	6 500	30
ES33	53	0.97	3 800	40
ES34	34	0.99	3 500	50
				fiber / grain (%)
ES40	173	0.91	5 200	20-80
ES41	167	0.96	4 500	40-60
ES42	218	0.87	6 300	60-40
ES43	307	0.81	7 400	80-20
ES44	310	0.78	8 100	100-0
				Grain size (mm)
ES50	337	0.75	11 300	< 0.5
ES51	359	0.74	11 100	0.5-1.0
ES52	385	0.74	10 200	1.0-2.0
ES53	425	0.74	9 800	2.0-4.0
ES54	440	0.73	8 100	> 5.0
				fiber length (mm)
ES60	351	0.70	9 600	< 1 mm
ES61	305	0.72	8 200	2 mm
ES62	293	0.75	7 700	4 mm
ES63	292	0.79	6 500	5-6 mm
ES64	280	0.83	5 700	> 6 mm
	kg.m^{-3}	-	N.s.m^{-4}	

instance the material inhomegeneity and its related uncertainties on the resulting properties.

The experimental procedure consisted in a controlled variation of the parameters listed above and systematic measurement of physical quantities, addressing both the acoustic and the mechanical/structural aspects. The quanties examined covered :

- the mass density ρ measured with an electronic precision weighing machine,
- the static air flow resistivity σ measured according to ISO 9053 [7],
- the open porosity ϕ of the material measured according to the method described in [8, 9],
- and the sound absorption coefficient for plane waves under normal incidence measured according to ISO 10534-2 [10].

The complete set of measured data for the first three parameters are shown in Table II while the results are discussed in the next section. To ease the observation, these results are plotted in separate graphs for each of the varying parameter : one for the first three parameters ρ, σ and ϕ and an additional one for sound absporption coefficients.

3. Influence of extrusion parameters

3.1. Binder concentration

As shown in Figure 3, increasing the binder concentration in the mix tends to lead to increase the open porosity and to decrease the resistivity. Meanwhile, the mass density varies significantly from around 200 kg.m^3 down to low values, around 35 kg.m^3. Evolution of the sound absorption coefficients are not linear. In particular, it is interesting to note that for binder levels equal or greater than 20% the maximum level of absorption coefficient and the frequency range in which it occurs can be tuned by controlling the binder level.

3.2. Fiber to grain ratio

Figure 4 shows the influence of the grain to fiber ratio on the acoustic properties of the extruded material. The mass densities achieved are intermediate, ranging from around 150 to 300 kg.m^3. Increasing the proportion of fiber into the mix tends to decrease notably the porosity while the effect on the resistivity is not significant, all values being lower than 10 k N.s.m^{-4}. This leads to increase the performances at low frequencies while decreasing the maximum level of absorption which is reached at higher frequencies. Clearl, a significant proportion of grain is advisable to achieve interesting sound absorption performances.

3.3. Grain size

The grain size has little influence on the porosity and on the resistivity. By adjusting the grain size, the mass density may be varied from 350 to 450 kg.m^3. The effect on the sound absorption is mainly located at high frequencies. It is likely that the measurement obtained of the 1-2 mm grain size is likely to be faulty.

3.4. Fiber length

Longer fibers lead to decrease the mass density of the resulting extruded material. However, the values, spanning from 350 to 280 kg.m^3, are much larger than those obtained by varying the binder concentration. Effects of this parameter are not significative at low frequencies. However, it governs the level of maximum absorption at higher frequencies, the smaller the fibers, the higher the sound absorption.

4. Extruded material with optimised vibro-acoustic properties

According to the large range of properties which could be achieved with the extrusion process, a series of tests have been conducted to produce a material with optimised vibro-acoustic properties. The results are presented in the following.

