MEASUREMENTS OF THE VELOCITY OF SOUND IN SHOCK-COMPRESSED QUARTZITE, DOLOMITE, ANHYDRITE, SODIUM CHLORIDE, PARAFFIN, PLEXIGLAS, POLYETHYLENE, AND FLUOROPLAST-4

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An important thermodynamic parameter which determines the state of a compressed substance is the propagation velocity in it of weak perturbations or the velocity of sound. Data concerning the velocity of sound is useful for studying the equation of state of the substance in the high-pressure region and is of interest for solid-state physics and geophysics.

In this paper, the results are stated of experimental measurements of the velocity of rarefaction waves in shock-compressed quartzite, dolomite, anhydrite, monocrystalline NaCl, paraffin, Plexiglas, polyethylene, and fluoroplast-4 by means of manganin pressure sensors, described in [1]. The scheme for carrying out the experiments is shown in Fig. 1a [1) explosive charge; 2) screen; 3) substance being investigated; 4) manganin pressure sensor; 5) electrocontact sensor; 6) outputs of manganin pressure sensor]. Figure 1b shows the x vs t diagram of the shock-loading process and subsequent relief of the substance being investigated. Compression of the sample being investigated was effected with a plane shock wave, formed as the result of the explosion of a cylindrical explosive charge, the diameter of which was 90-120 mm. The thickness of the aluminum or copper screen covering the sample was 10 mm. The pressure sensor is a sinusoid of manganin foil with a thickness of 0.05 mm and glued by means of epoxy resin between the surfaces of separation of the sample being investigated. The thickness L of the sample is 10-12 mm. The initial electrical resistance of the sensor R_0 was 1.5 to 2 Ω and the total resistance of the copper outputs of the probe $R_{out} \sim 0.02$ Ω. A pulsed voltage was applied to the sensor through a ballast resistance $R_b \gg R_0$ for several microseconds up to the instant of arrival at the sensor of the shock wave from a 4 μF capacitor. The change of voltage at the sensor outputs which occurs as a result of the change of the electrical resistance of the sensor during its shock loading and in the rarefaction wave was recorded by means of a type C1-24 oscilloscope. The signal to be recorded was applied without preamplification directly to the deflector plates of a cathode ray tube. The electrocontact sensor, positioned at the free surface of the sample, served to produce a time marker on the oscillogram (Fig. 2) corresponding to the instant of arrival of the loading shock wave on the surface mentioned. Figure 2a-d shows some of the oscillograms obtained in the experiments to measure the propagation velocity of rarefaction waves in quartzite, dolomite, sodium chloride, and fluoroplast-4, respectively. The frequency of the scaling sinusoid on all oscillograms is 5 MHz.

The maximum propagation velocity of the stress-relieving wave through the shock-compressed substance being studied was calculated by means of the expression

$$c = u + [L - u(t_1 + t_2)]/(t_1 + t_2 - L/D) = L/\sigma t_2,$$

where L is the initial thickness of the sample being investigated (see Fig. 1); D is the propagation velocity through the sample of the loading shock wave; u is the mass velocity behind its front; σ is the magnitude of the relative compression by the shock wave of the substance being investigated; t_1 is the time of passage of the shock wave through the sample from the manganin pressure sensor to the electrocontact, positioned at the free surface of the sample; t_2 is the time interval from the instant of closure of the electrocontact up to the instant of arrival of the rarefaction wave at the manganin pressure sensor. Corrections were introduced when carrying out the calculations, which take into account the thickness of the pressure sensor and the difference in the

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TABLE 1

Substance investigated, g/cm³	Screen material	Mass velocity in screen, u, km/sec	Parameter of shock-wave compression of sample				Rarefaction wave velocity c, km/sec
			D, km/sec	u, km/sec	σ	P, kbar	
Quartzite $\rho_0 = 2,65$	Copper	0,34	5,45	0,54	1,111	78	7,22±0,29
	Aluminum	0,69	5,67	0,79	1,163	118	7,62±0,13
	"	1,14	5,70	1,25	1,278	188	7,67±0,13
	"	1,24	5,70	1,37	1,317	206	8,58±0,10
	"	1,38	5,71	1,53	1,368	231	8,80±0,10
	"	1,50	5,72	1,68	1,415	255	9,12±0,13
	"	1,80	5,75	2,05	1,556	312	9,43±0,20
Dolomite $\rho_0 = 2,84$	"	1,50	6,92	1,51	1,279	297	8,34±0,10
Anhydrite $\rho_0 = 2,97$	"	1,50	6,29	1,55	1,327	290	7,00±0,10
Sodium chloride $\rho_0 = 2,16$	"	1,50	5,75	1,79	1,450	220	5,91±0,13
Paraffin $\rho_0 = 0,9$	"	1,14	5,49	1,67	1,438	82,3	6,53±0,10
	"	1,50	6,17	2,19	1,552	121,2	7,37±0,15
Plexiglas $\rho_0 = 1,18$	"	1,14	5,29	1,66	1,457	103	6,57±0,10
	"	1,50	5,88	2,13	1,568	148	7,56±0,17
Polyethylene $\rho_0 = 0,92$	Copper	0,34	3,65	0,63	1,208	21,1	4,48±0,11
	Aluminum	1,14	5,38	1,75	1,482	86,5	6,49±0,10
	"	1,24	5,58	1,89	1,512	97	6,64±0,10
	"	1,50	6,19	2,25	1,570	128	7,31±0,11
Polyethylene (fluoroplast) $\rho_0 = 2,19$	"	1,14	4,46	1,45	1,482	142	5,68±0,22
	"	1,50	5,16	1,86	1,564	210	6,59±0,10

