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IMPACT DYNAMICS OF POROUS POWDER

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Abstract: The shock adiabats have been built experimentally in the range of moderate pressures for three porous materials: Al_2O_3 , wheat flour, and their mixture. The model, which describes the behavior of porous powder materials under large-amplitude dynamic loading, has been constructed. The model applicability to describing the shock wave processes is confirmed by good agreement of the calculated shock adiabats and the data obtained in the experiments. The compressive strength of compacted samples has been determined. The possible trend of further researches is presented in conclusion.

Keyword: powder, porous matter, Hugoniot, shock compression, model, compressive strength.

1. INTRODUCTION

The study of behavior of porous materials under dynamic loading is of interest due to scientific and technological problems arising in compaction. This explains a great deal of the experimental and calculation works in which the authors develop the models and investigate the processes in porous media. At the same time, the available literature almost does not contain the studies which investigate the behavior of porous low-density (less than half as low as the density of solids) materials. We do not know the studies in which porous organic materials are investigated.

This work is devoted to studying the impact dynamics of low-density porous materials including the organic ones. The shock adiabats are determined experimentally for three porous materials: Al_2O_3 , wheat flour, and their mixture. To determine them, we used the original experimental procedure. The model which describes the behavior of porous powder materials under large-amplitude dynamic loading has been developed. The model applicability to describing the shock wave processes is confirmed by good agreement of the calculated results and the experimental data. The compressive strength of the compacted samples has been determined. A possible trend of further investigations in this field of research is formulated in conclusion.

The present report contains the chapters in accordance with tasks of the Agreement. Chapters 2-4 and 5-7 have the own notations for the values and functions in equations.

2. THE SELECTION AND CHARACTERIZATION OF SAMPLES

By agreement with LANL the following materials have been selected for the experiments:

- powder Al_2O_3 with particles $20 \dots 75 \mu m$ in size;
- wheat flour with particles $20 \dots 75 \mu m$ in size;
- mixture of these powders in volumetric ratio 1 : 1.

The mean linear size of the particles of each powder was $50 \mu m$ with mean square deviation $20 \mu m$.

The initial packing density of the powder of Al_2O_3 was equal to $1.06 \pm 0.02 g/cm^3$, the density of monolithic Al_2O_3 being $3.85 g/cm^3$. The volume of the pores was $72.5 \pm 1.4\%$ of the total volume. The initial packing density of wheat flour was equal to $0.65 \pm 0.02 g/cm^3$, the density of monolithic flour being $1.27 \pm 0.02 g/cm^3$.

In the framework of this contract the density of "monolithic wheat flour" is the density determined by static compression of wheat flour to the pressure 4 kbar with the subsequent load releaf to the atmospheric pressure. The volume of the pores was $48.8 \pm 2.2\%$ of the total volume.

The initial packing density of the mixture of Al_2O_3 powder and the wheat flour with volumetric ratio 1 : 1 was $0.87 \pm 0.02 g/cm^3$. The volume of the pores was $60.6 \pm 2.3\%$ of the total volume.

3. THE SELECTION OF EXPERIMENTAL PARAMETER BOUNDS

According to the Task 2.3 the Hugoniot of the above materials have been determined for the shock pressures(P) within the range of 7 *kbar* to 50 *kbar*, which was accepted by mutual consent. In the experiments we have determined the shock wave velocity (D) and the mass velocity (u) of the powder under the shock loading. On the basis of the measuring data the dependences (D, u) and (P, u) have been constructed from which the compaction ratio of the powder in the shock wave may be calculated.

The measurements have been conducted with the powder samples in the form of cylinder tablets 5 *mm* thick and 85 *mm* in diameter.

A detailed account of the experimental technique and the results of measuring the parameters of shock waves in the powders will be presented in the next chapter.

4. SHOCK HUGONIOTS OF Al_2O_3 POWDER, WHEAT FLOUR AND THEIR MIXTURE IN VOLUME RATIO 50/50

4.1. Introduction

According to Task 2.3 of the contract we determined experimentally the shock Hugoniots of the powder of Al_2O_3 , wheat flour and their mixture in equal volume ratios (the size of the particles ranged from 25 to 75 μm). For this purpose the powders were loaded by the shock waves of different intensity in the pressure range from 8 *kbar* to 50 *kbar* and the mass velocity and the velocity of the shock wave were measured. On the basis of the measurement results, the shock Hugoniots are plotted in the coordinates (D, u) and (P, u).

4.2. Arrangement and results of the experiments

Let us describe the methods of determining the mass velocity and the velocity of the shock wave in the powders tested.

Experimental set-up (Fig.1) was composed of a plane-wave generator 1, a basic explosive charge 2, a powder layer 3, an aluminum foil 4, at the surface of the latter a spiral coil 5 was placed. An inductive transducer 6 was placed under the powder layer, whereas contact pickups 7 and 8 registering the passage of the shock in the powder were positioned within the powder layer. The plane-wave generator consists of two parts filled with explosives with different detonation velocity. The geometry and the explosives were chosen appropriately so that the detonation wave at the lower section of the basic charge be plane. Special measurements by contact pickups have shown that the time discrepancy of the arrival of the detonation wave at the foil 4 is not less than 100 *nsec*.