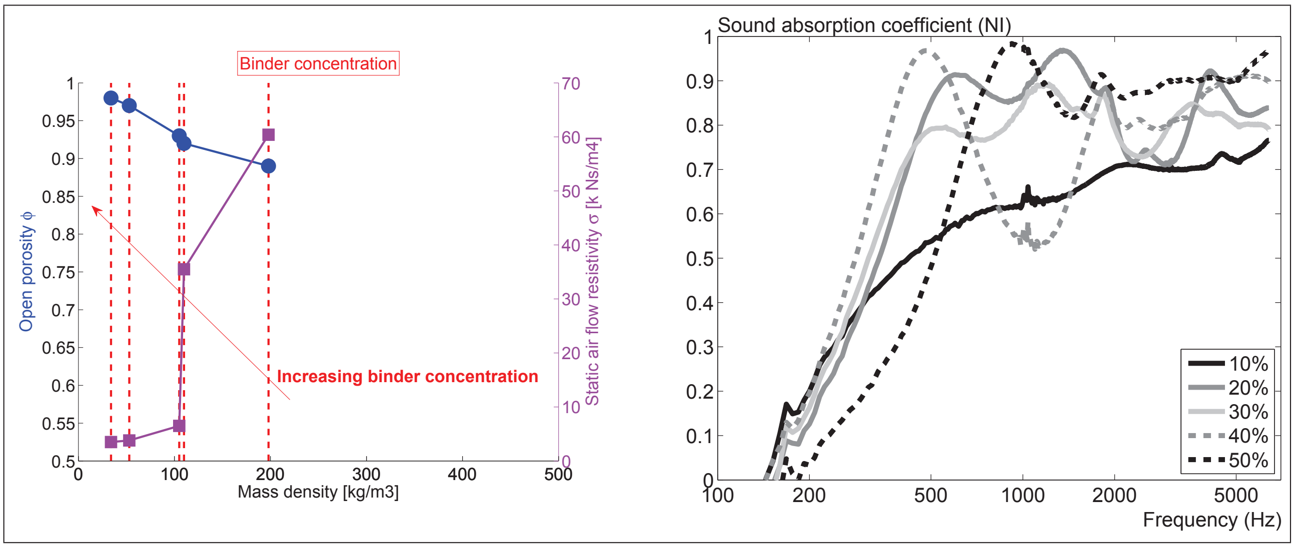

Figure 3. Effect of the binder concentration. Material thickness : 60 mm. Ambient conditions of temperature and pressure.

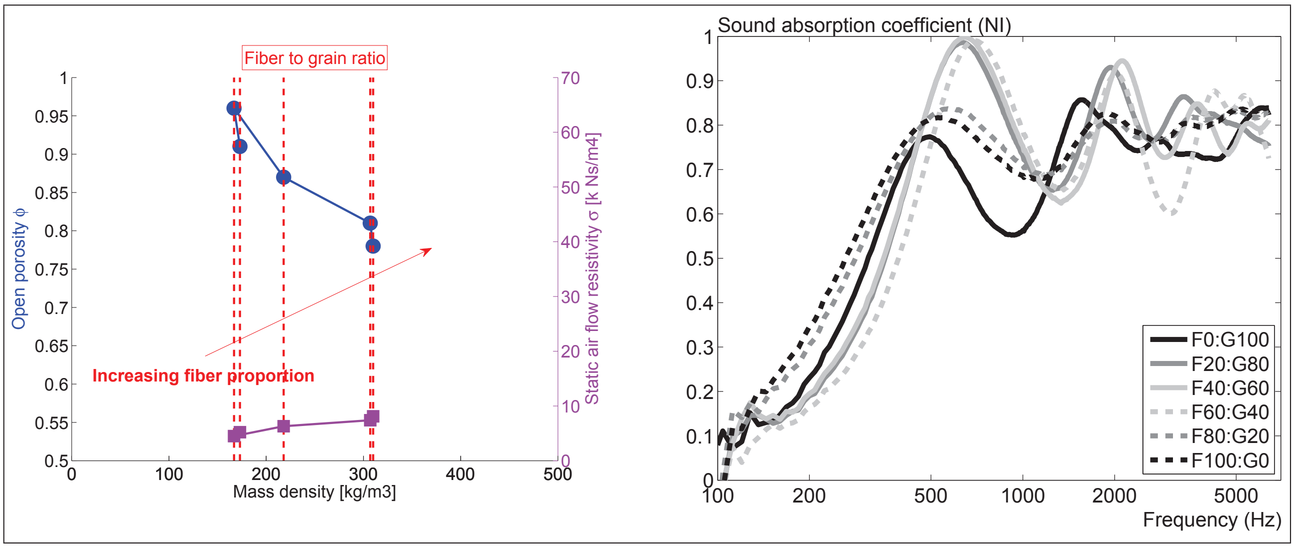

Figure 4. Effect of the fiber to grain ratio. Material thickness : 60 mm. Ambient conditions of temperature and pressure.

