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Acoustic absorption coefficient of open-cell polyolefin-based foams

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ABSTRACT

The acoustic absorption of open-cell polyolefin (PO) foams with densities between 23 and 64 kg/m^3 has been measured and compared with that of open-cell polyurethane (PU) foams. Acoustic parameters related to the cellular structure, such as porosity, tortuosity and airflow resistivity, were also measured. PO foams show higher tortuosity and airflow resistivity than the PU open-cell foam; as a consequence, they show a higher absorption coefficient than PU open-cell foam in the frequency range between 1000 and 2000 Hz. We also modeled the acoustic behavior using the Biot–Allard theory with the Johnson approach, fitted using a genetic algorithm. The fits of the acoustic absorption coefficient as a function of frequency were reasonably consistent with the experimental results.

1. Introduction

It is well known that the acoustic absorption capacity depends on the acoustic porosity content (open porosity). Indeed, scientists have focused on materials with interconnected porosity, especially foams made from polyurethane [1–8]. It is essential to determine parameters such as the airflow resistivity, tortuosity and acoustic porosity to understand acoustic phenomena.

Biot developed a sound propagation theory in an elastic frame [2], which assumes that both the fluid and the material structure convey the sound wave. This model is based on the equations of motion, coupling the plane wave in the fluid and in the solid, and taking into account the inertial forces in the fluid and the forces created by the fluid viscosity per unit volume [3]. Lambert [4,5] introduced a theoretical and experimental study on open-cell polyurethane (PU) foam. Most fundamental studies of acoustic behavior have been performed on open-cell PU foams, because these are the more widely used materials for acoustic absorption.

However, open-cell foams based on polyolefins have recently been developed, and, as far as we know, detailed analysis of the acoustic absorption of these materials has not yet been carried out. These foams are produced by a compression-molding technology in which the cells in a closed-cell foam block are opened by mechanical deformation. This particular foaming route results in cellular structures that are very different from those of typical open-cell PU foams [10]. The clear difference between the structures of both types of materials can be used to establish new knowledge on the influence of structure on the acoustic absorption properties of open-cell polymer foams. Several authors have attempted to identify optimal designs for porous materials that balance mechanical, thermal and acoustic properties using computational tools such as genetic algorithms (GAs) [9], neural network [10] and multi-stage regression analysis [11]. The concept of being able to predict the acoustic absorption of open-cell foams is very attractive, and is also considered in this paper. The three main aims of this work are to: (i) establish the structure–property (acoustic absorption) relationships for these new materials, (ii) compare the acoustic response of these materials with those of conventional open-cell PU foams and (iii) analyze the applicability of the Biot–Allard model to the materials under study.

2. Experimental

Materials: The foams were manufactured using a two-stage molding procedure [12]. The foams are blends of 40% ethylene vinyl acetate copolymer (EVA, VA content 18%), 40% of low density polyethylene (LDPE); 12% $CaCO_3$, azodicarbonamide as foaming agent and dicumyl peroxide as crosslinking agent [12]. Four foams with densities of 23–49 kg/m^3 were analyzed. To obtain a clearer understanding of their physical behavior, the foams were compared with a standard open-cell flexible PU foam with density 24 kg/m^3.

Techniques: The mean cell size in each foam direction was estimated with the intersection method [12] by SEM (JEOL JSM-820) micrographs. The average cell size was computed as the mean value of the cell sizes in the three different directions. All foams were isotropic.

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Acoustic porosity is related to the amount of air in the porous material that can participate in sound propagation [3,8]. This is measured using an air pycnometer (model 08.69 Eijkelkamp) which measures a well-known parameter, the "open-cell content" (f) [12]. The test was conducted according to ASTM Standard D 2856-94. Samples, $30 \times 30 \times 10\ \text{mm}^3$, were used and measured five times.

The resistance of each material to airflow [8] was evaluated using an air pressure difference (Δp) created by a steady airflow rate (Q) crossing the test specimen, with cross sectional area (A) and specific thickness (d). The airflow resistivity (σ) can be calculated as follows:

$$\sigma = (\Delta p/Q)(A/d) \tag{1}$$

The samples were cylindrical discs, $100 \times 10\ \text{mm}^2$. Each sample was measured three times.

Tortuosity (T) is defined as the ratio of the real to apparent distances that the air has to cover to move from one side to the other side of the sample. T depends only on the architecture of the porous material. As the foam does not conduct electricity, we followed Montejano's method to measure T [13]. The material is saturated with a conducting fluid (0.4 M $CaSO_4$ solution) and the resistivity (R_c) of the material is measured by applying a voltage and measuring the electrical current between two copper electrodes. T is given by [6,8,14]

$$T = f(R_c/R_f) \tag{2}$$

where R_f is the measured resistivity of the fluid. The resistance of each sample was measured in a range of 0–1.5 V, three times.

