Shock waves in porous media

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Abstract. The experimental data [1, 2] on the effect of the parameters of plane incident shock waves and the characteristics of a porous medium on the attenuation and reflection of waves from a rigid obstacle are examined. The propagation of waves with a pressure jumps of up to \( \Delta P/P_0 = 20 \) (\( P_0 = 0.1 \) MPa) in polyurethane foam blocks with a density of 20 kg/m³ and 35 kg/m³ and a length of up to 0.8 m, tightly adjacent to the walls and the end face of the driven section of the shock tube is studied. At lengths of the porous block greater than the extent of the shock wave, the porous block effectively attenuated the shock wave. For a wave of limited duration with a triangular pressure profile, a stronger attenuation of the wave in the polyurethane foam block was observed in comparison with that for an extended wave pulse. The reflection pressures of the waves in polyurethane foam with pressure jumps of \( \Delta P/P_0 \geq 12 \) exceed the reflection pressures of shock waves in air. The degree of attenuation or amplification of a wave depends on the material density and the ratio of the lengths of the foamed polyurethane block and the pressure pulse.

1. Introduction

Various applications of porous materials in industry motivate studies on the impact of shock waves on porous media. Porous materials differ from solid materials and gases in that their compressibility is higher than that of gases, but lower than that of solids or liquids. A high compressibility of porous materials and of gas–liquid bubbly, foamy, granular, and bulk-density systems makes the propagation of shock waves in these media essentially similar. Such media can be used to protect objects from the impact of explosions. To describe the characteristics of the interaction of a shock wave with a porous barrier and its propagation therein, it is necessary to know the velocities differences of the phases, viscoelastic behavior of the framework, and the dynamics of pore destruction at the stage of compaction of the porous material in the wave.

The characteristics of the propagation of shock waves in porous materials are of interest from a scientific point of view as well, not least because of the effect of interfacial interaction in velocities and stresses on the parameters and structure of shock waves in a porous material.
Porous media are used for attenuating and damping shock waves [1]. At the same time, high pressures behind reflected shock waves in porous materials have been measured [1, 2]. Thus, a porous layer can both weaken and amplify the impact of air shock waves on a rigid wall.

To determine the conditions of attenuation of a shock wave in a porous material, it is necessary to analyze the parameters of the incident and reflected shock waves at the given characteristics of the porous medium (gas volume fraction, pore size, density of foamed polyurethane).

The aim of the present work is to determine the conditions for changing the intensity of incident and reflected shock waves in a porous material. For this, the experimental data [1, 2] on the effect of the parameters of a plane incident shock wave and the characteristics of a porous medium on the reflection of the waves from a rigid wall are analyzed. The interaction of shock waves with porous materials [2–11] for a plane air shock wave incident on a polymer polyurethane block tightly adjacent to the walls and end of the pipe is studied experimentally and theoretically.

In [10], a method is proposed for calculating the characteristics of steady shock waves in a porous compressible medium the elasticity of which is determined by the elasticity of the gas in the pores. The numerical studies of the propagation and reflection of shock waves from a rigid wall covered with a porous material performed in [4–9] made it possible to determine the conditions for wave attenuation. In [10], the structure and behavior of reflected shock waves in porous media saturated with a liquid were studied experimentally and numerically. Recent experimental works [12, 13] have shown the effectiveness of nanoporous non-wetting media for the attenuation of compression waves.

2. Experimental setup
Experiments on the structure of pressure waves in a porous medium were carried out on a shock tube of rectangular cross section (45×30 mm, figure 1). Driven section 2, 1.5 m in length, was equipped with three piezoelectric pressure sensors, 3, 4, and 5. Sensors 4 and 5, located along the length of the driven section of the shock tube (figure 1) measured the parameters of the wave in foamed polyurethane. Pressure sensor 6 recorded the reflection pressure at the rigid end face of the tube. Driver section 1 (figure 1) of length 0.5 m could be shortened to generate short shock waves with a triangular pressure pulse. In the experiments, the propagation of waves in foamed polyurethane blocks, up to 0.8 m in length, inserted tightly into the driven section of the shock tube, without a gap to the walls and end face. The initial pressure was \( P_0 = 0.1 \text{ MPa} \).