4.1. Acousto-elastic characterisation

A complete characterisation of the acoustic, elastic and damping parameters has been carried out assuming that the material is isotropic. In addition to the direct measurement of the resistivity and the porosity, the acoustic characterisation parameters consists in the determination of the parameters of the Johnson-Champoux-Allard-Lafarge model. This method, fully described in [11, 12, 13] allows the analytical derivation of the following parameters : the high frequency limit of the dynamic tortuosity α_∞, respectively the viscous and thermal characteristic lengths Λ and Λ', and the static thermal permeability k_0'.

Once the parameters obtained, the sound absorption coefficient can be computed and compared to the measured data. Results are shown in Figure 7 which show validate the set of characterised acoustic parameters.

The elastic and damping parameters are determined from an inversion procedure inspired from the work in [14]. This technique consists in reproducing a mass-spring system where the mass is pescribed and the spring is the porous material. By using, samples having different shape factors, the damping loss factor η, Young's modulus E, Poisson's ratio ν can be retrieved.

The complete set of characterised parameters are shown in Table III.

4.2. Sound absorption performances

Sound absorption coefficient measured in impedance tube for the optimised material is compared now with those of a foam and a fibrous material used in many

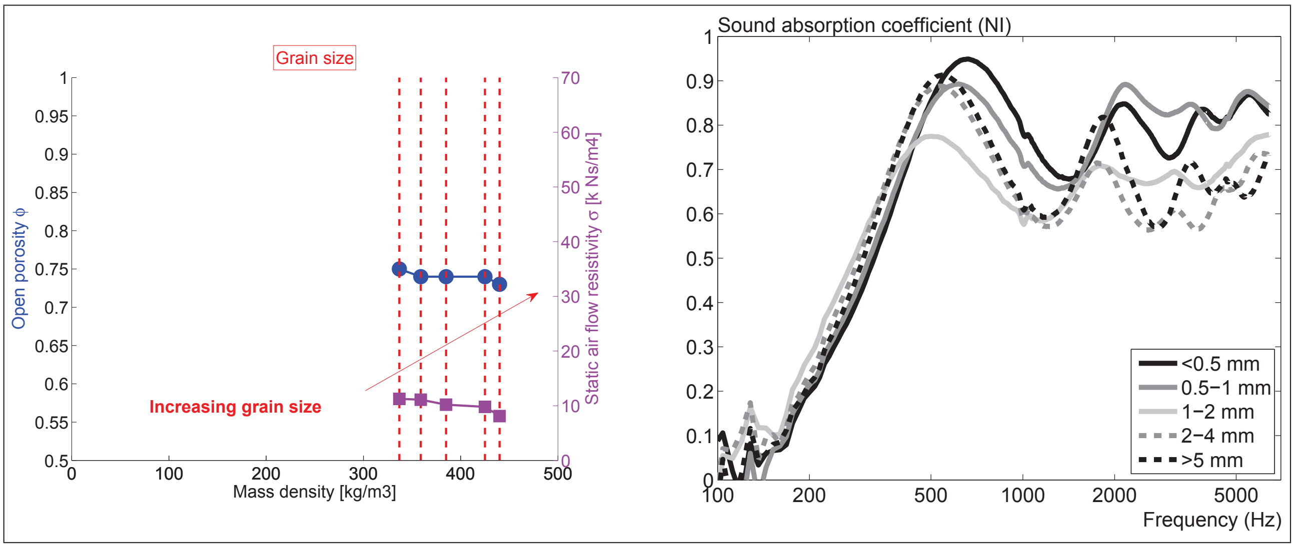

Figure 5. Effect of the grain size. Material thickness : 60 mm. Ambient conditions of temperature and pressure.

