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Determination of the Tortuosity of Porous Materials using new Air-coupled Ultrasonic Transducers

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INTRODUCTION

The tortuosity is an important parameter in the prediction of sound propagation in porous materials[1] . Up till now, the tortuosity was determined with an electric conductivity experiment where the sample had to be saturated with a conducting liquid, in many cases resulting in damage to the samples structure, especially in the case of samples with a high flow resistivity. The velocity of the air coupled wave in porous materials depends heavily on the tortuosity of the material. This phenomenon is used to determine the tortuosity of porous materials by measuring the phase velocity of Biot's slow wave of air saturated porous samples at high frequency. In this measurement, new air coupled capacitance transducers are used. The results obtained with this method will be compared with conductivity experiments.

TORTUOSITY AND SLOW WAVE VELOCITY IN A POROUS MATERIAL

The conductivity experiment

The tortuosity is a property of the skeletal frame and does not depend on the fluid filling the pores. In the original work of Biot, the tortuosity was defined as the ratio of the kinematic energy of the microscopic molecular velocity of an inviscid fluid and the kinetic energy of the macroscopic wave (see for instance reference 1) :

$$\alpha_{\infty} = \frac{\overline{v^2}}{\overline{v}^2} \qquad (1)$$

This tortuosity can be determined with an electric conductivity experiment[2]. The experimental setup is schematically shown in figure 1. The sample is mounted in a PVC tube which is terminated by two cylindrical electrode plates G_1 and G_2. The tube is completely filled with a conducting liquid (usually a saline water solution) and the electrodes generate a plane electric field in the tube. The electrode wires M_1 , M_2 and M_3 measure the potential differences V_1 and V_2 between M_1 and M_2 and between M_2 and M_3 respectively. The potential difference V_1 allows to determine the conductivity of the liquid, whereas V_2 allows to determine the conductivity of the sample. The tortuosity is then given by:

$$\alpha_\infty = \phi \, \frac{\sigma_s}{\sigma_f} \tag{2}$$

where ϕ is the porosity of the sample, σ_s the resistivity of the sample and σ_f the resistivity of the liquid. This is equal to :

$$\alpha_\infty = \phi \left(\frac{V_2}{V_1} \frac{d_1 - d_2}{d_s} - \frac{d_2 - d_3}{d_s} \right) \tag{3}$$

where d_1 , d_2 and d_3 are the distances from the electrodes M_1 , M_2 and M_3 to the nearest sample surface.

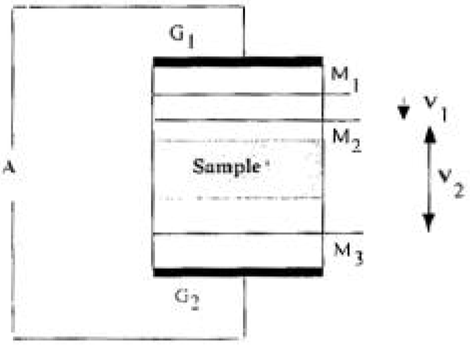

Figure 1. Experimental setup for the measurement of the turtuosity with a conductivity experiment.

This method only works if the frame of the material is an electrical insulator. Moreover, porous materials with a high flow resistivity (and hence small pores) are often difficult to saturate. The sample holder has to be brought in a vacuum chamber in order to saturate the sample completely. In this process, part of the cells of plastic sound absorbing materials like polyurethane foams may get damaged and hence the tortuosity measured with this technique is often lower than the tortuosity that is needed to model the surface impedance of sound absorbing materials, on the other hand, the presence of air bubbles in the material may result in a measured value that is too high[3].

Ultrasonic measuring setup

In order to overcome these problems, a new technique has been developed, based on the propagation of ultrasonic pulses in an air saturated porous sample[4,5]. As it has been observed by Nagy[6,7], the velocity of an ultrasonic pulse in an air saturated porous solid depends on the tortuosity. The tortuosity is related to the velocity C_{slow} of the acoustic wave of an inviscid fluid which saturates the frame[8] :

$$\alpha_\infty = \frac{C_0^2}{C_{slow}^2} \tag{4}$$

with C_0 the sound velocity in the fluid. For viscous fluids, the attenuation has to be taken into account and the velocity of the slow wave at high frequencies is given by[1]:

$$C = \frac{C_0}{\sqrt{\alpha_\infty}}\left[1-\frac{\delta}{2}\left(\frac{1}{\Lambda}+\frac{\gamma-1}{B\Lambda'}\right)\right]$$

The parameters Λ and Λ' are the viscous and thermal characteristic dimensions of the pores[1] and determine the attenuation of ultrasonic pulses in the material.

