VISCOSITY OF SOILS UNDER SHOCK LOADINGS

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We present experimental data on the bulk viscosity of soils under shock loadings with stress rates $\dot{\sigma}$ from quasistatic to $2 \cdot 10^{10}$ Pa/sec for loads up to $2 \cdot 10^8$ Pa. Data on the viscosity of certain soils (sands) are cited in the literature [1], but these values are incomplete, and the method used to determine them [2] has a number of limitations.

Table 1 lists the results of shock dynamic compression tests performed on four types of soils loaded under conditions of a simple state of strain.

The experimental procedure was similar to that used in [2]. The viscosity was calculated by using the model of an elastic viscoplastic medium described in [3] by the formula

$$\frac{\partial\varepsilon}{\partial t} = Q[\sigma - f(\varepsilon)] + \begin{cases} \dfrac{1}{E(\varepsilon)} \dfrac{\partial\sigma}{\partial t}, & \dfrac{\partial\sigma}{\partial t} \geqslant 0, \\ \dfrac{1}{E^*(\sigma, \varepsilon)} \dfrac{\partial\sigma}{\partial t}, & \dfrac{\partial\sigma}{\partial t} < 0, \end{cases} \quad (1)$$

where σ is the stress, ε is the strain, and t is the time during uniaxial deformation under conditions of a simple state of strain, and the function Q, which characterizes the viscosity, depends on two parameters λ and μ:

$$Q = \mu[\sigma - f(\varepsilon)]^{\lambda}.$$

Under extreme loading conditions

$$\sigma = f(\varepsilon) \quad \text{as} \quad \dot{\sigma} \to 0,$$
$$\varepsilon = \sigma/E(\varepsilon) + C \quad \text{as} \quad \dot{\sigma} \to \infty;$$

and during unloading $\varepsilon = \sigma/E^*(\sigma, \varepsilon) = C(\varepsilon)$.

The viscosity was determined by the following procedure: 1) the values of $\partial\varepsilon/\partial t$ and $\partial\sigma/\partial t$ were determined by the numerical differentiation of the experimental relations $\varepsilon = \varepsilon(t)$ and $\sigma = \sigma(t)$; 2) the moduli of quasistatic $f(\varepsilon)$ and maximum dynamic $E(\varepsilon)$ loadings were determined from the uniaxial strain diagrams of the soil $\sigma \sim \varepsilon$; 3) the parameters μ and λ, which determine the viscosity, were found by the method of least squares.

The method of calculation differed from that described in [3] in eliminating the a priori calculations of the moduli characterizing the unloading and extreme loading conditions. Large errors in the calculation of the tangential derivatives and cumbersome calculations were eliminated by using a computer to determining μ and λ by the method of random search.

The values of μ and λ determined from the experiments are given in Table 2 for all the soils. Intermediate results [graphs of $\sigma(t)$, $\varepsilon(t)$, and $\sigma(\varepsilon)$] are given for clay (Figs. 1, 3, and 5) and sand (Figs. 2, 4, and 6).

TABLE 1

Soil	Density, g/cm³	Moisture content, wt.%	Porosity, %	Mass per unit vol. of skeleton, g/cm³	Mass per unit vol. of skeleton, g/cm³
Clay	2,73	16,2	34,8	1,88	1,78
Loam	2,68	6,8	38,4	1,96	1,65
Sand	2,65	7,9	41,8	1,65	1,52
Loess	2,65	8,2	47,2	1,52	1,40

TABLE 2

Soil	λ	μ
Loam	0,30	0,0380
Loess	0,55	0,0076
Sand	0,16	0,0008
Clay	0,22	0,0095

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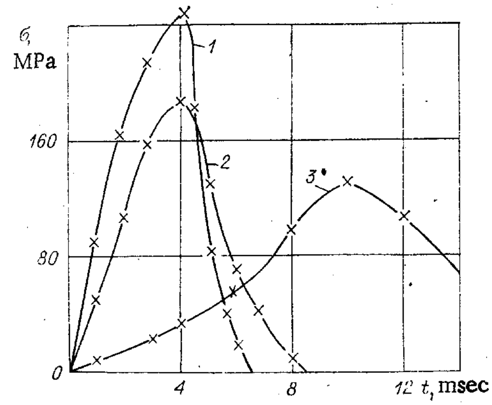

