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The role of the hydrostatic pressure under dynamic fracture of rocks

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ABSTRACT

Within the context of the structural-temporal approach, the dynamic effects of the strength characteristics of rocks arising due to hydrostatic pressure are analysed. The key idea of the proposed approach is the introduction of the incubation time parameter for describing material fracture processes, which is interpreted as the main measure of material response. Theoretical velocity dependencies of the fracture toughness for marble and granite, subjected to different values of external hydrostatic pressure, as well as for dry and wet sandstones, are predicted based on the proposed approach. The calculated incubation times for marble and granite are allowed to establish a linear function between incubation time and hydrostatic pressure. The obtained values of incubation times are compared according to the velocity dependencies of the fracture toughness and the velocity dependencies of the strength of rocks differing in external hydrostatic pressure or moisture level. It is shown that the incubation time depending on the external hydrostatic pressure or on the moisture of rocks is similarly changed.

KEYWORDS

dynamic fracture toughness • hydrostatic pressure • structural-temporal approach • fracture incubation time loading rate

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Introduction

The strength characteristics of rocks with a change of moisture content depending on the static or dynamic deformation mode are increased or are decreased. Dry and wet rocks were tested in different ranges of strain rates on a split Hopkinson–Kolsky bar tests: limestone (10^2–10^3 s^{-1}) [1], sandstone (10^1–10^2 s^{-1}) [2], tuff (10^0–10^1 s^{-1}) [3,4], granite (10^0–10^1 s^{-1}) [3,5]. Dynamic experiments on rocks [1–5], showed, that the dynamic and static strength of dry rock is greater than wet rock. A comparison of the strength of granite [5] under static loads and high-speed deformation of $\dot{\varepsilon}$ ~ 10^2 s^{-1} revealed that the highest dynamic strength of wet granite and the highest static strength of dry granite (Fig. 1) were observed. A significant increase in the tensile strength of wet rock under dynamic loading in comparison with the static loading is explained by the presence of hydrostatic pressure (confining pressure) in water-saturated samples, which has a different effect on static strength and dynamic strength at high strain rates. Under static loading conditions, the effect of hydrostatic pressure of the contained liquid in wet rocks reduces their strength characteristics in comparison with dry rocks. The static fracture toughness of the limestone [6,7], the granite [7,8], the marble [7], the sandstone [9,10] by the external hydrostatic pressure of the liquid in the rock was increased. The hydrostatic pressure effect on dynamic strength characteristics of rock was also considered in works [11–14]. In this paper, the mechanism of the influence of hydrostatic pressure on the strength characteristics of rocks under high-speed deformation is studied in detail.

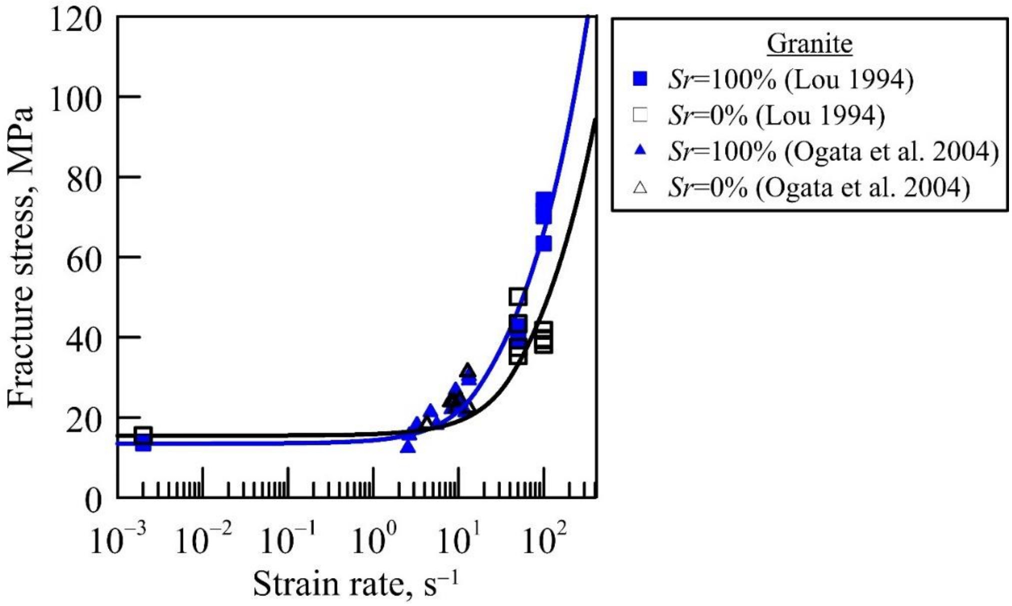

Fig. 1. Speed dependencies of fracture stress of granite [3,5] with different saturation ratio (Sr), predicted on the basis of the structural-temporal approach in study [15]