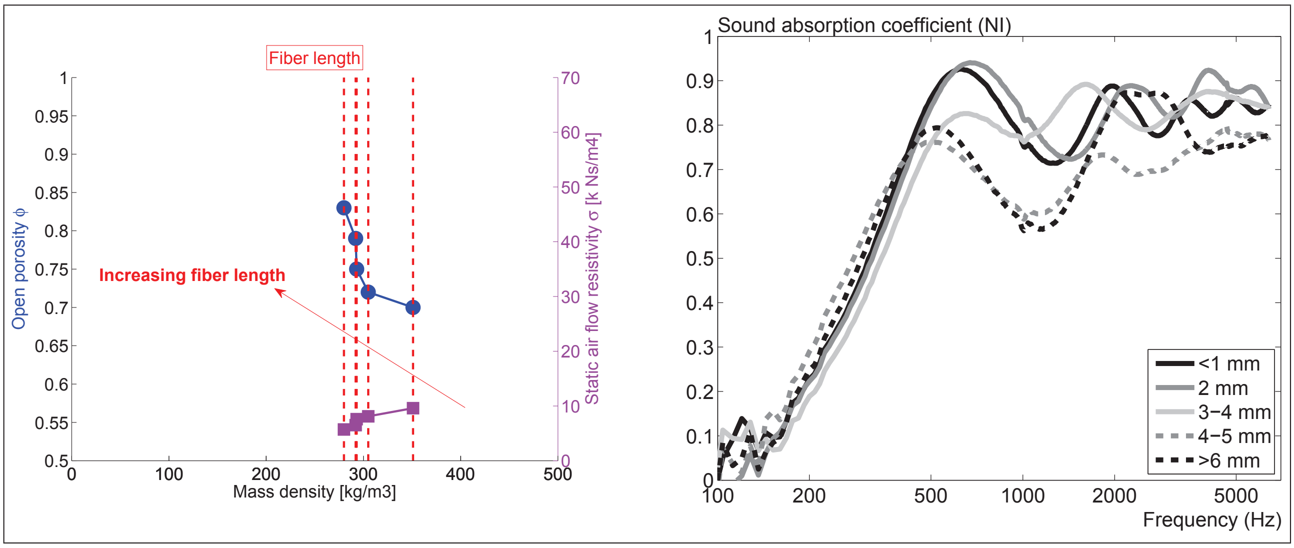

Figure 6. Effect of the fiber length. Material thickness : 60 mm. Ambient conditions of temperature and pressure.

Table III. Acoustic, elastic and damping parameters of the tested materials.

Material	σ	ϕ	α_∞	Λ	Λ'	k'_0	E	η	ν	ρ_1
ES 08	10 300	0.79	1.54	55	195	190	2 550	0.25	0.31	263
Rockwool	80 400	0.97	1.01	23	51	13	1 826	0.1	0.1	153
Concrete slab	-	-	-	-	-	-	$25\ 10^6$	0.1	0.23	2 150
Wood floor	-	-	-	-	-	-	$5\ 10^6$	0.01	0.0	613
Units	k N.s.m^{-4}	-	-	μ m	μ m	10^{-10} m^2	k Pa	-	-	kg.m^{-3}

current noise control solutions. Results presented in Figure 7 show that the performances of the optimised material are comparable to those of existing current solutions.

4.3. Air borne sound insulation

It is also interesting to compare the efficiency of the optimised material when assembled in a multi-layer system. A typical configuration found in building is depicted in Figure 8. Sound transmission results have been obtained with the commercial software $\alpha - Cell$

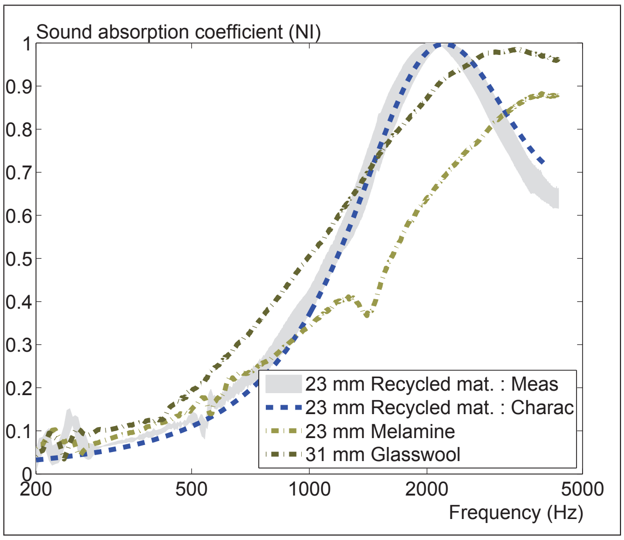

Figure 7. Sound absorption coefficient of recycled material measured in impedance tube and simulated after characterisation. Comparison with two other standard sound absorbing materials. Ambient conditions of temperature and pressure.