The foil 4 is an aluminum sheet of thickness 310 μm , at whose surface a spiral coil 5 (thickness 30 μm , outer diameter 40 *mm*) made of copper wire with the coil width 1.0 *mm* is positioned. The powder layer 3 is 5 *mm* thick. The measurements of the shock wave velocity were taken at this base. As the foil 4 begins motion, the shorting of the electric contact pickup 7 takes place, and after the arrival of the shock wave at the lower section of the powder layer, the contact 8 is closed. Immediately beneath the powder we placed a 10-turn coil of diameter 40 *mm* made of copper wire 0.3 *mm* in diameter, whose signal is registered by a digital oscillograph

with time resolution 50 nsec and amplitude resolution 1%.

At the time instant t_0 a pulse of constant current $I = 5 \text{ A}$ is fed to the coil 5. After $T \sim 300 \text{ sec}$ the shock wave achieves the surface of the foil 4, which destructs the coil 5. From this time instant the foil acquires the velocity equal to the mass velocity of the powder u . The magnetic field generated by the vortex currents in the foil 4 is determined in the domain below the foil by two images of the coil 5. The first image is identical to the coil 5 itself with the current I_0 . At the time instant $t_0 + T$ its position coincides with that of the coil 5. The velocity with which the first image moves along the z axis is $u - v$, with $v = 2/(\mu_0 \sigma \delta)$, where σ , δ are the volume conductivity and thickness of the foil 4, respectively. The second image has a reverse direction of current and is initially placed at the distance vT from the foil along the z axis. The velocity of this image is the same as for the first image. Let the coefficient of mutual induction of the coils 5 and 6 be $L(z)$, where z is the distance between them. Then the electromotive force arising in the coil 6 due to the motion of two images of the coil 5 is as follows

$$E(t) = \left[-I_0 \frac{\partial L(z)}{\partial z} \Big|_{z=z_0-(u-v)t} + I_0 \frac{\partial L(z)}{\partial z} \Big|_{z=z_0+vT-(u-v)t} \right] (u - v).$$

From this equation we find

$$u = v + \frac{E(t)}{I_0 \left[\frac{\partial L(z)}{\partial z} \Big|_{z=z_0+vT-(u-v)t} - \frac{\partial L(z)}{\partial z} \Big|_{z=z_0-(u-v)t} \right]}.$$

To calculate the dependence $L(z)/z$ let us use the following formulas. As follows from [1], the vector potential of linear circular current has only one component $A = A(r, z)$ and can be written down as

$$A(r, z) = \frac{I_0}{\pi k} (a/r)^{1/2} \left[\left(1 - \frac{k^2}{2}\right) K - E \right],$$

where

$$k^2 = \frac{4ar}{(a+r)^2 + z^2},$$

a is the radius of a turn of the circular current, K and E are the complete elliptic integrals of the first and second kinds of order

$$K = \int_0^{\pi/2} (1 - k^2 \sin^2 \Theta)^{-1/2} d\Theta, \quad E = \int_0^{\pi/2} (1 - k^2 \sin^2 \Theta)^{1/2} d\Theta.$$

One can easily calculate

$$\frac{\partial A(r, z)}{\partial z} = \frac{I_0 z}{2\pi r[(a+r)^2 + z^2]^{1/2}} \left[K - \frac{a^2 + r^2 + z^2}{(a-r)^2 + z^2} \cdot E \right].$$

Then the coefficient of mutual induction of two turns disposed coaxially at the distance z from each other and having the radii a and b will be equal to

$$L_*(z) = \frac{\mu_0 A(b, z)}{I_0} 2\pi b$$

and

$$\frac{\partial L_*(z)}{\partial z} = 2\pi b \frac{\mu_0}{I_0} \frac{\partial A(b, z)}{\partial z} = \frac{\mu_0 z}{[(a+b)^2 + z^2]^{1/2}} \left[K - \frac{a^2 + b^2 + z^2}{(a-b)^2 + z^2} \cdot E \right].$$

Hence, applying the superposition principle for the vector potential, one can calculate the coefficient of mutual induction for an arbitrary pair of axisymmetric coils. The values of mass velocity u were calculated from experimentally measured $E(t)$. The values of velocity of shock waves D were determined from the measured times of motion of a shock wave through a specimen. According to our estimates the error in determining D and u is not higher than 5%. The results are presented in Tables 1 to 3 which also contains the values of pressure P behind the wave, calculated from D and u in a standard way. Figures 2 to 7 present (D, u) and (P, u) plots of the powders under consideration.

The technique applied is one of the variety of electromagnetic methods of measuring the parameters of shock waves in condensed media. As compared to the original method of Zavoiskii (see [2], for example) and to the methods applied in [3, 4], this technique has essential advantages, since it does not require experimental determination of magnetic induction and its derivatives in a constant magnetic field.

4.3. Discussion

1. Initial packing density of Al_2O_3 powder was $1.06 \pm 0.02 \text{ g/cm}^3$ with the monolithic density 3.85 g/cm^3 . In the shock wave the powder is compacted due to the reordering (rearrangement) of the powder particles to a denser packing. Since pressure in the powder is not too high (up to 50 kbar),

one should not expect the crushing of the Al_2O_3 particles. The pressure of the order of 12 *kbar* is likely to be sufficient for dense package of the particles and further increase in the pressure fails to result in the increase in density until the stage of fragmentation of Al_2O_3 particles begins. The density about 2.5 g/cm^3 corresponds to dense package. In this case the size of pores is approximately 35% of the total volume of pressed powder ($\rho/\rho_0 \approx 2.3$, $D/u \approx 1.77$).