In [16–19], the competition effects of the rate dependences of the concrete strength with different levels of water saturation were observed. In [20], the hydrostatic pressure effect was considered in the context of the incubation time criterion. Using this criterion, the rate dependences of strength in [20] were predicted and calculated rate sensitivity parameters, called the characteristic relaxation times, were compared. The advantage of the incubation time criterion compared to other dynamic approaches [21–25] is the use of parameters that are invariant to the applied loading rate. It was found that the greater the incubation time for saturated concrete, the greater the dynamic strength in terms of critical stress. A significant (in several times) increase of incubation time values for saturated concrete samples is revealed.

In the paper, the rate dependences of the fracture toughness of rocks with different external hydrostatic pressure and water saturation levels are studied based on the structural-time approach [26–29]. A pattern has been revealed between hydrostatic pressure and incubation time.

Incubation time criterion of fracture

General formulation

Let us consider the fracture criterion proposed in [26–29] which is used to describe the brittle fracture of materials. The general form of the incubation time criterion is as follows:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{F(t')}{F_c}\right)^{\alpha} dt' \leq 1, \qquad (1)$$

where τ is the incubation time associated with the dynamics of the relaxation process prior to fracture, $F(t)$ is the intensity of the local force field that causes fracture of the medium, and F_c is the static limit of the local force field. The fracture time t_* corresponds to the condition for achieving equality in inequality (1), i.e., when the left side of inequality (1) becomes equal to 1. The parameter α characterizes the sensitivity to the intensity of the force field causing fracture.

Fracture criterion (1) implies the existence of the incubation period, preceding a macroscopic break of the material. In this case, an incubation process is an essential factor of the fracture process and takes place both in cases of quasi-static and fast impact loads. Due to the presence of the fracture incubation period, some specific effects do happen under dynamic loading. Among those effects is a well-known strain-rate dependency of strength. As one of the simplest interpretations of the fracture incubation time, let us consider an example of fracture caused by a slow ($t_* >> \tau$) linearly growing fracture toughness $K(t) = \dot{K}\, t\, H(t)$, where $\dot{K}$ = const and $H(t)$ is the Heaviside step function. Substituting $F(t) = K(t)$ into (1) we can calculate the time to fracture $t_* = \sigma_c/\dot{\sigma} + 0.5\tau$ and a value of the critical stress intensity factor at the moment of fracture $K_* = K(t_*) = K_c + 0.5\,\dot{\sigma}\,\tau$, where $K_c = F_c$ is the tabulated value of the material static fracture toughness. In the case of very slow stress growth $(\dot{K}\,\tau)/K_c << 1$, the ultimate stress does not differ much from the static strength $\sigma_* \approx K_c$. The obtained expressions show that according to (1) the material remains intact at the moment when the static strength limit is achieved $t_c = K_c/\dot{K}$. It is crucial that before the onset of the macroscopic rupture of the material, preparatory processes having a characteristic temporal period τ evolve in the material structure (Fig. 2).

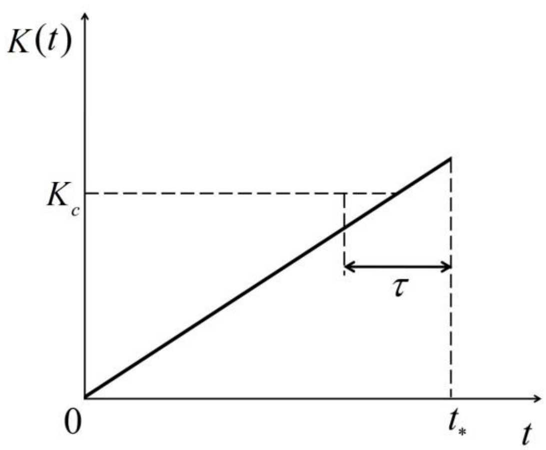

Fig. 2. Temporal dependence of stress for slow linear loading

The main feature of the approach is the introduction of the incubation time as a property of the material. This property is due to the preparatory relaxation processes of the evolution of microdefects in the material structure associated with microcracking. The key role of τ in the interpretation of the fracture process at different external loading rates is described in detail in [27,28].