Fig. 1

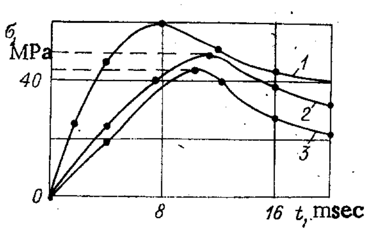

Fig. 2

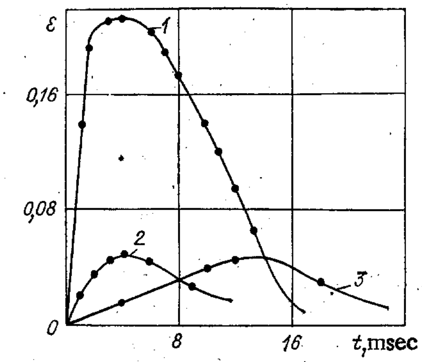

Fig. 3

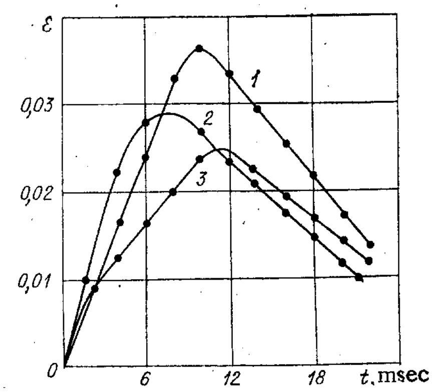

Fig. 4

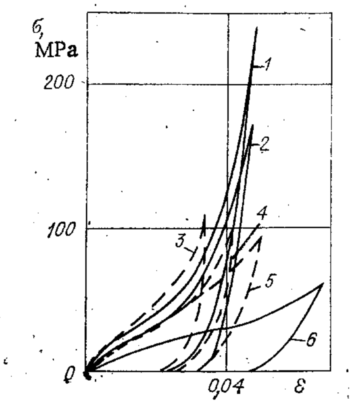

Fig. 5

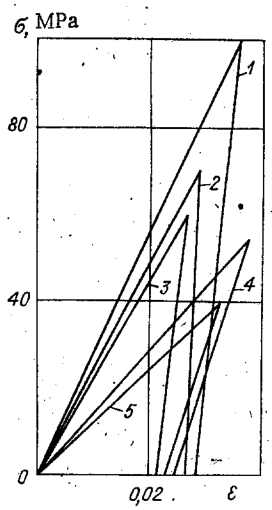

Fig. 6

The three graphs on each of Figs. 1-4 correspond to different rates of dynamic loading. On Figs. 1 and 3 curves 1-3 correspond to loading rates of $2 \cdot 10^{10}$, $4.67 \cdot 10^{9}$, and $1.85 \cdot 10^{9}$ Pa/sec, respectively; on Figs. 2 and 4 curves 1-3 correspond to 8.36, 4.35, and $4.28 \cdot 10^{8}$ Pa/sec, respectively.

The graphs on Figs. 5 and 6 also correspond to different loading rates. Curve 1 on Fig. 5 is for the maximum dynamic loading rate of $2 \cdot 10^{10}$ Pa/sec; curves 2-5 are for 4.67, 4.47, 1.85, and $0.74 \cdot 10^{9}$ Pa/sec, respectively; curve 6 is quasistatic loading. Curves 1-4 on Fig. 6 for loading rates of 22.0, 8.36, 4.35, and $4.28 \cdot 10^{8}$ Pa/sec, respectively; curve 5 is for quasistatic loading.

Analysis of the data of Table 2 shows that the function determining the viscosity of soil varies over wide limits. It is largest for loess and smallest for sand.

The small variation of λ confirms the substantial nonlinearity of the equation of state (1).

A comparison of our results with those in [1], obtained under different soil conditions by using a method which differs somewhat from ours, shows that λ is only slightly dependent on the soil conditions and the method of calculation; our results and those in [1] both lie in the range $0 \leqslant \lambda \leqslant 1$.

At the same time μ fluctuates widely, depending mainly on the moisture content, the porosity, and the granulometric composition of the soil. Our values of μ are considerably smaller than those in [1]. A direct correlation with a correlation coefficient of 0.95 was established between the moisture content of the soil and μ.

The accuracy of the determination of μ and λ was estimated by approximate calculations of the average error of the determination of these values as functions of directly measurable quantities. To do this we used the formula for the mean-square error m_φ of a function φ of several arguments (x, y, z,...) [4]:

$$m_\varphi = \sqrt{\left(\frac{\partial\varphi}{\partial x}\right)^2 m_x^2 + \left(\frac{\partial\varphi}{\partial y}\right)^2 m_y^2 + \left(\frac{\partial\varphi}{\partial z}\right)^2 m_z^2 + \dots}\,.$$

In the calculation the mean-square error of the determination of the running and limiting dynamic diagrams was taken equal to 0.15-0.18 for uniaxial dynamic compression, and 0.08-0.1 for limiting static compression.

The calculated value of the mean-square error of the determination of μ was 0.22-0.26, and that of λ 0.25-0.29.

The maximum relative deviations of the determination of these values calculated for individual input data were 0.44-0.58 with a probability of up to 0.99, and 0.3-0.4 for duplicate measurements of the input data.

LITERATURE CITED

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