2. Initial packing density of the wheat flour was $0.65 \pm 0.02 \text{ g/cm}^3$ with the monolithic density $1.27 \pm 0.02 \text{ g/cm}^3$. The "monolithic density" was determined by static compression of the wheat powder up to the pressure 4 *kbar* with subsequent load relief to atmospheric pressure. The compression curve of the wheat powder changes her behavior over the range $2 \div 3 \text{ kbar}$. We relate this to the fact that over the pressure range 0 to 3 *kbar* the pores between the particles collapse, and with further increase in pressure the compression of the monolith occurs. Maximum density at pressure 10 *kbar* achieves $1.50 \div 1.55 \text{ g/cm}^3$ ($\rho/\rho_0 \approx 2.35$, $D/u \approx 1.74$). .

3. Initial density of the mixture of Al_2O_3 powder with wheat flour in equal volume ratio was $0.87 \pm 0.02 \text{ g/cm}^3$. Under static compression to the pressure 12 *kbar* and subsequent load relief the density of the mixture is about 1.79 g/cm^3 . This indicates that flour does not fill all of the pores in the matrix formed by the Al_2O_3 particles. If all pores were filled, the mixture density would be 2.20 g/cm^3 . We believe that the mixture is first compressed in the shock wave to the density 1.79 g/cm^3 , and then without change in the porosity the wheat powder is compressed to $1.5 \div 1.55 \text{ g/cm}^3$. Then final density of the mixture should be 35% of the total volume of pressed powder 1.96 g/cm^3 ($\rho/\rho_0 \approx 2.25$, $D/u \approx 1.8$).

Fig. 1: Experimental set-up.

Tab. 1: Hugohiot data, Al_2O_3 powder.

<i>Exp</i> <i>N</i>	<i>Shock velocity</i> <i>D, m/s</i>	<i>Particle velocity</i> <i>u, m/s</i>	<i>Pressure</i> <i>P, kbar</i>
1	2800	1660	49.3
2	2370	1375	34.5
3	1670	962	17.0
4	1520	879	14.2
5	1440	815	12.4

Tab. 2: Hugohiot data, Wheat flour.

<i>Exp</i> <i>N</i>	<i>Shock velocity</i> <i>D, m/s</i>	<i>Particle velocity</i> <i>u, m/s</i>	<i>Pressure</i> <i>P, kbar</i>
12	3290	1775	38.0
13	3060	1630	32.4
14	1920	1090	13.6
15	1790	1067	12.4
16	1780	1040	12.0
17	1520	888	8.8

Tab. 3: Hugohiot data, Al_2O_3 + Wheat flour
(1:1 by vol.).

<i>Exp</i> <i>N</i>	<i>Shock velocity</i> <i>D, m/s</i>	<i>Particle velocity</i> <i>u, m/s</i>	<i>Pressure</i> <i>P, kbar</i>
6	3100	1690	45.6
7	2630	1380	31.6
8	2140	1260	23.5
9	1820	1050	16.6
10	1720	930	13.9
11	1420	820	10.1

Fig. 2: Hugoniot data, Al_2O_3 powder.

Fig. 3: Hugoniot data, Al_2O_3 powder.

Fig. 4: Hugoniot data, Wheat flour.

Fig. 5: Hugoniot data, Wheat flour.

Fig. 6: Hugoniot data, Al_2O_3 + Wheat flour (1:1 by vol.).

Fig. 7: Hugoniot data, Al_2O_3 + Wheat flour (1:1 by vol.).

5. THE MODEL FOR DESCRIBING THE BEHAVIOUR OF POROUS POWDER MATERIALS UNDER LARGE-AMPLITUDE DYNAMIC LOADING

5.1. Introduction

In accordance with Task 2.4 of the Contract, we have constructed the model for describing the behavior of porous-powder materials under large-amplitude dynamic loading. The model formulated for the arbitrary space case is suitable for incorporation in multi-dimensional hydrodynamics codes.

To analyze a priori the processes accompanying dynamic loading of porous media, we need the appropriate models. The models the most often used in calculations are analyzed in [5], which still is of current concern. The Carroll-Holt approach [6] is probably the most often used. The primary model constructed by these authors was modified by different researchers. The development of the approach from [6] can be exemplified by the model from [7]. In the most of the developed theories called in [5] the theories of the first approximation, the effect of shear resistance on behavior of the medium at irreversible compaction and further is neglected. i. e. a stress tensor is assumed to be a sphere tensor. In the case of shock wave loading, such a hypothesis can be inadequately validated. It is shown in [8] that in the vicinity of the shock front the normal (diagonal) components of the stress tensor are not equal and the shear ones substantially differ from zero. Herrmann [5] also comes to a conclusion that the shear resistance should be taken into consideration in further development of the models. This paper considers a more general model of dynamic deformation of porous media, in which the stress tensor is not assumed to be the sphere tensor. In construction, use is made of the Maxwell representation of stress relaxation.

