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Acoustic Impedance and Absorption Coefficient Measurements of Porous Materials used in the Automotive Industry

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ABSTRACT

A comparative study of the acoustic impedance (Z_0), *the absorption coefficient* (α) *and the reflection coefficient* (R) *of several thermoplastic porous compounds is presented.*

Seven closed cell crosslinked polyolefin foams and a carpet of polypropylene staple fibres were analysed. Measurements of the commonly used polyurethane foams were also recorded to compare them with the results obtained with the above recycleable materials.

The behaviour of the sound absorption in terms of the mean pore size and the type of cell (closed or open) is considered for the analysed samples.

INTRODUCTION

Acoustic analytical techniques are used on all the materials found in advanced automobile development to help determine the materials' performance *in situ* and as a tool in future design. For instance, airborne noise attenuation and sound insulation are decisive factors to be considered in the design of prototypes.

The airborne attenuation can be evaluated by means of different techniques. One of the most accepted tests is based on the standing wave method[1] which has been widely used for measuring acoustic properties of foams (polyurethane) and fibrous absorbents (glass wool),[2-4] materials

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TABLE 1
Porous Thermoplastic and Polyurethane Materials

Material	*Commercial name*	*Approximate density* (kg/m^3)	*Approximate mean pore size* (μm)[a]	*Available thickness* (*mm*)
Chemically crosslinked (closed cell) polyethylene foam[b] using the continuous three stage process: extrusion, crosslinking, foaming	Plastiroll-IS	22	1100	5–10
Chemically crosslinked (closed cell) polyethylene foam[c] using the discontinuous block process	Alveolux XA 0605	167	100	5
	Alveolux XM 2005	48	110	5–10
	Alveolux XE 3005	30	120	5
Physically crosslinked (closed cell) polyolefin foam[c] using the continuous three stage horizontal foaming process: extrusion, crosslinking, foaming	Alveolen NE 0705 (PE)	143	450	5
	Alveolen NP 2906 (PP + PE)	35	800	5
Polypropylene foam (closed cell with a high number of interconnected cells)[d]		220	750	5
Porous-fibrous carpet of polypropylene staple fibres[e]	Tapis cofre	140	50[g]	5–10
Polyurethane–polyether (open cell) foam[f] using the block process		25	800	9
Polyurethane–polyester (open cell) foam[f]		66	400	10

[a] Diameter of a spherical pore.
[b] Manufactured by BXL España, S.A., BP Group, Spain.
[c] Manufactured by Alveo AG, Luzem, Switzerland.
[d] Supplied by the National Chemical Laboratory for Industry, Tsukuba, Japan.
[e] Manufactured by Pont, Aurell & Armengoll, Spain.
[f] Manufactured by Gunasa S.A., Spain.

normally used in the vehicle industry. However, there are no studies on the acoustic properties of polyolefin foams or carpets, in spite of the fact that these materials represent a challenge in this industry because of their recycleable properties.

It should be pointed out that the mechanisms and final acoustic behaviour of fibrous and open cell foams are similar due to the fluid (air in most cases) flow through the sample,[3,5] whereas in the case of closed cell foams the absorption characteristics are different (scattering of sound from small cavities[6]).

In this work we have measured the acoustic impedance and the absorption and reflection coefficients[7,8] of the thermoplastics listed in Table 1. Experimental values were obtained using a two-microphone impedance measurement tube applying the 'transfer function method' established by Chung & Blaser.[1] This technique represents a clear improvement when compared with the classic Kundt's tube method.[9]

Essentially in this facility, the transfer function can be derived by measuring the pressure exerted by the sound standing wave at two different locations inside the rigid tube. The absorption coefficient, the complex reflection coefficient (magnitude and phase) and the complex normalized acoustic impedance are obtained from the transfer function data with a resolution much higher than that achieved with the Kundt's tube. Furthermore, the possibility of obtaining the coherence function between the two microphone signals allows for error detection and more reliable data.

EXPERIMENTAL

Materials

The main characteristics of the industrial materials used in this investigation are summarized in Table 1; these consist of five polyethylene (PE) foams, one polyethylene–polypropylene (PE–PP) foam, one polypropylene (PP) foam, one polypropylene carpet and two referential polyurethane (PUR) foams. Conventional electron micrographs were taken of these porous materials (Figs 1 and 2).

