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IMPULSIVE HYDRAULIC RUPTURE OF A POROUS MEDIUM

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In recent years, the problem of impulsive hydraulic rupture of solids has acquired great practical significance, mainly in mining. This method of rupture is used in mining for directional change of rock permeability, which is done to raise the rate of geotechnical processes. To date, a number of theoretical [1-3] and experimental [4] studies have been done, which make it possible to predict the conditions for the appearance of cracks and their dimensions, for a given spatial configuration. This was done without accounting for porosity – one of the characteristic properties of natural and man-made geometricals. In addition, the earlier work gave too little attention to the influence of the strength properties of the rock (rupture strength) on the rate and dimensions of the cracks.

Here, we present the results of an experimental study of the effects of porosity and strength of the solid on crack development in the hydraulic rupture regime.

We used a man-made stone as a material which simulates a porous medium of the sulfur-containing limestone type. The stone was manufactured from a sand–cement mixture (the matrix) and crushed rosin (a low-strength filler component) with a grain size of no larger than 7 mm. The rosin content c_r was 10, 30, and 50%, which is in the range of elemental sulfur content in limestones from deposits in the western regions of the Ukrainian SSR. Samples of this mixture were held at room temperature for 28 days or more to reach the required strength, as determined by uniaxial compression tests to be 20-90 MPa. The porosity of the model material varied from 4-8%. These physicomechanical properties of the sample are characteristic of many natural and man-made geomaterials.

In this work, we used the experimental method described in detail in [4]. Just as in [4], we used two types of working fluids for hydraulic rupture of the models. Their kinematic viscosity coefficients are $2.2 \cdot 10^{-6}$ and $6.8 \cdot 10^{-4}$ m^2/sec. The amplitude–time regime of the pulsed pressure generated in the fluids was chosen so that the observational results could be applied to prediction of the operation of present-day borehole equipment and impulsive rupture technology. Thus, the pressure in the working fluids was up to 20-30 MPa, the pressure growth rate was 10^9-10^{10} Pa/sec, and the pulse duration time was 20-30 msec. The relation between the sample dimensions and the loading conditions was chosen so that the developing crack did not reach the free surface of the sample. The crack dimensions were determined by direct measurement after cutting the samples perpendicular to the plane of the crack. This was done according to traces of penetration of the tinted rupture fluid.

The experiments were designed according to the requirements of statistics, with a confidence level of 0.9. The number of parallel experiments with identical conditions was taken as no fewer than 5, and the results of these were averaged. The total number of experiments was 180. Based on analysis of these experiments, we were able to establish the following.

During impulsive hydraulic rupture of porous media, just as during rupture of a material as homogeneous as polymethyl methacrylate (PMMA) [4], the spatial orientation of the developing cracks depends on the presence of stress concentrators. It also depends on the symmetry of the load, which is determined by the relation between the height of the barefoot interval

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Fig. 1

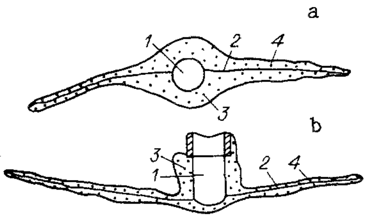

Fig. 2

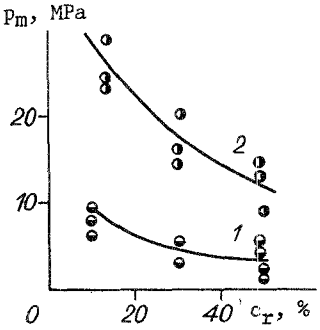

Fig. 3

h in the rupture zone and the borehole diameter d_b. For $h \geqslant (2\text{-}3)d_b$, rock fracture is accompanied by the formation of vertical cracks; while for $h \leqslant (1\text{-}2)d_b$ – by radial-circumferential cracks, which as a rule are initiated at the casing boundary (Fig. 1).

For both porous and nonporous geomaterials, the number of cracks which develop during impulsive rupture depends on the load rate $\dot{p}$ (the rate of growth of the pressure in the rupture zone). For $\dot{p} \leqslant 10^{10}$ Pa/sec, a single crack is formed as a rule. For $\dot{p} > 10^{10}$ Pa/sec, the number of cracks increases.

A characteristic feature of impulsive hydraulic rupture of porous media having nonzero percolation permeability is that, simultaneously with the formation of the main cracks, a region of infiltration 3 forms around borehole 1 and cracks 2 (Fig. 2). In this region, the pore space is partially or completely filled with the working rupture fluid. The characteristic form of the infiltration region during rupture of the rock by low-viscosity fluid is shown in Fig. 2 for (a) vertical and (b) radial-circumferential cracks.