The structural-temporal approach (1) can be used for both problems of crack propagation and problems of fracture of initially undamaged media that do not a priori contain macrocracks or sharp notches.

Modes I fracture toughness in a wide range of the loading rate

Using the structural-temporal approach, we derive the fracture condition for a three-point bending experiment (Fig. 3), to construct the strain rate dependences of the mode I fracture toughness. According to [30], the relationship between the dynamic force applied to the specimen and the mode I fracture toughness in three-point bending tests is linear:

$$K_I(t) = Y_I(\beta)\frac{P(t)\sqrt{\pi a_I}}{2RB}, \quad (2)$$

where $P(t)$ is time dependence of loading force in the specimen, $Y(\beta)$ is the dimensionless geometric factor, determined in the case of three-point bending test in the study [11] as $Y(\beta) = 0.4670 + 3.9094\beta - 8.7634\beta^2 + 16.845\beta^3$, $\beta = a_I/R$, s is the distance between two supporting pins, R is the specimen radius, a_I is the notch length, B is the specimen thickness. Taking into account Eq. (2), criterion (1) is rewritten in the following form:

$$Y_I\frac{\sqrt{\pi a_I}}{2RB}\frac{1}{\tau_I}\int_{t-\tau_I}^{t} P(s)\,ds \le K_{IC}, \quad (3)$$

where K_{IC} is the static mode I fracture toughness, τ_I is the fracture incubation time under the mode I fracture toughness limit condition.

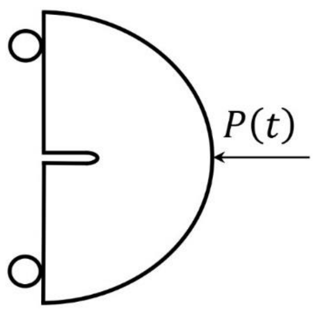

Fig. 3. Three-point bending test configuration for a notched semi-circular specimen

Here we use the experimental data on three-point bending of semicircular specimens of sandstone [31] and granite [11], where the time dependence of the applied force $P(t)$ changes linearly:

$$P(t) = \dot{P}tH(t), \quad (4)$$

where $\dot{P}$ is the force growth rate, and $H(t)$ is the Heaviside function.

For linear loading (4) we plot the rate dependence of the mode I fracture toughness. Considering that the condition of equality (3) determines the time to fracture in the specimen, we can calculate the dependence of the moment of fracture on the mode I fracture toughness rate $\dot{K}_I$ ($\dot{K}_I$=$Y_I(\beta)\frac{\dot{P}(t)\sqrt{\pi a_I}}{2RB}$):

$$t_*(\dot{K}_I) = \begin{cases} \frac{K_{Ic}}{\dot{K}_I} + \frac{\tau_I}{2}, & t_* > \tau_I, \\ \sqrt{\frac{2K_{Ic}\tau_I}{\dot{K}_I}}, & t_* \le \tau_I, \end{cases} \quad (5)$$

and substitute the resulting dependence into the dynamic mode I fracture toughness $K_{ID} = K_I(t_*)$:

$$K_{Id}(\dot{K}_I) = \begin{cases} K_{Ic} + \frac{1}{2}\dot{K}_I\tau_I, & t_* > \tau_I, \\ \sqrt{2K_{Ic}\tau_I\dot{K}_I}, & t_* \le \tau_I. \end{cases} \quad (6)$$

To construct theoretical dependences (6), it is necessary to determine the incubation time, which is estimated from experimental data by the least squares.