Method of measurement

The acoustic impedance, the absorption and reflection coefficients of the different materials were measured in a Brüel & Kjaer type 4206, two-microphone impedance measurement tube. A block diagram of the apparatus is presented in Fig. 3. Careful calibration of the gain factor and

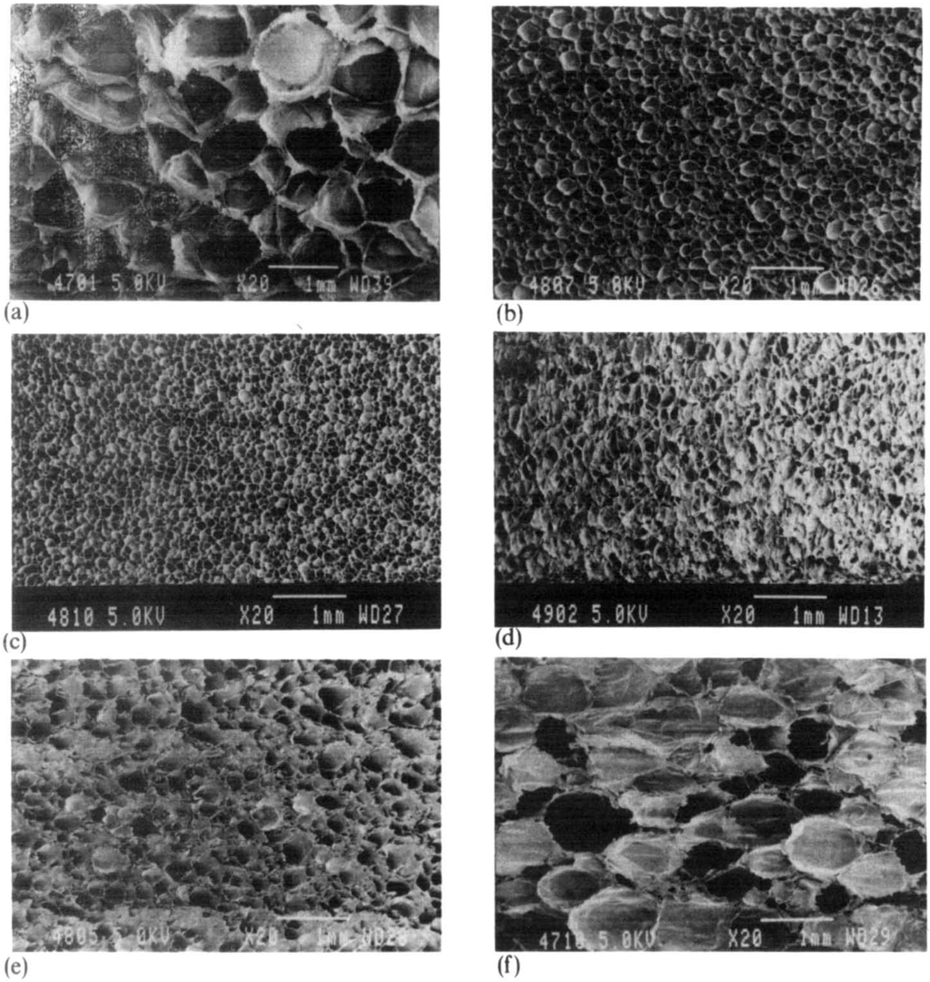

Fig. 1. SEM micrographs of polyolefin closed cell foams (× 20). (a) PE Plastiroll IS; (b) PE Alveolux XA 0605; (c) PE Alveolux XM 2005; (d) PE Alveolux XE 3005; (e) PE Alveolen NE 0705; (f) PE–PP Alveolen NP 2906.

the phase factor of the entire system was performed to ensure that the results were not affected by a phase or amplitude mismatch between the two measurement channels. This calibration procedure was carried out by means of a 'sensor-switching technique'.[1]

Although the impedance tube is based on the same physical phenomenon as the Kundt's tube, i.e. the formation of a standing wave pressure pattern between a loudspeaker and a sample backed by a rigid wall placed at the two ends of a tube,[10] the method employed is completely different. The signal emitted by the loudspeaker is not a single harmonic but a