![Figure 1. Schematic diagram of the shock tube and porous blocks.](image)

The porous material samples were cellular-structure polyurethane foams with a low (~20 kg/m\(^3\)) and a higher density (35 kg/m\(^3\)), with up to 96.5% of the volume of which was occupied by the gas phase. The cell size in the low-density polyurethane foam was 2–6 mm. The denser polyurethane foam had 1-mm cells. For the given cell size, the number of longitudinal and transverse skeletal elements in the denser polyurethane foam exceeded three to four times their number in the low-density material of the same volume. Such a change in the internal structure increased the strength of the denser polyurethane foam.
Pressure waves in the polyurethane block were generated by reflection of an air shock wave at the polyurethane–air interface. We investigated waves with a pressure jump of $\Delta P_1/P_0 = 1.5−20$ under normal conditions. The measured parameters were the propagation velocity, pressure in the incident wave, the pressure of reflection of the wave at the end face of the driven section, and the degree of attenuation of the shock wave in the polyurethane foam.

3. Results

It turned out that the pressure in waves in porous media, in contrast to gaseous media, increases gradually over several hundred microseconds. There was no pressure jump at the front of the shock wave in the foamed polyurethane medium. The time of increase in pressure decreased with increasing wave intensity. The pressure in the reflected shock wave also increased gradually, without a sharp pressure jump.

The authors of [3, 8] explained the considerable length of the wave front in polyurethane foams is by filtering the gas through the permeable skeleton of the porous material into the unperturbed region ahead of the wave front. In addition, gas filtration helps reduce the pressure drop at the front of the wave and reduce its intensity and velocity.

The deceleration of extended waves was recorded in porous material blocks of lengths 0.6 and 0.8 m and density 35 kg/m$^3$. For example, over a distance of 0.6 m, at a front pressure maximum of 1.2 MPa, the wave velocity decreased from 320 to 200 m/s. The pressure $\Delta P_1$ of a wave propagating through the porous material decreased at a rate of 0.6 MPa/m. The rate of attenuation of the wave depended on the wave intensity $\Delta P_1/P_0$. A wave with a pressure maximum of $\Delta P_1/P_0 = 7.0$ attenuated at a rate of 0.3 MPa/m. A porous inset with a length comparable to or longer than the length of the wave effectively attenuated the shock wave.

Weak waves with a pressure maximum of $\sim0.2$ MPa were weakened more slowly. A decrease in the density of foamed polyurethane led to a decrease in the rate of damping of the wave. The attenuation of the wave with the distance traveled in the polyurethane foam sample of density 35 kg/m$^3$ turned out to be approximately twice as large as that for the low-density polyurethane foam, with a density of 20 kg/m$^3$.

That the pressure of a wave in the dense porous material was lower can be explained by increases in the energy spent on compression, pore destruction, deformation of skeletal elements, and acceleration of condensed particles to the gas velocity. A stronger weakening of shock waves in the dense polyurethane foam as compared to the less dense material can be used to effectively attenuate shock waves in dense porous barriers.

A wave of limited duration with a triangular pressure profile experienced a stronger attenuation in a block of polyurethane foam than a wave with an extended pressure profile did. For example, in a 0.5 m – long porous block, a $\Delta P_1/P_0 = 4$ wave with a triangular pressure profile of duration 1 ms and a length of 0.3 m was attenuated to $\Delta P_1/P_0 = 1.5$. Short pressure pulses were observed being effectively attenuated in long porous blocks. By contrast, extended-pulse waves, with a length exceeding the length of the porous inset remained practically unattenuated. To assess the effectiveness of wave attenuation in porous materials, the most important characteristics are the lengths of the porous material block and the pressure pulse length. The pressure pulse profile, as well as the density and cell size of the porous material influenced the attenuation of the wave to a lesser extent.