Modes II fracture toughness in a wide range of the loading rate

On the basis of the structural-temporal approach we lead out the fracture condition for the dynamic short core in compression test [32–34] (Fig. 4), proceeded on the split Hopkinson pressure bar tests, to plot the strain rate dependences of the mode II fracture toughness. The relationship between the dynamic force applied to the specimen and the dynamic short core in compression test [12] is linear:

$$K_{II}(t) = Y_{II}(\gamma)\frac{P(t)\sqrt{\pi a_{II}}}{DC}, \quad (7)$$

where $Y_{II}(\gamma)$ is dimensionless geometric factor, $\gamma = C/H$, C is the distance between two notches, H is the specimen height, D is the specimen diameter, a_{II} is the notch length. Taking into account expression (7), criterion (1) is rewritten in the following form:

$$Y_{II}\frac{\sqrt{\pi a_{II}}}{DC}\frac{1}{\tau_{II}}\int_{t-\tau_{II}}^{t} P(s)\,ds \le K_{IIC}, \quad (8)$$

where K_{IIC} is the static mode II fracture toughness, τ_{II} is the fracture incubation time under the mode II fracture toughness limit condition.

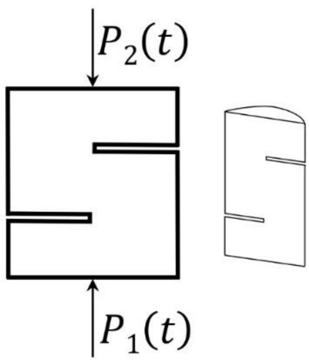

Fig. 4. Scheme of the dynamic short core in compression test [29] for a notched cylindrical specimen

Here we use the experimental data on dynamic short core in compression test of notched cylindrical specimens of marble [32], where the time dependence of the applied force $P(t)$ changes linearly.

Similarly to the previous section, substituting Eq. (4) to the equality condition Eq. (8) we determine the dependence of the fracture moment on the rate of the mode II fracture toughness $\dot{K}_{II}$=$Y_{II}(\gamma)\frac{\dot{P}(t)\sqrt{\pi a_{II}}}{DC}$. Therefore, the dependence of the dynamic mode II fracture toughness K_{IID} = K_{II} (t_*) on fracture toughness rate $\dot{K}_{II}$ is given as:

$$K_{IId}(\dot{K}_{II}) = \begin{cases} K_{IIc} + \frac{1}{2}\dot{K}_{II}\tau_{II}, & t_* > \tau_{II}, \\ \sqrt{2K_{IIc}\tau_{II}\dot{K}_{II}}, & t_* \le \tau_{II}. \end{cases} \quad (9)$$

Dependence of dynamic fracture toughness on loading rate

The effect of water saturation

Let us apply the criterion (3) for calculation of rate dependences of mode I fracture toughness based on experimental data of sandstone [31], obtained as a result of a static and dynamic tests in three-point bending tests with following parameters: a_I = 5 mm, B = 20 mm, R = 25 mm. In [31], values of quasi-static toughness K_{Ic} = 0.51 MPa·m $^{1/2}$ for dry sandstone with a density ρ = 2374.7 kg/m^3 and K_{Ic} = 0.29 MPa·m $^{1/2}$ for wet sandstone with a density ρ = 2457.8 kg/m^3 were presented.

Using the least squares method to the experimental data under consideration [27] according to the numerical scheme (6), estimate of the incubation time for wet τ_I = 0.196 ms and dry sandstone τ_I = 0.155 ms. Figure 5 shows the theoretical dependences of the fracture stress on the strain rate and experimental data [31] for dry and wet sandstone. Plotted theoretical dependences for dry and saturated sandstone in Fig. 5 have a good correspondence with an experimental data [31]. The dynamic and static fracture toughness of dry sandstone in the considered range of loading rate 10–100 GPa·m$^{1/2}$/s are greater than wet sandstone (Fig. 5), and the incubation time of wet sandstone is longer than dry sandstone. The data given in Fig. 5 indicates the fracture toughness and incubation time of wet samples approaching that of dry samples.