5.2. Basic statements of the model

To describe dynamic deformation of porous media, it is suggested to use the Maxwell representations of the strain mechanisms and the principles of describing them. The earlier formulated model of a viscoelastic body [9] is generalized in the case of a porous medium which is supplementarily assumed to relax volumetrically. The corresponding system of equations

comprises the laws of conservation of mass, pulse, and energy, and the differential equations which describe the evolution of components of the effective elastic strain tensor. In the main axes of the strain tensor which coincide with those of the stress tensor, the system has the form

$$\begin{aligned}
\frac{d\rho}{dt} + \sum_{i=1}^3 \rho \frac{\partial u_i}{\partial r_i} &= 0, \\
\rho \frac{du_i}{dt} - \frac{\partial \sigma_i}{\partial r_i} &= 0, \\
\rho \frac{dE}{dt} - \sum_{i=1}^3 \sigma_i \frac{\partial u_i}{\partial r_i} &= 0, \\
\frac{dh_i}{dt} - \frac{\partial u_i}{\partial r_i} &= -\frac{h_i - (h_1 + h_2 + h_3)/3}{\tau_1} - \left(\frac{\partial u_i / \partial r_i}{\sum \partial u_i / \partial r_i} \right) \cdot \frac{(h_1 + h_2 + h_3)}{\tau_2}, \\
\rho &= \rho_* \exp(-h_1 - h_2 - h_3).
\end{aligned} \tag{1}$$

Here t , r_i are the time and space coordinates, ρ is the medium density. u_i are the velocity vector components, E is the specific density of internal energy, σ_i are the main values of the stress tensor, h_i are the main values of the Hencky strain tensor, and τ_1 and τ_2 are for the relaxation time of shear and volumetric deformations. The system is given in the assumption that mass forces, volumetric sources, and heat transfer are absent. The main hypothesis adopted in formulating the model is that during the process of loading the density of the material ρ_* which corresponds to the relief state changes. In this case, it relaxes to the current density ρ . Hence, the compression ρ/ρ_0 is given as the production of elastic compression ρ/ρ_* and irreversible one ρ_*/ρ_0

$$\frac{\rho}{\rho_0} = \frac{\rho}{\rho_*} \cdot \frac{\rho_*}{\rho_0},$$

(ρ_0 is the initial density of the medium).

The system is closed by the equation for the density of internal energy with the non-spherical strain tensor $E = E(h_i, S)$, Murnaghan formulas $\sigma_i = \rho \partial E / \partial h_i$ and the dependences for $\tau_1 = \tau_1(h_i, S)$ and $\tau_2 = \tau_2(h_i, S)$.

The methods for constructing the relations for E and τ_1 are described in [10, 11] and are not considered in this report. The dependence $E = E(h_i, S)$ constructed for Al_2O_3 has the form

$$E = E_C(\delta, \alpha) + E_D(\delta, D, \alpha) + E_T(\delta, s), \quad \delta = \rho/\rho_*, \quad \alpha = V/V_s$$

$$E_C(\delta, \alpha) = \frac{c_v^2(\alpha)}{k_1(k_1 + 1)}(\delta^{k_1} - 1) + \left(\frac{c_v^2(\alpha)}{(k_1 + 1)} - \frac{(A - C)}{\rho_{s0}} \right) (\delta^{-1} - 1) + \\ + \frac{3(A/B - C)}{\rho_{s0}}$$

$$E_D(\delta, D, \alpha) = 2c_t^2(\alpha)\delta^{k_2}D, \quad D = \frac{1}{2}(d_1^2 + d_2^2 + d_3^2)$$

$$E_T(\delta, s) = \frac{3R\nu}{\mu}\Theta_0\delta^G g(s), \quad g(s) = s + 0.05/s$$

Here c_v, c_t are the volumetric and shear velocity of sound in the initial state [12], Θ_0 is the initial Debye temperature, G is the Grüneisen coefficient, ν is the number of atoms in the Al_2O_3 molecule, μ is the molar mass, R is the universal gas constant, and A, B, C, k_1 and k_2 are the constants, V, V_s are the specific volumes of porous and solid materials, S and s are the entropy and a function of entropy. The parameters presented have the following values:

$$\rho_{s0} = 3.85 \frac{g}{cm^3}, \quad c_v(1.) = 7.63 \frac{km}{s}, \quad c_t(1.) = 6.25 \frac{km}{s}, \quad \Theta_0 = 1000K,$$

$$G = 1.6, \quad \nu = 5, \quad \mu = 101.96 \frac{g}{mol}, \quad R = 0.00831 \frac{g \cdot km^2}{s^2 \cdot grad \cdot mol},$$

$$k_1 = 1.80, \quad k_2 = 2.35,$$

$$A = 276.454 GPa, \quad B = 4.5, \quad C = 279.973 GPa.$$

The relaxation time of shear stresses

$$\tau_1 = \tau_{10} \frac{\exp(\sigma_0/\sigma)}{N_0 + M\varepsilon}$$

where σ and ε are the stress and strain intensities,

$$\tau_{10} = 10 \frac{da\mu s}{cm^2}, \quad \sigma_0 = 55 GPa, \quad N_0 = 10^6 cm^{-2}, \quad M = 10^{10} cm^{-2}.$$

