ELASTIC CHARACTERISTICS OF POROUS MATERIALS

V. V. Polyakov and A. V. Golovin UDC 530.217

Investigations of the characteristics of matter under extreme conditions of impact-wave loading have incited considerable interest in the analysis of the elastic characteristics of porous materials [1]. The importance of investigating the elastic wave velocity and the elastic moduli of porous media is also seen in designing new composite materials suitable for operation under conditions of high pressure and temperature and variable mechanical fields [2, 3]. The characteristics of porous solids are usually described within the frame work of the mechanics of continuous media by devising geometric structure models [4]. We shall investigate here the elastic characteristics of porous materials by using the semi-empirical Morse equation for the energy of a strained solid.

Using the intrinsic energy as a function of the volume V, assigned by the Morse equation [5], we write the adiabatic modulus of cubic compressibility B in the following form:

$$B = \frac{B_0}{\alpha} x^{1/3} \{2 (x^{-1/3} + \alpha) \exp 2\alpha (1 - x^{1/3}) - (2x^{-1/3} + \alpha) \exp \alpha (1 - x^{1/3})\},$$

where $x = V_0/V$; B_0 and V_0 are the modulus and the specific volume of the free material, respectively. The α parameter, which characterizes the forces of interatomic repulsion and attraction, was determined in [5] with respect to the energy and the modulus B in the unstrained state. According to the proposed approach, the elastic characteristics of a porous solid were considered as the parameters of the effective medium obtained as a result of cubic expansion of a free, compact body by repulsive forces to a density corresponding to a porous material. Introducing the porosity defined by $P = (V - V_0)/V$, we have the following expression for the elastic modulus:

$$B (P) = \frac{B_0}{1 + \alpha} y (y + \alpha) \exp 2\alpha (1 - 1/y) \tag{1}$$

$(y = 1 - P)^{1/3}$. Equation (1) makes it possible to determine the expression for the volume wave velocity C_w:

$$C_w(P) = C_{w0}\left\{\frac{y + \alpha}{(1 + \alpha) y^2} \exp 2\alpha (1 - 1/y)\right\}^{1/2} \tag{2}$$

(C_{w0} is the value of C_w for P = 0). It should be noted that C_w is of interest as the first term in the expression of the impact wave velocity with respect to the mass velcotity in the material [6]. Equations (1) and (2) were used for calculating the velocity C_w and the modulus B for porous iron. The values of the parameter α, borrowed from [5], and of the modulus B_0, borrowed from [7], that were used in calculations are given in Table 1. The calculation results are represented by the curves in Fig. 1b and 2b.

In order to check the adequacy of this approach, we performed ultrasound measurements of the longitudinal C_ℓ and the transverse C_t velocities of elastic waves. The test specimens were cylindrical and had a diameter of 10 mm and a length of 15 mm. They were made of PZhRV2 iron powder with a mean particle size of 81 μm by pressing and sintering in vacuum at 1450 K. The porosity of the specimens was specified in the range from 4 to 45%. The mean dimension a of the pores, which emerged as the basic scattering centers, was measured by means of a NEOPHOT-32 optical microscope and was monotonically increased from a = 7 μm for P = 5% to a = 16 μm for P = 40%.

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TABLE 1

Material	α	B_0	E_0	μ_0
		GPa		
Fe	3,64	166	211	82
Ti	3,28	107	114	43
Co	3,64	190	215	82
Ni	3,60	183	221	86
Cu	3,60	137	128	48
Mo	4,16	263	320	125
W	3,96	310	409	160
MgO	3,72	159	307	130

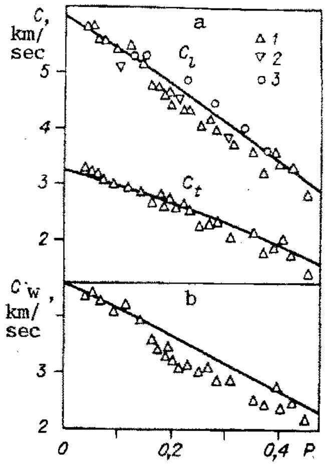

Fig. 1

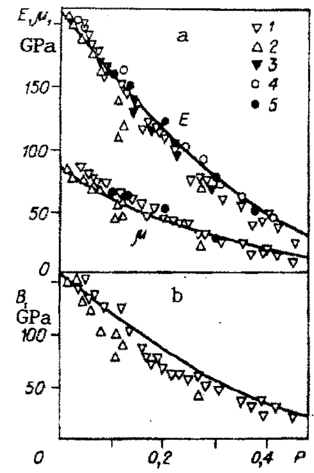

Fig. 2

The measurements were performed according to the phase interference method with separately matched piezoelectric transducers [8]. The ultrasound velocity was determined by automated analysis of the phase shift between the emitted and the received signals. The frequency of the ultrasound signal was equal to f = 2.5 MHz, which corresponded to the case $ka = (2\pi f/C)\, a \ll 1$. For specimens of compact Armco iron (P = 0), the error in measuring C_{l0} and C_{t0} was less than 1%.

As the porosity increases, considerable dispersion of elastic waves is possible due to the increasing size and concentration of pores. The relative contribution of the dispersion to the ultrasound velocity was estimated to be $C_{l0}\, P\, (ka)^2/C_l$ in accordance with [9]. The experimental values of this contribution varied from 0.002% for P = 5% to 0.35% for P = 40%.