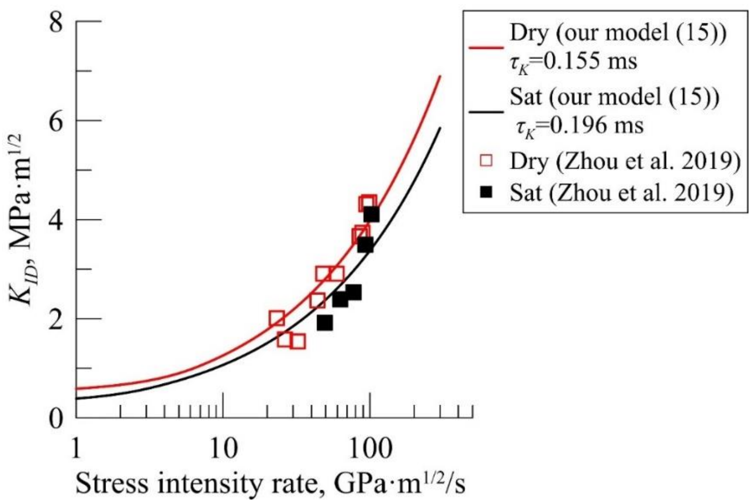

Fig. 5. The water saturation effect of sandstone on the theoretical and experimental dependencies of the fracture toughness rate based on the proposed model (6), respectively, and experimental data [28]

The opposite effect of hydrostatic pressure under static and dynamic loading is discussed in Fig. 1. The incubation time of the wet granite 21 μs (for dry granite 11.8 μs [15]) is the biggest. The reason for the decreasing static fracture toughness is the presence of additional hydrostatic fluid pressure in the voids (pores, cracks, caverns) of wet sandstone samples in comparison with dry sandstone samples. The hydrostatic pressure of liquid in voids under dynamic loads has the opposite effect on the fracture toughness of rock: the presence of liquid in voids leads to "compression" of microdefects and microcracks in the structure of the material, which slows down relaxation processes. In terms of the structural-temporal approach, this means that the incubation time of rocks with a high moisture content is greatest. In [20], using the example of rate dependences of the strength of dry and wet granite, predicted based on the structural-time approach for strength (1). The hydrostatic pressure effects are opposite at low (acceleration of relaxation processes) and high (deceleration of relaxation processes) strain rates. Despite the higher values of the dynamic fracture toughness of the dry sandstone in the considered range of loading rates of 10–100 GPa·m$^{1/2}$/s, the incubation time of wet sandstone (as well as wet granite) is slightly longer.