For wheat flour,

$$E = E_S(\delta, \alpha) + E_T(\delta, s), \quad \delta = \rho/\rho_*, \quad \alpha = V/V_s$$

$$E_S(\delta, \alpha) = \frac{c_v^2(\alpha)}{k_1(k_1 + 1)}(\delta^{k_1} - 1) + \frac{c_v^2(\alpha)}{(k_1 + 1)}(\delta^{-1} - 1)$$

$$E_T(\delta, S) = C_V^0 T_0 \delta^G (\exp(s/C_V^0) - 1)$$

where C_V^0 is the specific heat capacity at a constant volume. The parameter values are the following:

$$\rho_{s0} = 1.30 \frac{g}{cm^3}, \quad c_v(1.) = 1.20 \frac{km}{s}, \quad G = 1.275,$$

$$k_1 = 6.40, \quad C_V^0 = 0.1 \frac{J}{mg \cdot grad}.$$

It should be noted that for the wheat flour the dependence $E = E(h_i, S)$ corresponds to the hydrodynamic behavior of the material.

5.3. Relaxation time of volumetric deformations

The relaxation time of volumetric deformation (hydrostatic pressure) is naturally assumed to be inversely proportional to the velocity of volumetric deformation, which is characterized by the specific volume V :

$$\tau_2 \sim \left(\frac{dV}{dt} \right)^{-1}$$

Thus, the problem of determining τ_2 is reduced to constructing the dependence of velocity of the specific volume change on the parameters characterizing the loading and the current state of the medium. As in the case of constructing τ_1 [11], to determine the characteristic features of the dependence τ_2 , we use a representation of the structural mechanisms of irreversible volumetric deformation. Unlike the construction of τ_1 , at which the main level of shear stress relaxation is the microstructural level (evolution of dislocation ensemble) [11], the volume relaxation is mainly due to the processes occurring at the mesostructural level. In this case, the pore collapse with a plastic flow of grain material and the grain fracture are determining. It is often supposed that the time of onset of equilibrium is

equal to the time of compaction (time of pore collapse). Actually, during compaction there appear the zones of high concentration of stresses, equalization of which requires the characteristic time. This leads to formation of "hot spots" which is observed as heterogeneous heating of compacted material known from the experiments. Thus, the time of pore collapse does not determine wholly the time of onset of the thermodynamically equilibrium state of compacted material. In particular, the aforesaid shows that the statements of a widely used Carroll-Holt model [6] should be seriously corrected when applying it to describe the dynamic and shock wave processes. To characterize the change in the specific volume, it is convenient to use the value of porosity α . The parameters of a model Carroll-Holt sphere [6] are connected with α :

$$b - a = b \left(1 - \sqrt[3]{1 - \frac{1}{\alpha}} \right),$$

where b and a are the outer and inner radii of the sphere. In this case, the time of stress equalization under compression is proportional to $(b - a)/c \sim R_0/c$. Here c is the sound velocity in the solid material and R_0 is the characteristic grain size (the average size of a solid region in the porous material with a skeleton). The introduction of R_0 as one of the parameters allows us to take into account the grain sizes.

For a series of materials, the irreversible strain rate in a certain strain rate range is connected with the stress by the relation $\sigma \sim \ln \dot{\epsilon}$, where $\dot{\epsilon}$ is the strain rate. Taking into account this relationship, we can write for the irreversible strain rate that

$$\frac{dV}{dt} \sim \exp \left(\frac{P}{P_c} \right),$$

where P and P_c are the pressure, and P_c corresponds to the beginning of irreversible compaction. The utility of such a qualitative dependence of $\dot{V}$ on P is evidenced by the equation describing the equilibrium of a spherical shell in the plastic state, which is known in the plasticity theory. This solution is generalized in [6] for the dynamic case.

Based on the above qualitative analysis, we can write

$$\tau_2 = \frac{b}{c} \frac{\tau_{20}}{\omega} \frac{(\alpha_0 - 1)^n}{(\alpha - 1)^n} \left(1 - \sqrt[3]{\frac{\alpha_0 - 1}{\alpha}} \right) \exp \left(-\frac{P}{P_c} \right), \quad (2)$$

where ω is the volumetric strain rate which is obviously connected with the velocity of the specific volume change, and the multiplier $(\alpha_0 - 1)^n / (\alpha - 1)^n$ reflects the relationship between the relaxation time and the initial α and current values of porosity. The structure of dependence (2) corresponds to that after compression to the monolithic state the volumetric strain becomes elastic. The constants τ_{20} and n are determined by comparing the calculation results with the experimental data. It should be noted that the proposed form of the dependence for τ_2 has the phenomenological character, and its applicability can be substantiated only by comparing the calculated and experimental data. With the fixed grain size, we can introduce R_0/c into the constant τ_{20} , then $\tau_{20} = \tau_{20} R_0 / c$.

For Al_2O_3 , the parameters of dependence (2) have the following values:

$$\tau_{20} = 0.131, \quad n = 4,$$

$$P_c = \frac{2}{3} Y \ln\left(\frac{\alpha_0}{\alpha_0 - 1} k_3\right), \quad k_3 = \frac{1}{1 - \rho_{00}/\rho_{s0}}, \quad \rho_{00} = 1.06 \frac{g}{cm^3}.$$

For wheat flour,

$$\tau_{20} = 0.333, \quad n = 0,$$

$$P_c = \frac{2}{3} Y \ln\left(\frac{\alpha}{\alpha - 1} k_3\right), \quad k_3 = \frac{1}{1 - \rho_{00}/\rho_{s0}}, \quad \rho_{00} = 0.65 \frac{g}{cm^3}.$$

Here Y is the dynamic yield point.