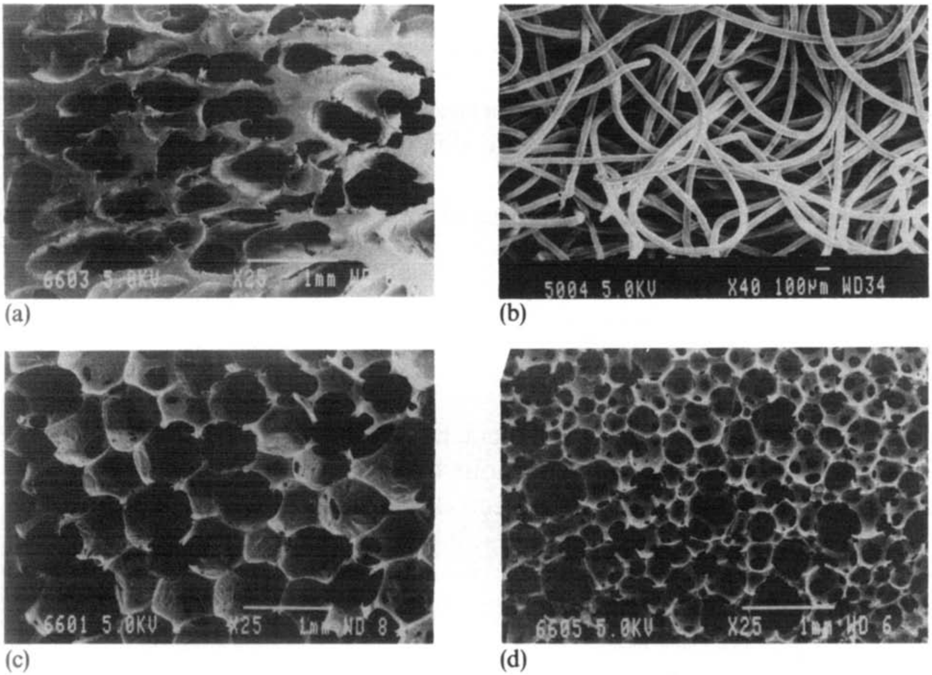

Fig. 2. SEM micrographs of open cell materials. (a) PP foam of a high number of interconnected cells (× 25); (b) PP carpet (× 40); (c) polyurethane–polyether foam (× 25); (d) polyurethane–polyester foam (× 25).

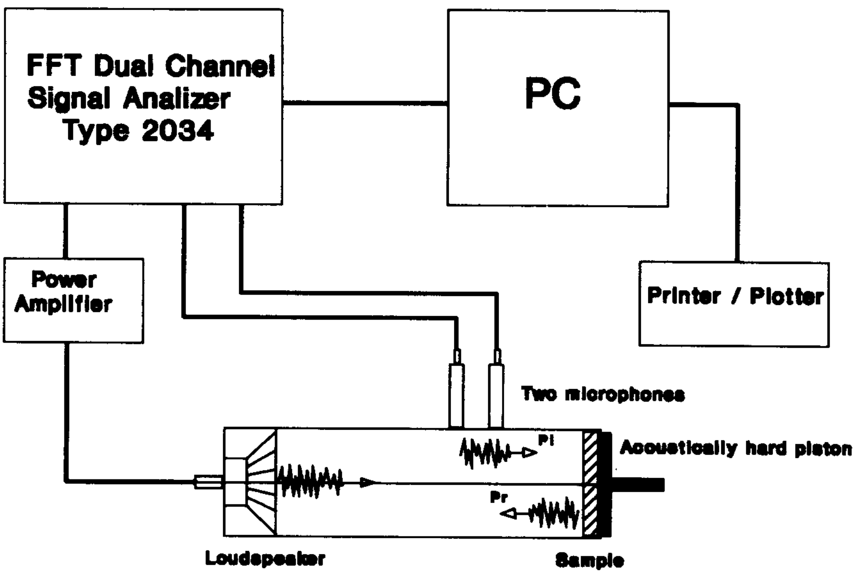

Fig. 3. Two-microphone impedance measurement tube set-up.

broadband random signal. The 'transfer function method' involves the decomposition of the resultant broadband stationary random signal into its incident (p_i) and reflected (p_r) components. These components are determined from the relationship between the acoustic pressure measured by two microphones located at two different positions on the wall of the heavy tube.