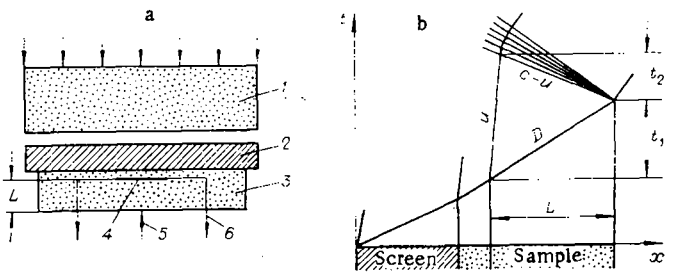

Fig. 1

scanning speed of the oscillograph beam. The parameters used in the calculations for the samples compressed by the shock waves were determined on the basis of the experimentally measured values of the wave velocities in the samples, $D = L/t_1$, and the pressures at the shock front p. The magnitude of the shock-loading pressure p was determined, starting from the experimentally measured value of the electrical resistance of the manganin sensor behind the shock front, equal to $R = (R_0 + R_{out})z/z_0 - R_{out}$ [1], where z/z_0 is the ratio of the amplitude of the beam deflections on the oscillogram (see Fig. 2). For this, the dependence of the electrical resistance of the manganin on the shock-loading pressure $R/R_0 = f(p)$ from [1] was used. Correspondingly, the magnitude of the mass velocity behind the loading shock front $u = p/\rho_0 D$ and the magnitude of the relative compression of the sample by the shock wave $\sigma = \rho/\rho_0 = D/(D - u)$ were used. In addition, the values of p and u were found by the method of "reflection" [2] with respect to the known parameters of state in the screen and the experimentally measured wave velocity in the sample. The shock adiabats of the screens used for this were taken from [3]. In the coordinates of wave velocity D vs mass velocity u, their adiabats are described by the relations $D = 5.25 + 1.39u$ and $D = 3.95 + 1.50u$ for aluminum and copper, respectively. Comparison of the shock-compression parameters obtained in this way for quartzite, dolomite, and fluoroplast-4 with the previously published data [4-6], determined under these conditions by the electrocontact method, show their excellent agreement.

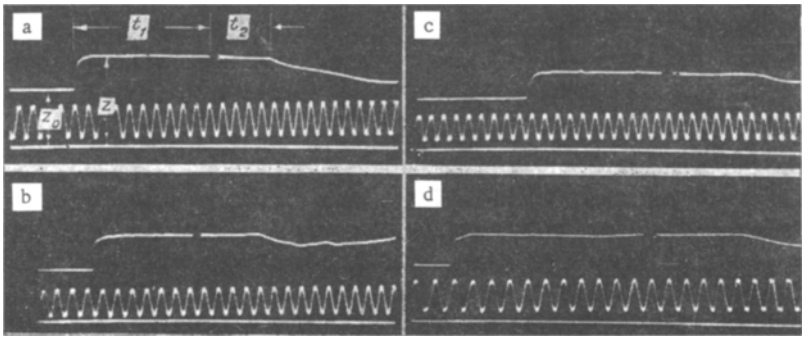

Fig. 2

The propagation velocities of rarefaction waves in the materials studied obtained by this method are given in Table 1 together with the parameters used in the calculations for the shock-wave loading of the samples. Every value given in the table for the velocity of the rarefaction wave is the result of averaging 5-10 independent recordings made in a series of identical experiments. The mean-square errors of the rarefaction wave-velocity measurements are given in the table. The results of the rarefaction wave-velocity measurements in fluoroplast-4, obtained by means of the manganin pressure sensor, are found to be in excellent agreement with the data of similar measurements in [5], carried out by means of a magnetoelectrical method for measuring the mass velocities. The agreement between the experimental data themselves, obtained by the different methods, confirms the validity of the values of the shock-loading wave velocity measured by means of the manganin pressure sensor.