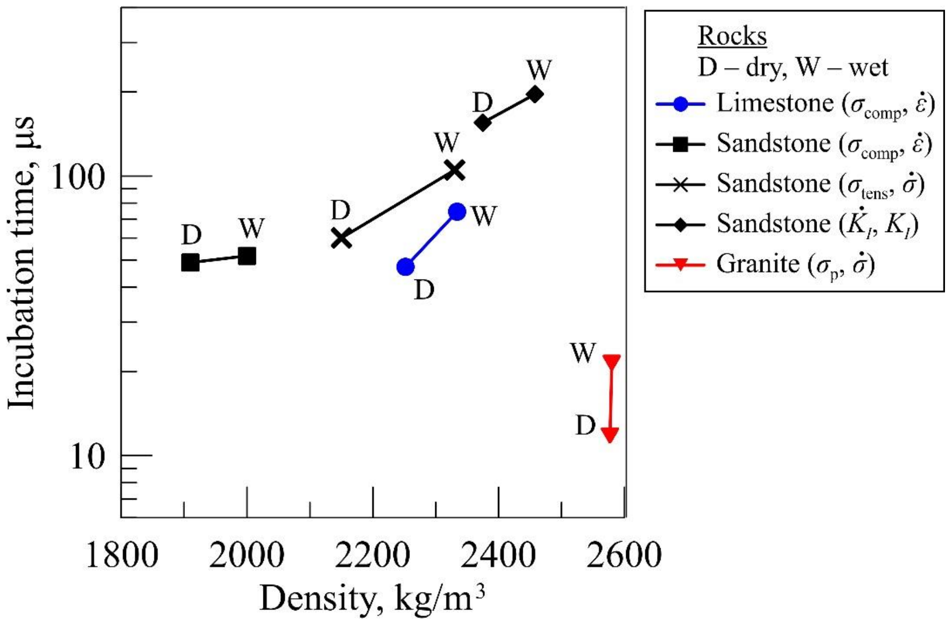

Fig. 6. Dependence of incubation time on rock density, present in results this paper for sandstone (K_I,$\dot{K}_I$) and papers [15,20] for limestone (σ_{comp},$\dot{\varepsilon}$), sandstone (σ_{comp},$\dot{\varepsilon}$), (σ_{tens},$\dot{\varepsilon}$) and granite (σ_{tens},$\dot{\sigma}$). References to experimental data used for calculations: limestone (σ_{comp},$\dot{\varepsilon}$) – [1], sandstone (σ_{comp},$\dot{\varepsilon}$) – [32], sandstone (σ_{tens},$\dot{\sigma}$) – [2], sandstone (K_I,$\dot{K}_I$) (black diamonds) – [31], granite (σ_{tens},$\dot{\sigma}$) – [3,5]

The incubation time values increase with rock density, as shown in [20]. Since water-saturated rocks have a higher density in comparison with dry rocks, they have the greatest strength under dynamic conditions. Let us plot the dependence of the incubation time on the density of the rock based on the results obtained and compare it with the results of studies [15,20]. Figure 6 shows the dependence of incubation time on density for limestone, sandstone, granite based on the results of the presented paper and papers [15,20]. The calculated incubation times for wet and dry sandstone (this section), obtained from the rate dependences of the mode I fracture toughness, are a continuation of the linear dependence for the incubation times of sandstones. The higher the moisture content of the material, the greater the density and incubation time of the rock. As noted above, the main factor in the greater strength characteristics (strength, fracture toughness) at high strain rates for wet rock compared to dry rock is hydrostatic pressure, and not the density of the material.

Effect of external hydrostatic pressure

Based on the incubation time criterion (1), we consider the influence of external hydrostatic pressure on the rate dependences of the fracture toughness of rocks and their incubation times. Experimental data [11,12] are used to verify the criterion. In [11], the results of dynamic tests for three-point bending of the Laurentian granite, tests at various hydrostatic pressures 0, 5, 10, 15, and 20 MPa were discussed. In [11], values of quasi-static toughness K_{Ic} = 1.5 MPa·m$^{1/2}$ for granite with a density at zero hydrostatic pressure ρ_0 = 2630 kg/m3 and other parameter of tests a_l = 5 mm, B = 25 mm, R = 25 mm, were presented. In [12], the dynamic fracture of marbles tested according to the scheme of dynamic short core in compression test [32–34] with five external hydrostatic pressures 0, 5, 10, 15, and 20 MPa, was examined. In [12], values of quasi-static toughness K_{Ic} = 1.5 MPa·m$^{1/2}$ for granite with a density at zero hydrostatic pressure ρ_0 = 2630 kg/m^3 and other parameter of tests a_l = 5 mm, B = 25 mm, R = 25 mm, k = 0.74 MN/m were presented.

Table 1. Estimated incubation times of Laurentian granite for different values of hydrostatic pressures [11] and densities

Hydrostatic pressure, MPa	ρ, kg/m3 (Eq. (12))	τ, μs
0	2630	100
5	2632.6	145
10	2635	190
15	2637.5	235
20	2640	295

Table 2. Estimated incubation times of marble for different values of hydrostatic pressures [12] and densities

Hydrostatic pressure, MPa	ρ, kg/m3 (Eq. (12))	τ, μs
0	2850	25.6
5	2850.2	26.7
10	2850.4	31.3
15	2850.6	33.1
20	2850.8	33.3

In terms of the structural-temporal approach, it is assumed that the incubation time of the rock for each hydrostatic pressure is different. In terms of the structural-temporal approach, it is assumed that the incubation time of the rock for each hydrostatic pressure is different. Based on the experimental results obtained in [11,12] on the study of the dynamic fracture of Laurentian granite at various hydrostatic pressures, theoretical calculations of the rate dependences of the dynamic fracture toughness on the loading rate using the time criterion (1) are carried out. Tables 1 and 2 show the incubation times estimated by applying criterion (1) to the experimental data of granite [11] and marble [12]. The plotted theoretical dependences of mode I fracture toughness on loading rate for granite in comparison with experimental data [11] are shown in Fig. 7. The constructed theoretical dependences of mode II fracture toughness on loading rate for marble in comparison with experimental data [12] are presented in Fig. 8. A good agreement between the experimental results and the calculations are observed.