In the sample with vertical cracks, the medium consisted of 10% low-strength component (c_r = 10%). The load rate $\dot{p}$ and duration of fluid injection τ were $3.13 \cdot 10^9$ Pa/sec and 26.9 msec. In the sample with radial-circumferential cracks, c_r = 50%, $\dot{p} = 4.34 \cdot 10^9$ Pa/sec, and τ = 6.2 msec.

The experiments showed that the dimensions of the infiltration region depend on the viscosity of the rupturing fluid and on the permeability of the medium. The infiltration region is reduced with growth in the viscosity of the fluid. Thus when using a fluid with viscosity $\nu = 6.8 \cdot 10^{-4}$ m^2/sec, infiltration through the borehole walls spreads to a distance of $(1.1\text{-}1.2)d_b$, but when using the fluid with $\nu = 2.2 \cdot 10^{-6}$ m^2/sec, this region grows to $(2\text{-}2.5)d_b$.

The width of the filtration wedge 4 (Fig. 2), that is, that part of the infiltration region which forms in the vicinity of the cracks, is largest at the borehole wall and reaches $(0.5\text{-}1.2)d_b$. At first it decreases monotonically with increasing distance from the borehole axis. Then at a distance of $(2.5\text{-}3.5)d_b$, the wedge becomes approximately constant with a value of $(0.15\text{-}0.25)d_b$ during rupture by the low-viscosity fluid, and a value of $(0.05\text{-}0.1)d_b$ for rupture using the fluid with high viscosity. Increasing the low-strength mineral phase content in the rock results in a reduction in the absolute dimensions of the filtration wedge.

Just as for the fracture of homogeneous media [4], the dynamic and kinematic parameters of the impulsive rupture process depend sensitively on the viscosity of the working fluid, which is graphically demonstrated by the results of experiments shown in Figs. 3-6.

Figure 3 shows the threshold rupture pressure of the medium p_m for vertical cracks as a function of the low-strength component content, which to a significant degree characterizes the strength of the medium. When constructing the plots, we considered only experiments with the same pressure growth rate in the pulse ($\dot{p} = 5 \cdot 10^9$ Pa/sec). Curves 1 and 2 were constructed for the fluids with $\nu = 2.2 \cdot 10^{-6}$ and $6.8 \cdot 10^{-4}$ m^2/sec, respectively. Comparing these curves, we immediately notice that with a 310-fold increase in the viscosity of the working fluid, the threshold rupture pressure of media with different physicomechanial characteristics grows by a factor of 2-3. This result agrees qualitatively with the results of theoretical and experimental studies of stationary hydraulic rupture of rocks [5]. This is of great practical

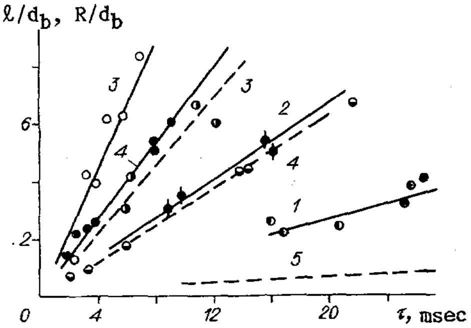

Fig. 4

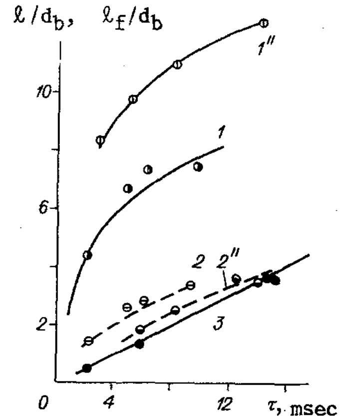

Fig. 5

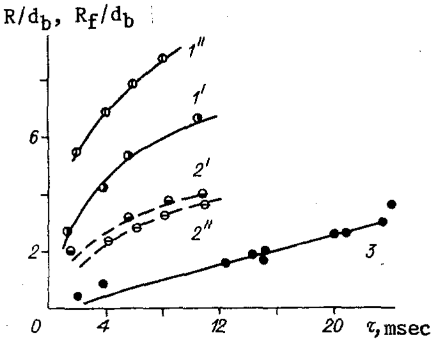

Fig. 6

significance in terms of the choice of working rupture fluids which provide for the least energy content of the fracture process (provided the need to secure a prescribed crack size — length and width (opening) — does not influence this choice: the crack dimensions also depend on the fluid viscosity).

Let us compare these results for a porous medium with data published in [4] on the rupture of a nonporous medium. The compressive and tensile strengths of PMMA are 100-130 MPa and 60-70 MPa, respectively. Porous medium samples with an 8-10% low-strength component content show such compressive strength. However, their tensile strength is significantly less than for PMMA (only 10-12 MPa), which is characteristic of minerals. Since the inception of cracks is determined to a signficant degree by the tensile strength of the medium, it might be assumed that the threshold rupture pressure of the mineral used in the experiments must be considerably less than that of the polymer studied in [4]. In reality, however, the threshold pressures are comparable in both media. This is evidently because the infiltration region in the porous medium is formed before the cracks are initiated, and in accordance with the principle of effective stresses, the rise in pore pressure results in an increase in the tensile strength of the medium and in the threshold rupture pressure.