We know that the total pressures at two points x_1 and x_2 in the tube can be expressed by

$$\begin{cases} p(x_1, t) = p_i(x_1, t) + p_r(x_1, t) \\ p(x_2, t) = p_i(x_2, t) + p_r(x_2, t) \end{cases}$$

On the other hand, from the incident and reflected components of the sound pressure at the two microphone locations x_1 and x_2 it is possible to estimate the auto- and cross-spectral densities S_{11} and S_{12} at these points:[11]

$$\begin{cases} S_{11} = \frac{1}{T}[P_1(f, T)P_1^*(f, T)] \\ S_{12} = \frac{1}{T}[P_1(f, T)P_2^*(f, T)] \end{cases}$$

where f is the frequency of the pressure wave, T is the record length of the time series and the quantities $P_1(f, T)$ and $P_2(f, T)$ are the finite Fourier transforms of the pressure time series at points x_1 and x_2; the asterisk denotes complex conjugate.

In our experiments a FFT dual channel signal analyser (Brüel & Kjaer type 2034) allowed calculation of the Fourier transforms over a wide frequency range with a 2 Hz resolution.

From the values of S_{11} and S_{12} the frequency response function (transfer function) can be calculated as

$$H_{12} = \frac{S_{12}(f)}{S_{11}(f)} \tag{1}$$

and similarly, the transfer functions associated with the reflected component $H_r(f)$ and the incident component $H_i(f)$ can be obtained:

$$H_r(f) = \frac{S_{1r2r}(f)}{S_{1r1r}(f)} \tag{2}$$

$$H_i(f)=\frac{S_{1i2i}(f)}{S_{1i1i}(f)} \tag{3}$$

Thus, from eqns (1), (2) and (3) the expression of the complex reflection coefficient is defined by

$$R(f)=\frac{H_{12}(f)-H_i(f)}{H_r(f)-H_{12}(f)} \tag{4}$$

Using this last equation, the absorption coefficient (α) is given by

$$\alpha=1-|R|^2=1-\left|\frac{H_{12}-H_i}{H_r-H_{12}}\right|^2 \tag{5}$$

and the complex normalized acoustic impedance is

$$\frac{Z_0}{\rho c}=\frac{1+|R|}{1-|R|} \tag{6}$$

where ρ is the density of air, c is the speed of sound in air and ρc is the characteristic impedance.

The three acoustic functions expressed in eqns (4), (5) and (6) are readily evaluated using a PC with an application software that controls the FFT analyser via an IEEE interface.

RESULTS AND DISCUSSION

Absorption coefficient

Absorption coefficient measurements for the materials studied are displayed in Fig. 4. Figure 4(a) shows that for foams with closed cells, the one with the greatest pore size ($\phi=1{\cdot}1$ mm: Plastiroll) is the most effective and that the densities are not directly related to the sound absorption. Figure 4(b), 5 mm thick samples, shows that the PP foam with a high number of interconnected cells and a big pore size ($\phi=0{\cdot}8$ mm) gives the best results up to 3000 Hz with a maximum around 1000 Hz, a significant result since the frequency range between 100 and 1000 Hz is the representative scale of airborne noise propagated in vehicles. In Fig. 4(c), two polyolefin foams with closed cells of different pore sizes ($\phi=1{\cdot}1$ mm: PE Plastiroll; $\phi=0{\cdot}11$ mm: PE Alveolux XM) are compared with a PP carpet and two