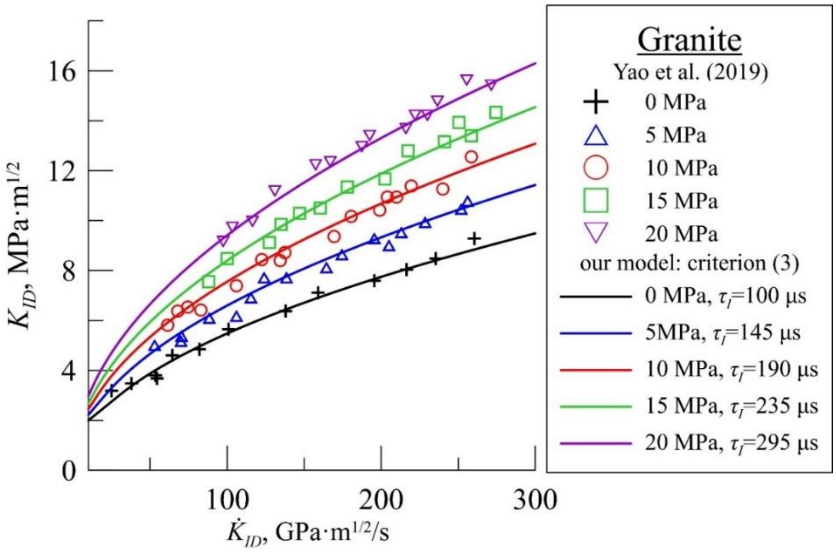

Fig. 7. Dependence of mode I fracture toughness on rate fracture toughness at different hydrostatic pressures, predicted by the incubation time criterion of fracture based on experimental data of granite [11]

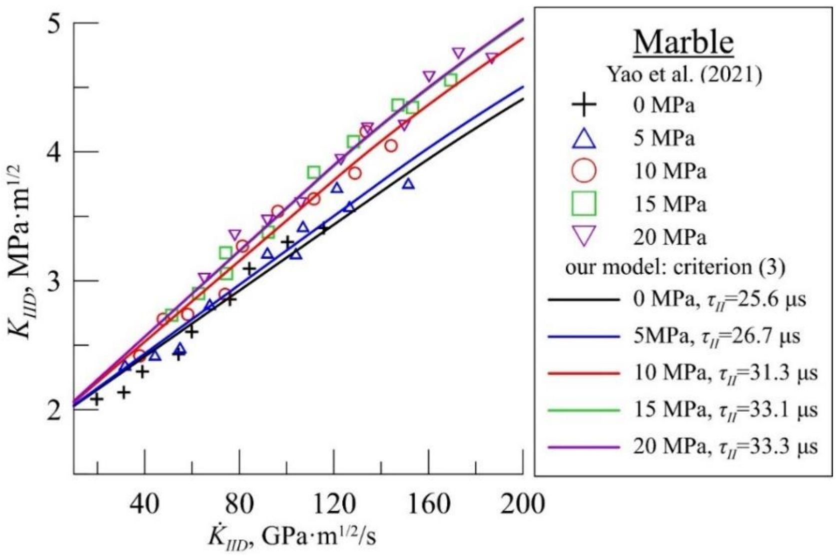

Fig. 8. Dependences of mode II fracture toughness on rate fracture toughness at different hydrostatic pressures, predicted by the incubation time criterion of fracture based on experimental data of marble [12]

The results show that the dynamic fracture toughness of mode I and mode II under hydrostatic pressure increases with loading rate. This is due to the influence of hydrostatic pressure, when, under the influence of a high strain rate, microcracks do not have time to propagate and microcracks in rocks close, which leads to an increase in dynamic fracture toughness.

Let us study the dependence of incubation time on rock density, expressing the density in terms of hydrostatic pressure. Fractional variation ϑ, associated with the action of hydrostatic pressure, is defined from the following expression:

$$\theta = \frac{1-2\nu}{E}3p, \tag{10}$$

where ν is the Poisson's ratio, E is the Young's modulus. According to the law of conservation of mass:

$$\rho_0 V_0 = \rho_1 V_0 (1+\theta), \tag{11}$$

where ρ_0 is the density of rock without the action of hydrostatic pressure, ρ_1 is the density of rock with the action of hydrostatic pressure.