6. THE VERIFICATION OF MODEL AND CALCULATION RESULTS

6.1. Calculation of shock adiabats for porous Al_2O_3 , wheat flour and their mixture

To calculate the shock adiabats of porous materials investigated under the present contract, we use the one-dimensional variant of system (1) in the plane case:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial r} = 0 ,$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial (\rho u^2 - \sigma_1)}{\partial r} = 0 ,$$

$$\frac{\partial \rho (E + u^2/2)}{\partial t} + \frac{\partial (\rho u (E + u^2/2) - \sigma_1 u)}{\partial r} = 0 ,$$

$$\frac{\partial \rho h_2}{\partial t} + \frac{\partial \rho u h_2}{\partial r} = -\rho \frac{d_2}{\tau_1} , \tag{3}$$

$$\frac{\partial \rho h_3}{\partial t} + \frac{\partial \rho u h_3}{\partial r} = -\rho \frac{d_3}{\tau_1} ,$$

$$\frac{\partial \rho k_0}{\partial t} + \frac{\partial \rho u k_0}{\partial r} = -\rho \frac{k}{\tau_2} ,$$

$$\rho = \rho_* \exp(-h_1 - h_2 - h_3), \quad k = \ln \left(\frac{\rho_*}{\rho} \right), \quad k_0 = \ln \left(\frac{\rho_*}{\rho_0} \right) ,$$

$$d_2 = h_2 - \frac{(h_1 + h_2 + h_3)}{3}, \quad d_3 = h_3 - \frac{(h_1 + h_2 + h_3)}{3} .$$

The problems of discontinuity decay were solved numerically for the given values of mass velocity u behind the shock front. Mathematically, this corresponds to the solution of system (3) with the following initial and boundary conditions:

$$h_1 = h_2 = h_3 = 0 , \quad u = 0 , \quad \rho_* = \rho_0 , \quad s = s_0 \text{ for } t = 0$$

$$u = u_0 = \text{const for } t > 0 , \quad r = 0 \text{ (left)}$$

$\sigma_1 = 0$ for $t > 0$, $r = r_0$ (right).

The calculation results are compared with the experimental data in Figs.8-13 (Figs.8 and 9 are for Al_2O_3 ; Figs.10 and 11 show the data for wheat flour; Figs.12 and 13 are for mixture; D is the shock wave velocity). The solid lines show the hydrodynamic shock adiabats obtained by the above equations of state by the method described in [13]; 1 and 2 correspond to the experimental and calculated data, respectively. The data (calculated and experimental) in the upper part of the Figs.10 and 11 are obtained for monolithic wheat flour. For the mixture, the calculation points 2 are obtained by the laws of the theory of mixtures. As the figures show, the discrepancy between the calculated and experimental data is in the limit of the experimental error.

6.2. Calculation of compression curves

To validate the applicability of the model, we shall use the experimental data on dynamic compaction of solid and porous alumina. The initial boundary value problem of uniaxial deformation of a material layer (a layer of material in a rigid casing), which corresponds to the experimental procedure, is obtained from (3). The condition of uniform deformation is used supplementarily. As a consequence, all the functions in (3) are considered to depend only on time. For example, the system for porous material is reduced to the system of ordinary differential equations:

$$\begin{aligned} \frac{dh_1}{dt} &= \dot{\varepsilon}_1 - \frac{d_1}{\tau_1} - \frac{k}{\tau_2}, \\ \frac{dh_2}{dt} &= -\frac{d_2}{\tau_1}, \\ \frac{dk_0}{dt} &= -\frac{k}{\tau_2}, \\ \frac{dS}{dt} &= \frac{\sigma_i d_i}{\rho T \tau_1} + \frac{\sigma_1 k}{\rho T \tau_2}, \\ h_3 &= h_2, \sigma_i = \rho \frac{\partial E}{\partial h_i}, T = \frac{\partial E}{\partial S}, d_i = h_i - \frac{(h_1 + h_2 + h_3)}{3}, \end{aligned} \quad (4)$$

$$\rho = \rho_* \exp(-h_1 - h_2 - h_3), \quad k = \ln\left(\frac{\rho_*}{\rho}\right), \quad k_0 = \ln\left(\frac{\rho_*}{\rho_0}\right),$$

$$\tau_1 = \tau_1(h_i, S), \quad \tau_2 = \tau_2(h_i, S), \quad E = E(h_i, S),$$

where $\dot{\varepsilon}_1$ is the strain rate in the direction of compression, in this case it is equal to ω . The analogous system for solid material is given in [11]. With the given volumetric strain rate, the system are solved by the Runge-Kutta method of the fourth order.

Figure 14 presents the calculation results for porous alumina compared with the experimental data. Curves show the calculated dependences for $\dot{\varepsilon}_1 = 10^4 \text{ s}^{-1}$. The points show the experimental data: 1-3 from [5], 4 from [14]. The curves depict the effect of initial porosity on the stress (pressure) value, with which the elastic deformation changes to the irreversible compaction. Upon attainment of the monolithic state, transition to the elastic volumetric compression occurs again. It can be admitted that the calculated and experimental data agree well.