The relation is noteworthy between the wave and mass velocities, and the rarefaction wave velocities for paraffin, polyethylene, fluoroplast-4 and Plexiglas. If, from the data of the table, we calculate the tangent of the angle of lateral loading [7] $\tan\alpha = \sqrt{(C/D)^2 - [(D-u)/D]^2}$ for the materials listed, then the quantity obtained amounts to 1.0-1.1, which exceeds considerably the values of $\tan\alpha$ measured in [7] for a number of metals, and also for NaCl (see Table 1), which amount to only ~0.7. It cannot be excluded that such high (1.0-1.1) values of $\tan\alpha$ are characteristic for organic materials. An increase of $\tan\alpha$ for quartzite in the region examined from 1 to 1.5 which is proportional to the increase of pressure is explained, obviously, by the occurrence in quartzite of a phase transition of the first order, similar to that observed earlier when studying boron carbide [8] and boron nitride [9]. Accordingly, the Mach numbers $(D-u)/c$ of the substances studied are also less by a factor of 1.5 to 2 by comparison with the materials investigated in [7].

As the results of the experiment showed, the use of the manganin pressure sensor permits reliable measurements to be carried out of the velocity of sound in nonmetals in the region of relatively low (100-300 kbar) pressures, i.e., in the region where the use of the methods of "overtaking" and "edgewise" stress relief [7] with the photochronographic recording method becomes very difficult because of inadequate brightness of the emission originating during impact of the thin "separating" indicator with the surface of the receiver, made of Plexiglas or some other optically transparent material. The merit of the proposed method is also the possibility of a direct and independent determination in each individual experiment simultaneously of the velocity of sound, the wave velocity, and the pressure.

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EXPERIMENTAL INVESTIGATIONS OF THE COMPRESSIBILITY OF SANDY SOILS AND THE CONDITION OF PLASTICITY DURING BRIEF DYNAMIC LOADINGS

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§1. Experimental investigations of samples of sandy soils with a bulk weight of $\gamma_0 = 1.50$ g cm^3, moisture content $w = 0.003$ (air-dried soil) and 0.05; 0.15 were carried out on a quasistatic type of equipment, similar in construction to that described earlier in [1]. The equipment consists of a vertically standing cylinder with the sample of soil distributed in it in a special collar with a diameter of $D_0 = 150$ mm and height $h_0 = 30$ mm and a piston which transmits a shock loading to the soil sample. Different conditions of deformation of the samples were created by means of rubber spacers and by varying the drop height of the load. In addition, static tests of the samples were carried out at a rate of deformation of $\varepsilon = 2 \cdot 10^{-3}$ to $0.5 \cdot 10^{-5}$ sec^{-1}. Each sample was subjected to a triple loading. A fivefold repeat of the experiments was provided for, under one and the same conditions (series of experiments).

The principal stresses in the sample $\sigma_1(t)$ and $\sigma_2(t)$ were recorded by means of tensometric probes, installed in the center of the piston, in the center and edge of the cylinder bottom (four probes), and in the lateral surface of the collar (two probes). The total force transmitted to the sample by the shock was recorded also by means of a tensometric thimble.

The tensometric probes for measuring the stresses had a diameter of the sensitive element (a round thin plate, pinched around the outline) of $d = 22$ mm and a thickness of $\delta = 2$ to 4 mm. The systematic errors of the stress measurements with these probes in the range of loads investigated were studied in [3] and did not exceed ±3 to 5% in the experiments.

Comparison of the readings of the probes located in the center of the piston and in the center and edge of the cylinder bottom confirms their agreement with an accuracy up to the random measurement errors. A similar conclusion can be drawn with respect to the data on the stresses $\sigma_1(t)$ obtained by measurements of the total force transmitted to the sample by the shock. Therefore, in the future, all probes for measuring the stresses $\sigma_1(t)$ will be treated as equally justified. It was assumed, therefore, that the stresses over the height of the sample and over its diameter are distributed uniformly.

The deformations of the sample were measured by means of three tensometric displacement probes, positioned at angles of 120° (in the plane of the sample). The displacement probe consisted of two arms, rigidly attached in the lower part of the cylinder. A wedge, joined to the movable piston of the equipment, was installed between the arms. Tensometers were secured to the arms, the signals from which are proportional to the displacement of the piston.

The deformation was determined in quasistatic approximation by the relation $\varepsilon(t) = u(t)/h_0$, where $u(t)$ is the displacement of the piston. The stresses to be recorded $\sigma_{1i}(t)$ and $\sigma_{2i}(t)$ and the deformation $\varepsilon_i(t)$ (i =

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