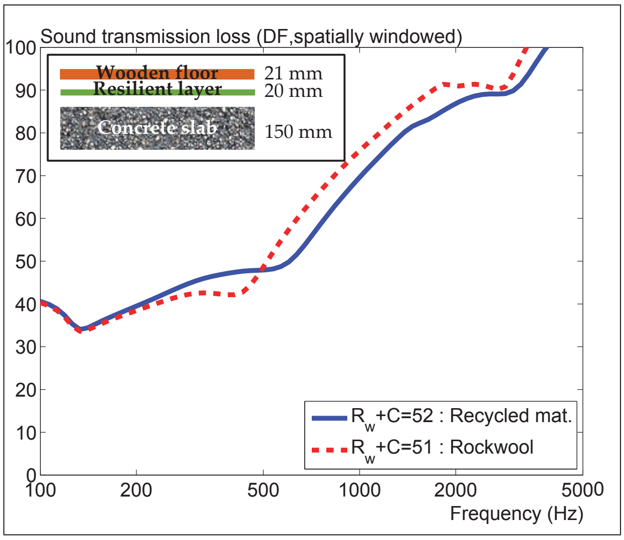

Figure 8. Efficiency of two resilient layers on airborne sound. Sound transmission loss in diffuse field conditions. Spatial windowing for dimensions 3×4 m^2. Ambient conditions of temperature and pressure.

which allow to account for the finite dimensions of the studied system. The efficiency of the extruded material, both for the spectrum and for the weighted sound reduction index are comparable to those of a current solution commercially available.

5. CONCLUSIONS

The present work is concerned with the production of sound absorbing materials made from an energy efficient extrusion process. The systematic procedure presented above allows to relate the acoustic properties of the extruded materials to relevant manufacturing parameters such as screw speed, fiber / grain ratio and binder concentration.

The experimental data and the simulation results show that there exists a potential in using the extrusion process for developing low cost noise control solutions made fom waste.

Acknowledgement

The authors are grateful for the financial support provided by Egide and the British council in Paris within the framework of Alliance projects for the realisation of this work.

References

[1] J. Pfretzschner, R. M. Rodriguez: Acoustic properties of rubber crumbs, Polymer testing, **18**, pp. 81-92 (1999)

[2] M. J. Swift, P. Bris, K. V. Horoshenkov: Acoustic absorption in re-cycled rubber granulates, Appl. Acoust., **57**, pp. 203-212 (1999)

[3] L. White: Mechanisms of mixing and dispertion, Elsevier, (1996)

[4] A. Khan,K. V. Horoshenkov, K. and H. Benkreira: Controlled Extrusion of Porous Media for Acoustic Applications, In Proc. of 1^{st} SAPEM conference, Lyon-France (2005)

[5] M. Swift: Physical properties of porous recycled materials, PhD thesis, University of Bradford, U.K. (2000)

[6] G. Pispola, K.V. Horoshenkov, A. Khan: Comparison of two modeling approaches for highly heterogeneous porous media, J. Ac. Soc. Am., **121**, pp. 961-966 (2007)

[7] ISO 9053: Acoustics – Materials for acoustical applications – Determination of airflow resistance, International Organization for Standardization, Geneva (1991)

[8] L. L. Beranek: Acoustic impedance of porous materials, J. Ac. Soc. Am., **13**, pp. 248-260 (1942)

[9] Y. Champoux, M. R. Stinson, G. A. Daigle: Air-based system for the measurement of porosity, J. Ac. Soc. Am., **89**, pp. 910-916 (1991)

[10] ISO 10534-2: Acoustics – Determination sound absorption coefficient and impedance in impedance tubes. 2. Transfer-function method, International Organization for Standardization, Geneva (2002)

[11] X. Olny, R. Panneton, J. Tran-Van: An indirect acoustical method for determining intrinsic parameters of porous materials, In Poromechanics II, proceedings of the 2^{nd} Biot conference (2002)

[12] R. Panneton, X. Olny: Acoustic determination of the parameters governing viscous dissipation in porous media, J. Ac. Soc. Am., **119**, pp. 2027-2040 (2006)

[13] X. Olny, R. Panneton: Acoustic determination of the parameters governing thermal dissipation in porous media, J. Ac. Soc. Am.,**123**, pp. 814-824 (2008)

[14] C. Langlois, R. Panneton, N. Atalla: Polynomial relations for quasi-static mechanical characterization of isotropic poroelastic materials, J. Ac. Soc. Am., **110**, pp. 3032-3040 (2001)