6.3. Calculation of shock wave deformation

The calculation of shock-wave processes in porous alumina is made by system (3) with the corresponding initial and boundary conditions.

The evolution of a triangular compression pulse with the maximum amplitude $\sigma_{10} = 40 \text{ GPa}$ which was applied at the boundary of a porous alumina half-space with $\rho_0 = 2.475 \text{ g/cm}^3$, is calculated analogously with [15]. The corresponding initial and boundary conditions have the form :

$$h_1 = h_2 = h_3 = 0, \quad u = 0, \quad \rho_* = \rho_0, \quad S = S_0 \text{ for } t = 0,$$

$$\sigma_1 = \begin{cases} \sigma_{10}(1 - t/t_0), & 0 < t < t_0, \\ 0, & t \geq t_0, \end{cases}, \quad r = r_0, \text{ (left)},$$

$$\sigma_1 = 0 \text{ for } t > 0, \quad r = r_0 \text{ (right)}.$$

In calculations, $t_0 = 0.5 \text{ } \mu\text{s}$. The results are presented in Figs.15 and 16 in the form of the dependences $u(r)$ and $\sigma_1(r)$ for different time moments. A weak elastic precursor leading the shock front is seen on the profiles. The amplitude of the pulse is shown to quickly decay with its propagation.

The change in the maximum pulse amplitude in solid alumina is shown in Figs.15 and 16 by curves 1. In addition to the abrupt quantitative distinction in the level of the amplitude change, in Fig.15 we observe the substantial qualitative difference in the dependences $u(r)$. In solid alumina, the pulse keeps the triangle-like form (if we neglect the elastic precursor ahead of the wave and elastic relief behind its front). In porous material, after the compression wave has passed a certain relatively small distance, almost constant velocity distribution takes place behind the compaction wave front. The similar character of the change in the pulse form in porous medium was described in [15]. In the coordinates σ and r , the pulse keeps the triangular form, however, its duration increases many times.

The profiles of the different-amplitude compaction waves are shown in Fig.17 for the time moment $t = 1 \mu s$ from the beginning of the process in porous iron with $\rho_0 = 2.475 \text{ g/cm}^3$. In this case, we solve the problem of piston motion specified by the boundary condition:

$$h_1 = h_2 = h_3 = 0, \quad u = 0, \quad \rho_* = \rho_0, \quad S = S_0 \text{ for } t = 0,$$

$$u = u_0 = \text{const for } t > 0, \quad r = 0 \text{ (left)},$$

$$\sigma_1 = 0 \text{ for } t > 0, \quad r = r_0 \text{ (right)}.$$

Curves 1-3 are calculated for $u_0 = 500, 300, 100 \text{ m/s}$. Curve 3 corresponds to a rather elastic pulse in the case, where the irreversible compaction of the material does not occur at all. As in other cases, in this case a small amplitude signal, the front point velocity of which is equal to the longitudinal sound velocity in solid material, runs away forward. Under the conditions, with which curve 2 was obtained, the partial irreversible compaction to non zero residual porosity occurs, in the case of curve 1, compaction goes almost to the monolithic state. All the irreversible compression waves have the different propagation velocities and width.

The effect of the grain size on the shock wave compression is illustrated in Fig.18, which presents the wave profiles of the same amplitude in mass velocity $u_0 = 500 \text{ m/s}$ for porous alumina with $\rho_0 = 2.475 \text{ g/cm}^3$ (for curves 1 and 2, the grain sizes differ by an order) at the time moment $t = 1 \mu s$. The forms of curves, wave velocity, and stress amplitude, which correspond to the beginning of irreversible compaction of the porous

material, and the values of σ_1 and P behind the wave front are different. All the aforesaid evidences that the grain size plays an important role in the processes of dynamics deformation of porous media.

Fig. 8: Shock adiabat of alumina

Fig. 9: Shock adiabat of alumina

Fig. 10: Shock adiabat of wheat flour

Fig. 11: Shock adiabat of wheat flour

Fig. 12: Shock adiabat of mixture

Fig. 13: Shock adiabat of mixture

Fig. 14: Calculated curves for alumina under uniform uniaxial dynamic compression in comparison with experimental data[5,14].

Fig. 15: Calculated mass velocity profiles for initially triangular pulse propagating over porous alumina.

Fig. 16: Calculated normal stress profiles for initially triangular pulse propagating over porous alumina.

Fig. 17: Comparison of the calculated shock-wave different-amplitude profiles in porous alumina for the time moment $t = 1\mu s$.

Fig. 18: The effect of grain size variation on shock wave structure in porous alumina.

7. THE COMPRESSIVE STRENGTH OF COMPACTED SAMPLES

In accordance with Task 2.6, we have studied the compressive strength of precompacted samples of the materials under investigation. The samples were prepared by compaction in a rigid pressmold (casing) using a press with a force up to 10 *tons* and a pneumatic hammer capable of accelerating the striker, 30 *kg* in mass, up to 20 *m/s*. Because of the technological reasons, the samples had a slightly conical form, the angle of deviation from the cylindrical form was about $2^{\circ}30'$. The samples were about 20 *mm* high, their lower and upper foundations were about 22 and 20 *mm* in dia., respectively. To determine the compressive strength, the above press was used. The force applied and the sample deformation were measured during the loading.