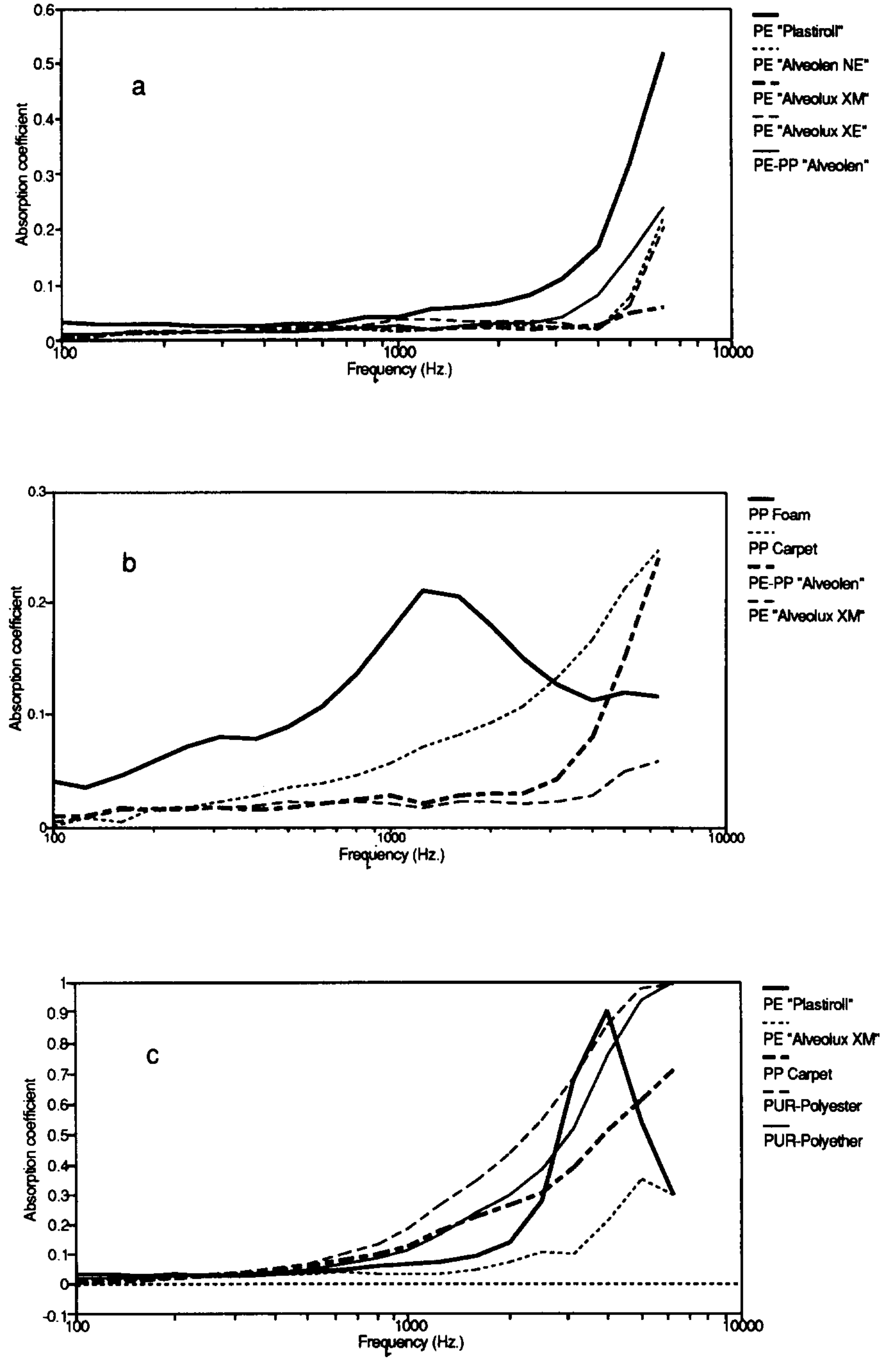

Fig. 4. Absorption coefficients. (a) Polyolefin materials (closed cell)—thickness 5 mm; (b) polyolefin materials (closed–open cell)—thickness 5 mm; (c) polyolefin–polyurethane materials (closed–open cell)—thickness 10 mm.

PUR foams with open cells. It has been pointed out that the behaviour of the carpet should be similar to an open cell material.[3,5] These results suggest that open cells help sound absorption; moreover, it is manifest that as the thickness of the samples is larger, the absorption coefficient is higher and its maximum moves to lower frequencies. Therefore, a polyolefin foam with a big pore size and an open cell structure would be expected to give a good absorption performance comparable to, or even better than, what is achieved with PUR foams.