The results of measuring the parameters of reflected shock waves are shown in figure 2. The dependence of the dimensionless pressure of the reflected shock wave, $\Delta P_2/\Delta P_1$, on the pressure maximum ratio of the incident wave, $\Delta P_1/P_0$, is displayed in figure 2. As can be seen from figure 2, weak incident waves, with $\Delta P_1 \sim 0.2$ MPa, are reflected with a reflection coefficient of $K = \Delta P_2/\Delta P_1 = 2$. The velocity of such waves is close to the speed of sound in foamed polyurethane, 200 m/s [1].

The intensity of the shock wave reflected from the rigid wall after passing through the polyurethane foam block ahead of it increases with the intensity of the incident wave. For example, for an incident shock wave in a gas with a pressure rise ratio of $\Delta P_1/P_0 = 5$, the dimensionless pressure reflection from a foamed polyurethane block at the end face of the shock tube is $\Delta P_2/P_0 \sim 15$. The reflection
coefficients of increases with the intensity of the incident shock wave. For an incident wave with a pressure maximum of $\Delta P_1/P_0 \sim 12$, the reflection coefficient is comparable with that for an air shock wave. In the case of intense incident shock waves, the reflection coefficients $K = \Delta P_2/\Delta P_1$ for foamed polyurethane exceed those for air. The measured values of the reflection coefficient was $K = \Delta P_2/P_1 \geq 7$.

**Figure 2.** Dependence of the reflection coefficient for a shock wave in polyurethane foam, $K = \Delta P_2/P_1$ on the pressure maximum ratio of the incident shock wave, $\Delta P_1/P_0$. $\Delta P_2$ is the pressure maximum of the reflected shock wave, $\Delta P_1$ is the pressure maximum of the incident shock wave, and $P_0$ is the normal pressure.

4. **Discussion**

When the shock wave falls onto a boundary gas–polyurethane foam interface, the reflected wave travels back into the gas, whereas the refracted wave penetrates into the porous block, compressing it and transmitting an impulse to the condensed material. In the shock wave, the porous structure is destroyed and condensed particles (fragments) of the material are accelerated to the velocity of the gas flow behind the wave. The stoppage of the two-phase flow at the rigid end face of the shock tube produces pressure rise. The reflection of the two-phase flow pulse explains why a high pressure zone arises behind the reflected shock wave. This wave has an oscillatory structure, with the pressure amplitude exceeding that of the reflected wave at the gas–foamed polyurethane interface. The model [2, 3, 6] for a pseudo gas with an effective adiabatic exponent closely reproduces the high pressure recorded when a wave is reflected from the boundary between a porous block on a rigid wall.

Experiments with a porous material in which the cells were predestroyed showed that the reflection pressure of the wave in the skeletal material (without cells) was significantly lower than the reflection pressure in intact polyurethane foam. The skeletal structure of the material hinders the acceleration of the condensed material in the flow behind the wave because of a decreased resistance to the gas flow, thereby reducing the reflection pressure of the wave.

In the case of strong waves, the movement of the two-phase flow entrains the entire solid phase in which the bulk of the porous material is concentrated, a factor that contributes to increasing the pressure in the reflected wave as compared to that in air. In weak incident waves, solid material is entrained only partially. Therefore, the reflection coefficient for weak waves is $\Delta P_2/P_0 \sim 2$. The degree of attenuation or amplification of a wave depends on the length of the polyurethane foam, duration of the wave pressure pulse, cell size, and density (or gas volume fraction) in the porous material.

The reflection coefficients for short pressure pulses in a porous medium are lower than those for extended waves of the same intensity. This is also explained by an incomplete entrainment of solid
material by the two-phase flow in a short pressure pulse. In this case, the impulse transferred from the two-phase flow to the rigid wall turns out to be smaller than that characteristic of an extended shock wave.

5. Conclusions
Thus, the presence of a foamed polyurethane layer on a rigid wall can lead both to an increase in the amplitude of the reflected extended pulse and to an attenuation of the incident shock wave. The porous layer enhances the dynamic effect on the barrier for extended waves and reduces it in the case of short pulsed impacts. The degree of attenuation or amplification of the wave depends on the length of the polyurethane foam block, pulse duration, and density (gas volume fraction) of polyurethane foam. The reflection pressures for shock waves in polyurethane foam at pressure maximum ratios of $\Delta P/P_0 \geq 12$ exceed those for waves in the air.

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6. References
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