The pictures (photos) of the samples before loading and the characteristic fragments after fracture are presented in Fig.19, in which the upper horizontal row is the wheat flour sample and fragments, the middle row presents the Al_2O_3 sample and fragments, and the lower one is the sample and fragments of their mixture.

The fracture took place according to the known type of fracture over the maximum shear stress surface being at a 45° angle to the direction of compression. The results of measuring the compressive strength and the limiting deformation versus the initial sample density are given in Tables 4-6 for Al_2O_3 , wheat flour, and their mixture, respectively. The manufacture technology was different for three groups of samples. The samples of group I were press-compacted only. The samples of group II were prepared in two stages. First, they were press-compacted; second, they were additionally compacted at one stroke of the hammer. The samples of group III were first compacted and then twice shock-loaded by the hammer.

The analysis of results shows that the compressive strength of the Al_2O_3 samples almost does not depend on the sample manufacture procedure and is due, in the first place, to only the density of porous sample. The density dependence is very strong. In the studied density range, the compressive strength of the samples changes by more than an order with the density change by about 30%. The value of the limiting deformation increases much slower. It is almost constant for the samples manufactured by shock loading.

The analysis of results for the wheat flour and mixture is more difficult because a great spread of the obtained values is observed along with correlation of the experimental data and the sample manufacture procedure. Probably, in this case it is necessary to study the physicochemical processes accompanying compaction in a more detail than in the analysis of the shock loading results. The properties of the porous samples obtained are due, to a great extent, to the irreversible processes of change of their initial structure (chemical destruction, polymerization, etc.). In further investigations in this field of research, it would be expedient to use the model materials, which possess (unlike the wheat flour) the uniform initial structure and the chemical properties of which are well-studied.

Fig. 19: The samples before loading and the characteristic fragments after fracture

Tab. 4: Compressive strength, Al_2O_3 .

	A		B				C	
$\rho_0, g/cm^3$	1.52	1.58	1.81	1.814	1.82	1.84	1.89	1.95
$\sigma_f, kg/cm^2$	21.30	26.6	116.	113.2	111.8	114.8	215.	313.8
ε_f	0.016	0.02	0.024	0.025	0.025	—	0.026	0.026

Tab. 5: Compressive strength, wheat flour.

	IA			II				III			
$\rho_0, g/cm^3$	1.22	1.22	1.22	1.23	1.28	1.29	1.34	1.28	1.28	1.29	1.29
$\sigma_f, kg/cm^2$	41.4	27.6	30.4	49.7	77.3	77.3	124.6	65.6	101.	76.5	102.
ε_f	0.046	0.033	0.047	0.028	0.032	0.032	0.041	0.044	0.038	0.029	0.027

Tab. 6: Compressive strength, mixture.

	I		II				III	
$\rho_0, g/cm^3$	1.43	1.46	1.46	1.58	1.60	1.61	1.67	1.69
$\sigma_f, kg/cm^2$	75.1	144.8	150.1	245.9	251.	262.3	300.5	396.2
ε_f	0.050	0.055	0.044	0.043	0.043	0.039	0.020	—

8. CONCLUSION

In accordance with the specified task, we have studied experimentally the shock compression of three porous materials: Al_2O_3 , wheat flour, and their mixture. The shock adiabats have been determined in the moderate pressure range, the dependences (D, u) and (P, u) which connect the shock wave pressure P and the main kinematic parameters, such as, the shock wave velocity D and mass velocity u , have been obtained.

The shock adiabats of all the three materials are quite well described in the coordinates (D, u) by the straight lines $D = bu$, leading to the parabolic form of the $P - u$ dependence. In this case, in the studied range of the shock wave intensity up to the maximum pressure, the pores do not close completely in any of the materials studied. It can be expected, in particular, for Al_2O_3 containing materials that the shock adiabat behavior will change qualitatively with further increase in pressure up to the values sufficient for fragmentation of Al_2O_3 particles.

The model, which describes the behavior of porous powder materials under large-amplitude dynamic loading, has been constructed. The model applicability to describing the shock wave processes is confirmed by good agreement of the calculated shock adiabats and the data obtained in the earlier-performed experiments. For the mixture of Al_2O_3 and wheat flour, a comparison of the calculation results and the experimental data shows that the use of the theory of mixtures to describe the behavior of this mixture under the shock loading gives good results. The model formulated allows us to take into account the effect of the grain (powder particle) size on the behavior of the shock wave processes in porous media. The model constructed is suitable for incorporation into multi-dimensional hydrodynamics codes.

The compressive strength of the compacted samples has been determined. The analysis of results of studying the fracture of wheat flour and mixture samples has shown that in this case the physicochemical processes accompanying compaction have a greater influence than in the case of shock compression. The strength and fracture of the samples of such porous materials should be connected with the irreversible changes in the chemical structure of the material due to the change in the character of bonds in a complicated molecule. In further investigations in this field of research, it would be expedient to use the model materials, which possess (unlike the

wheat flour) the uniform initial structure and the chemical properties of which are well-studied.

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