It is clear from Fig. 3 that with increasing percentage of low-strength mineral-phase content of the rock, there is a reduction of the threshold rupture pressure. This is natural, since with growth in c_r, the tensile strength of the rock is reduced.

In Fig. 4, curves 1-3 are constructed for the impulsive rupture by a low-viscosity fluid of porous media with low-strength components of 10, 30, and 50%, and pressure amplitudes of 8.1-9.8, 3.6-5.3, and 1.8-5.1 MPa, respectively. Curve 4 in Fig. 4 is for the rupture of PMMA. The solid lines represent $\ell(\tau)$, the dashed are $R(\tau)$. For comparison with the impulsive fracture technology, curve 5 shows the radius of radial-circumferential cracks as a function of injection time for a low-viscosity fluid during hydraulic rupture [6]. The subject material was sandstone in the roof of a coal bed, with an ultimate tensile strength of 12-15 MPa and a surface fracture energy of $\gamma = 39.5$ J/m^2 [6].

Figures 5 and 6 show the influence of the injection time of the viscous fluid ($\nu = 6.8 \cdot 10^{-4}$ m^2/sec) on the rupture zone ℓ, R (solid lines) and on the fluid penetration depth ℓ_f, R_f (dashed lines) for vertical and radial-circumferential cracks, respectively. (Curves 1 and 2 are for a medium with $c_r = 10\%$ at rupture pressures of 23.5-29.0 MPa; 1' and 2' for $c_r = 30\%$ and stress amplitudes of 15.0-20.0 MPa; 1" and 2" for $c_r = 50\%$ at 9.5-13.5 MPa.) For comparison, curve 3 in Figs. 5 and 6 shows tensile crack formation in PMMA.

From Fig. 4 it is clear that the crack propagation depth grows practically linearly with the acting pressure duration time τ during rupture of the test medium by the low-viscosity fluid. A similar dependence is also observed in the rupture of PMMA. When using a high-viscosity fluid, $\ell(\tau)$ and $R(\tau)$ have a distinctly nonlinear character (Figs. 5 and 6), and there are two characteristic sections which are distinguished by the rate of crack growth. On the first of these sections, in the region of short injection times, the crack jump during rupture by the viscous fluid is significantly larger than during rupture by the low-viscosity fluid. This is due to the larger energy reserve stored in the sample up to the moment of critical equilibrium, and to the larger crack opening in the initial stages of crack movement (the wedge effect). On the second (flatter) section, for longer fluid injection times ($\tau > 8$-10 msec), the growth in crack dimensions proceeds considerably more slowly, due to the viscous flow strength of the fluid in the crack. This feature fundamentally distinguishes porous material rupture by a viscous fluid from homogeneous material rupture (for example, PMMA [4]).

It is clear from Figs. 5 and 6 that during rupture of a porous medium, just as for fracture of a nonporous one [4], there is a delay of the fluid front in the crack from its vertex ("spout"). However, the delay is more significant in the porous medium and grows with decreasing strength properties of the medium.

In conclusion, we note that a reduction of the viscosity of the working fluid, an increase in the percolation permeability of the porous medium and its strength leads to a decrease in the rupture zone dimensions. This is due to the growth of percolation loss and the quasi-brittle tensile strength of the medium.

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DO BRITTLE AND PLASTIC MATERIALS DIFFER WHEN SPALLING?

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We examine the energy description of spalling for brittle and plastic materials. We cite experimental data which justifies the use of one and the same relations for these materials.

Advances in fracture mechanics have demonstrated the fruitfulness of the energy approach in the description of brittle fracture. However, direct use of fracture mechanics is made difficult by the peculiarities of material fracture during spalling. Therefore, in [1], an attempt was made to use the balance of the elastic strain energy and the work of brittle fracture of the material as the necessary condition for failure, without imposing any sort of limitation on the failure mechanism itself.

This necessary condition can be written in the form

$$\int_0^\delta \frac{\sigma^2\,dx}{AE} \geqslant \lambda, \tag{1}$$

where σ is the tensile stress; x is the coordinate, reckoned from the free surface of the material; E is Young's modulus; λ the specific work of brittle material fracture per unit area; A is a function of Poisson's ratio ν, equal to $2(1-\nu)[(1+\nu)(1-2\nu)]^{-1}$.

It follows from (1) that the fracture stress σ_f and the thickness of the spallation layer of material δ are related by the inequality

$$\sigma_f^2\delta \geqslant \alpha\lambda EA. \tag{2}$$

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