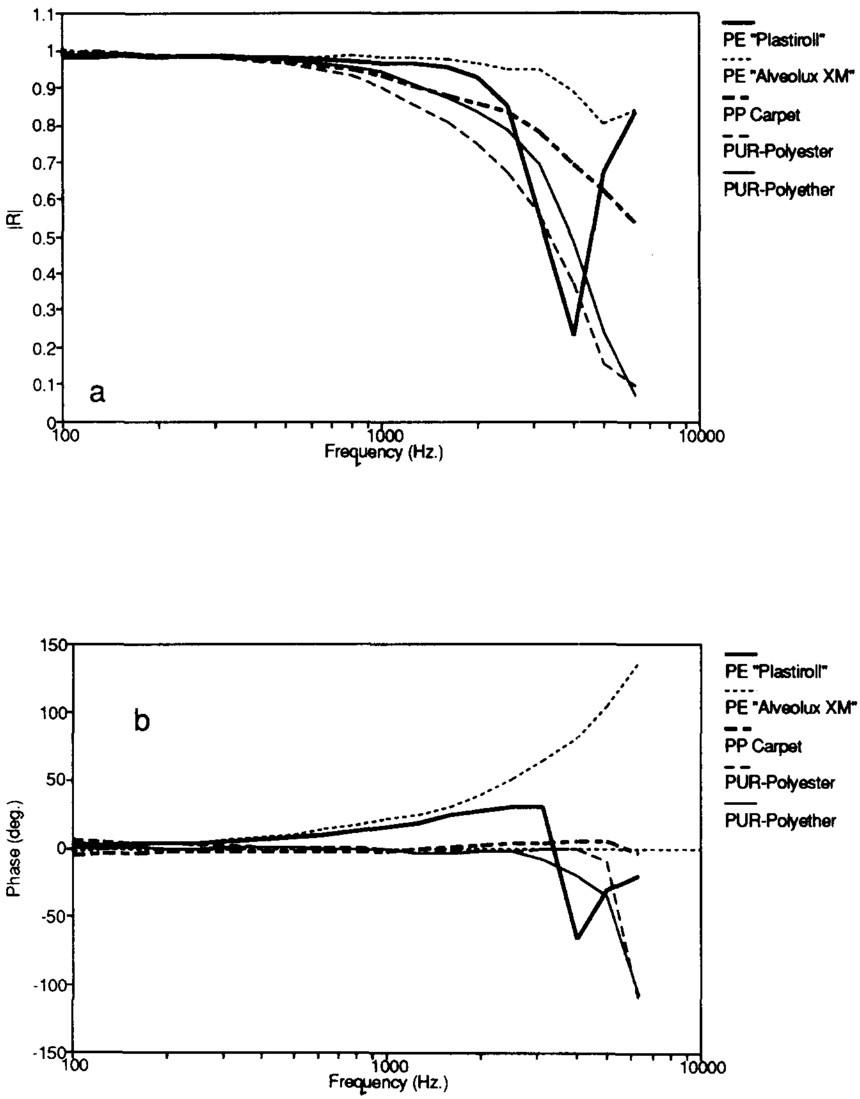

Fig. 5. Reflection coefficients of polyolefin–polyurethane materials (closed–open cell)—thickness 10 mm. (a) Modulus; (b) phase (deg.).

Reflection coefficient

Figure 5 shows the moduli and the phase mismatch of the reflection coefficients of the 10 mm thick samples. The definition of the reflection coefficient is $R = p_r/p_i$, where p_r is the acoustic pressure of the reflected wave and p_i is the acoustic pressure of the incident wave. Its modulus is directly connected to the absorption coefficient (eqn 5).