The measured ultrasound wave velocities are given in Fig. 1a (points 1), which also shows the experimental data: 2 [10] and 3 [11]. The velocity of volume waves was determined by means of the equation

$$C_w = (C_l^2 - 4C_t^2/3)^{1/2}$$

(Fig. 1b). A monotonic reduction in the velocity with an increase in porosity was observed.

The measured ultrasound velocity made it possible to determine the elastic characteristics of porous iron as functions of P. The experimental values of the modulus of cubic compressibility B, Young's modulus E, and the shear modulus μ were determiend by means of the expressions

$$B = (C_l^2 - 4C_t^2)/3V, \quad E = (3C_l^2 - 4C_t^2)\, C_t^2/(C_l^2 - C_t^2)\, V, \quad \mu = C_t^2/V.$$

The measurement results are given in Fig. 2 (points 1), which also shows the experimental data: 2 [12]; 3 [13]; 4 [14]; 5 [15].

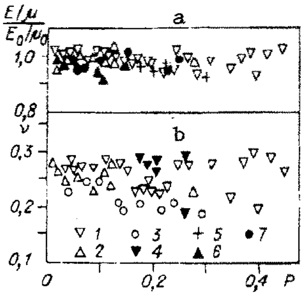

Fig. 3

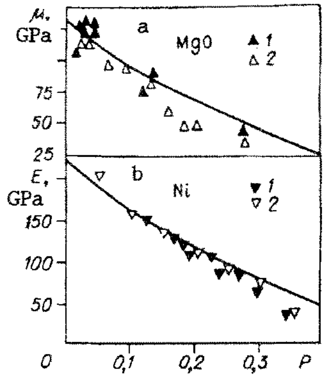

Fig. 4

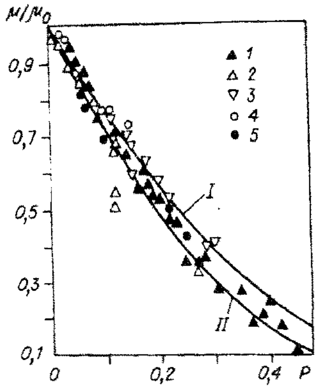

Fig. 5

Measurement of a sensitive characteristic, such as the Poisson bracket ν, involves special difficulties [14]. The theoretical concepts based on the model [4, 14] indicate that ν diminishes with an increase in P, while the experimental results are rather contradictory [15, 16]. We have determined the experimental values of ν with respect to the measured ultrasound velocity by means of the equation

$$\nu = (C_l^2 - 2C_t^2)/2\,(C_l^2 - C_t^2).$$

They are given in Fig. 3b (points 1), where points 2 correspond to data from [12], 3 represent data from [14], and 4 are data from [15]. On the whole, a slight reduction in ν was observed with an increase in P. In measurements, the value of ν is usually determined with respect to the E and μ moduli by means of the expression $\nu = E/2\mu - 1$ [14, 16]. Therefore, for a more reliable analysis of the Poisson bracket, we determined for a number of materials the experimental ratio $(E/\mu)/(E_0/\mu_0)$, where E_0 and μ_0 are the compact-state characteristics borrowed from [7], which are given in Table 1. The results obtained are given in Fig. 3a for iron, copper (5: [14]), molybednum (6: [17]), and tungsten (7: [17]). It is evident from Fig. 3 that the variation of porosity hardly affects this ratio. These data support the assumption that the Poisson bracket is independent of porosity in estimating the mechanical characteristics of porous materials.

In utilizing the above assumption, the moduli E and μ can be calculated, like the modulus B, on the basis of expression (1), and the velocities C_ℓ and C_t, like C_w, by means of (2). The calculation results for iron are represented by the curves in Figs. 1a and 2a.

This agreement with experimental data made it possihle to use the proposed approach for a wide range of porous materials. The parameter α and the elastic characteristics necessary for calculations are given in Table 1 for Ti, Ni, Co, Cu, Mo, W and MgO on the basis of data from [5, 7, 18]. As an example of typical results, Fig. 4b provides the curve representing Young's modulus of porous nickel as a function of P. It lies close to the experimental data from [19] (points 1) and [11] (points 2). Figure 5 shows the theoretical values of the relative shear modulus μ/μ_0 for titanium and molybdenum as functions of porosity (curves I and II). The calculated values of the moduli of other metals lie between these curves. There is a tendency to a stronger dependence of the elastic characteristics on porosity for metals with a large atomic number, which is a due to an increase in the α parameter in passing from titanium to molybdenum and tungsten. The experimental results for a number of metals virtually overlap and fit well within the interval between curves I and II (Fe: points 1 — present paper, 2 [12]; Cu: 3 [14]; Mo: 4 [17]; W: 5 [17]).

Description of porous ceramic materials is of considerable interest. Figure 4a shows the results obtained in calculating the shear modulus μ for magnesium oxide. The theoretical curve is in good agreement with experimental data from [18] (points 1) and [20] (points 2). This indicates a fairly broad applicability of the proposed approach in investigating the elastic characteristics of porous materials.

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