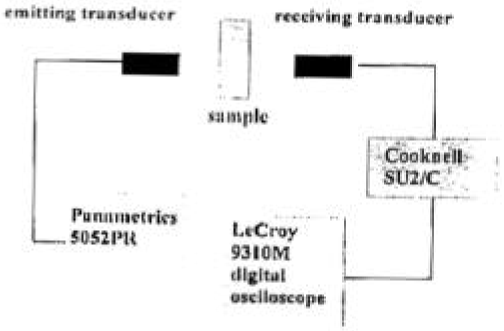

Figure 2. Experimental setup for measuring the tortuosity with an ultrasonic transmission method.

Figure 2 shows the experimental setup. The transducers used in this experiment are air-coupled micromachined silicon electrostatic transducers that have been developed at the university of Warwick, UK (see reference 9 for more details). The transducers consist of a metallized polymer membrane (a Kapton polymide film), stretched over a roughened backplate electrode to which a bias voltage is usually applied. When used as a detector, motion of the membrane causes variations in the electric field between the electrodes and thus also in the effective charge on the electrodes, which may then be detected using a charge sensitive amplifier. In the generation mode, a driving voltage applied to the rigid backplate causes motion of the membrane. The quantity and dimensions of the air pockets formed between the roughened backplate and the membrane determine beam profile, sensitivity and frequency response of the device.

Figure 3 shows two time signals recorded with this setup. Figure 3a is the time signal without a sample between source and transducer and figure 3b is the time signal with a 5 mm polyurethane foam between source and receiver. The phase velocity of the slow wave can be determined from the unwrapped phase of the Fourier transform of these signals and the attenuation can be estimated from two measurements on samples of different thickness.

Table I.

sample	conduct. exp.	ultrason. exp.
1	1.5 ± 0.1	1.52 ± 0.05
2	1.7 ± 0.1	1.44 ± 0.05
3	1.5 ± 0.1	1.42 ± 0.05

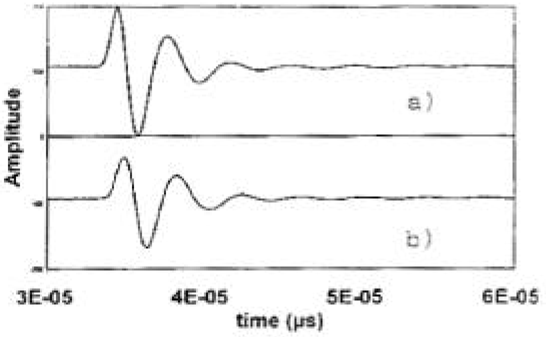

Figure 3. Time signal recorded with the capacitance transducers. Fig 3a: no sample between source and receiver; fig 3b : 5 mm polyurethane foam between source and receiver.

Table I summarises some experimental results obtained on different foams with the conductivity and the ultrasonic technique.

Figure 4 shows the velocity of the slow wave as a function of frequency for a low density polyurethane foam of low flow resistivity.

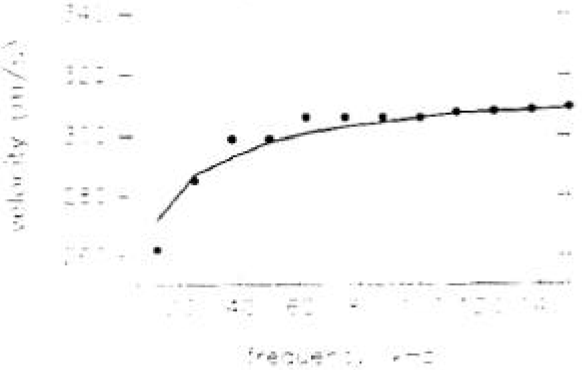

Figure 4. Velocity of the slow wave as a function of frequency for a low density polyurethane foam.

REFERENCES

1.**J.F.Allard** Propagation of sound in porous media. Modelling sound absorbing materials (Chapman&Hall, London, 1993)
2.**R. Brown** Geophysics **45** (1980) 1269-1275
3.**J.F.Allard, C.Depollier,W.Lauriks** J.Sound Vib. **132** (1989) 51-60
4.**J.F.Allard,B.Castagnede,M.Henry,W.Lauriks** Rev.Sci.Instrum **65**(1994) 754-755
5.**N.Brown,B.Castagnede,W.Lauriks,M.Melon** accepted for publication in C.R.Acad.Sci.Paris
6. **P.Nagy, L.Adler** Appl.Phys.Lett **56** (1990) 2504-2506
7. **P.Nagy** J.Acoust.Soc.Am. **93** (1993) 3224-3234
8.**D.L.Johnson,T.Plona,C.Scala,F.Pasieb,H.Kojima** Phys.Rev.Lett.**49**(1982) 1840
9. **W.Wright,D.Schindel, D.Hutchins** J.Acoust.Soc.Am. **95** (1994) 2567-2575
10.**D.Lafarge,J.F.Allard,B.Brouard,W.Lauriks** J.Acoust.Soc.Am **93**(1993) 2474-2478