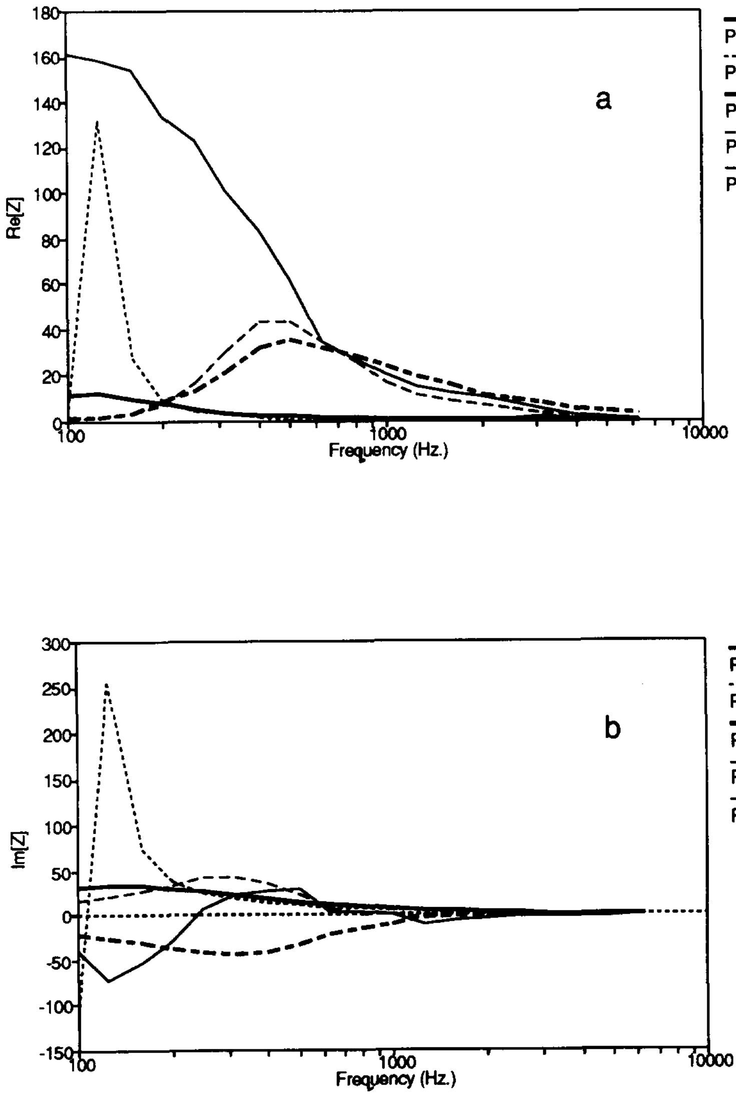

Fig. 6. Normalized acoustic impedances of polyolefin–polyurethane materials (open–closed cell)—thickness 10 mm. (a) Real part; (b) imaginary part.

Normalized acoustic impedance

The normal acoustic impedances of the 10 mm thick materials are presented in Fig. 6. This parameter, describing the relation between the acoustic pressure exerted on the surface of the sample and the velocity of the particles forming the surface, characterizes the medium through which the plane wave propagates in duct acoustics.

The transfer function method allows measurement of the normal sound absorption coefficient and the normal acoustic impedance in a very efficient way. However, obtaining these properties is not enough to completely characterize the porous materials; it is more important to obtain the characteristic impedance and propagation constant. It is possible to calculate them using the two cavities method,[4] i.e. calculating the acoustic impedances of a sample backed by two air cavities of different thicknesses. Obtaining these new properties in polyolefin foams will be the subject of a later study.

As a conclusion, we can say that, although the acoustic behaviour of the PUR foams was in general better, the results obtained in polyolefin materials make for optimism. In our opinion, controlling the mean pore size and the type of cell would lead to an enhancement of the acoustic performance of thermoplastics materials.

REFERENCES

1. Chung, J. Y. & Blaser, D. A., Transfer function method of measuring in-duct acoustic properties. I. Theory. *J. Acoust. Soc. Am.*, **68** (3) (1980) 907–13.
2. Yaniv, S. L., Impedance tube measurement of propagation constant and characteristic impedance of porous acoustical material. *J. Acoust. Soc. Am.*, **54** (5) (1973) 1138–42.
3. McIntosh, D., Zuroski, M. T. & Lambert, R. F., Standing wave apparatus for measuring fundamental properties of acoustic materials in air. *J. Acoust. Soc. Am.*, **88** (4) (1990) 1929–38.
4. Utsuno, H., Tanaka, T., Fujikawa, T. & Seybert, A. F., Transfer function method for measuring characteristic impedance and propagation constant of porous materials. *J. Acoust. Soc. Am.*, **86** (2) (1989) 637–43.
5. Lambert, R. F., The acoustical stιucture of highly porous open-cell foams. *J. Acoust. Soc. Am.*, **72** (3) (1982) 879–87.
6. Jarzinski, J., Mechanism of sound attenuation in materials. In *Sound Vibration Damping with Polymers*, ed. R. D. Corsaro & L. H. Sperling. ACS Symposium Series (1990).
7. Zwikker, C. & Kosten, C., *Sound Absorbing Materials*. Elsevier, New York, 1949.
8. Beranek, L. L., *Noise and Vibration Control*. McGraw-Hill, New York, 1971.

9. Alonso, M., González, A., Requejo, A., Arribas, M. & de Saja, J. A., Air-borne sound absorption and sound speed in talc-filled polypropylene, *Polymer Testing*, **11** (1992) 71–118.
10. Beranek, L. L., Acoustical properties of homogeneous isotropic, rigid tiles and flexible blankets. *J. Acoust. Soc. Am.*, **19** (1947) 556–68.
11. Seybert, A. F. & Ross, D. F., Experimental determination of acoustic properties using a two-microphone random-excitation technique. *J. Acoust. Soc. Am.*, **61** (5) (1977) 1362–70.