Absorption coefficients were measured by the two-microphone method (Brüel & Kjaer 4206). The measurement was performed from 500 to 6400 Hz with two ¼ in. microphones in accordance with ASTM E1050 and ISO 10534-2:2002 [14]. The samples were cylinders, $29 \pm 0.1 \times 10 \pm 0.1\ \text{mm}^2$. Each material was measured six times.

Acoustic model: The Biot–Allard theory with the Johnson approach is used to explain the behavior of acoustic foams. The equation relates the inertial and viscosity forces interacting in the fluid per unit volume [3,4,8]. Elastic constants P, Q, R and N are defined by [6,8]

$$P = 4/3N + K_b + (1-f)^2/fK_f \tag{3}$$

$$Q = K_f(1-f) \tag{4}$$

$$R = fK_f \tag{5}$$

where N is the shear modulus of the frame [8], K_b is the bulk modulus of the material and K_f the bulk modulus of the fluid. K_f is the energy lost in the pores through heat conduction from the compression/dilatation cycle in the plane sound wave [3]. Johnson defined, $G(\omega)$, as a function of frequency (ω) and can be calculated by [15]

$$G(\omega) = (1 + j(4T^2\eta\rho_0\omega)/(\sigma^2\Lambda^2 f^2))^{1/2} \tag{6}$$

where j is $(-1)^{1/2}$, η is the air viscosity, and Λ is the characteristic dimension of the viscous forces Eq. (7), which depend only on the geometry of the frame, T, σ and ρ_0 (air density). The characteristic dimension for the thermal exchanges (Λ') is calculated by

$$\Lambda = 1/c((8\eta T)/(\sigma f))^2 \tag{7}$$

$$\Lambda' = 1/c'((8\eta T)/(\sigma f))^2 \tag{8}$$

The c and c' parameters depend on the pore cross-section and also related to the viscous and thermal effects inside the foam cells [6,8]. Allard predicted the surface impedance at normal incidence, based on the Biot theory, as Z_s [6,8]. From Z_0 (air impedance), the theoretical sound-absorbing coefficient (α_{the}) is calculated by

$$\alpha_{the} = 1 - abs(Z_s - Z_0)/(Z_0 - Z_s) \tag{9}$$

In this paper we use the above equations describing absorption of sound in porous materials to calculate the theoretical absorption coefficient as a function of frequency.

Genetic algorithms (GAs): In the present paper a GA was built to fit the theoretical absorption coefficient based on the two fitting parameters c and c'. The objective function was to minimize the error Eq. (10) between the experimental and theoretical Eq. (9) absorption coefficients

$$error = abs(\alpha_{exp} - \alpha_{the}) \tag{10}$$

The solid matrix is considered elastic. As the material is supported on a highly reflecting solid surface, only longitudinal and transverse waves propagating in the material have been taken into account; shear waves have not been considered. Parameters such as tortuosity, airflow resistivity and the modulus of compressibility were based on experimentally measured values. According to Allard, c and c' values are within 0.3–3.0 [3]. Therefore, the algorithm searches for the optimal values of c and c' within this interval. The algorithm is initiated with some values, and solves the equations to obtain an absorption coefficient value, which is

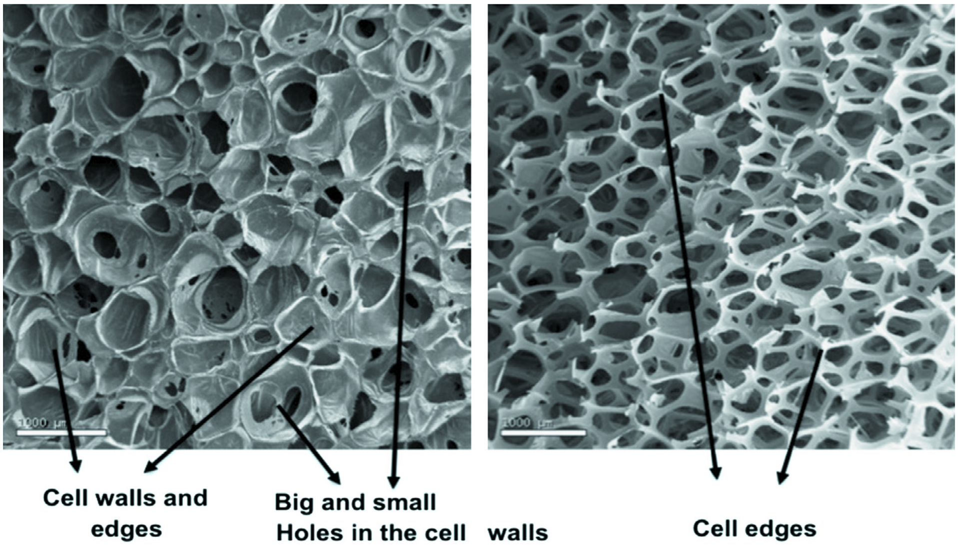

Fig. 1. Typical cellular structure of (a) open-cell crosslinked PO foam and (b) open-cell PU foam.