Tables 1 and 2 show the calculated values of rock density according to Eq. (11) at different hydrostatic pressures. Changes in rock density relative to the initial density at zero hydrostatic pressure were 0.4 % for granite and 0.02 % for marble. The observed trend of increasing incubation time is more related to hydrostatic pressure than rock density. Thus, an increase of the incubation time and the dynamic fracture toughness at high strain rates of wet rock compared to dry rock is hydrostatic pressure, and not a significant change in density (Fig. 6). Thus, an increase of the incubation time and the dynamic fracture toughness at high strain rates of wet rock compared to dry rock is related with the hydrostatic pressure, and not a significant change in density (Fig. 6).

Thus, the increase of the incubation time with rock moisture is directly related to hydrostatic pressure. This will make it possible: to explain the effect of water saturation (the previous section), to compare rocks with different static and dynamic strength characteristics and to select the optimal material with the level of water saturation for the selected deformation mode.

Fracture incubation time under hydrostatic pressure effect

Incubation time as a parameter of the speed sensitivity of a material is a significant characteristic when valuation of the dynamic strength characteristics of rocks. As hydrostatic pressure increases, the incubation time for destruction increases. Based on the results of the previous section, we will analyze the incubation time from hydrostatic pressure. Let us assume that there is a linear dependence of the incubation time on hydrostatic pressure, given by Eq. (12):

$$\tau = \tau_0 + k * p, \tag{12}$$

where τ_0 is the value of incubation time in the absence of external hydrostatic pressure (0 MPa), i.e. τ_0 = 100 μs for granite and τ_0 = 25.6 μs for marble, k is the constant proportionality factor, p is the hydrostatic pressure. Figure 9 shows the calculated values of incubation time for granite and marble corresponding to external hydrostatic pressure and the calculated linear dependencies with the estimated parameter k = 9 μs/MPa for granite and k = 0.44 μs/MPa for marble. Plotted linear dependencies according to Eq. (12) have good agreement with the incubation times.

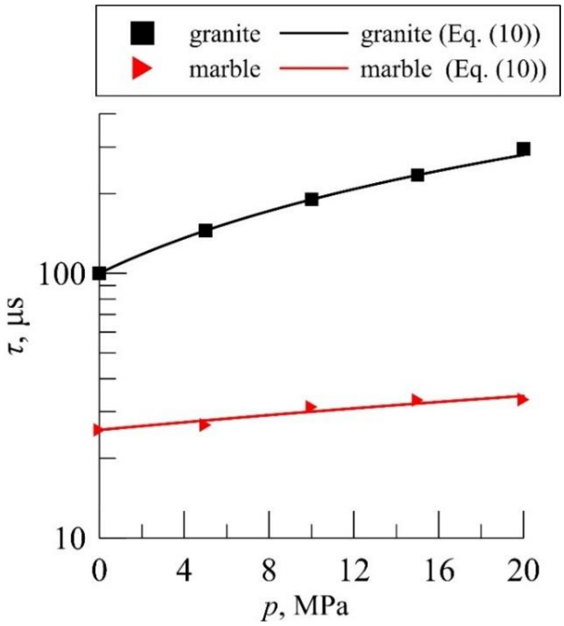

Fig. 9. Dependence of incubation time on hydrostatic pressure. References to experimental data used for calculations: granite (K_I, $\dot{K}_I$) (red triangles) – [11], marble (K_{II}, $\dot{K}_{II}$) – [12]

It supports the hypothesis that the difference in incubation times between rocks with different degrees of water saturation is caused by different levels of hydrostatic pressure resulting from rapid impact. Hydrostatic fluid pressure slows down the incubation process of micro-cracking, therefore, the characteristic relaxation time increases.

Conclusions

The rate dependences of fracture toughness according to mode I for sandstone and granite and according to mode II for marble were predicted based on the incubation time criterion. Theoretical dependencies of dry and saturated sandstones were plotted. The highest value of incubation time, characterizing the speed sensitivity of the material, was observed for saturated sandstone. The trend of increasing incubation time with the addition of water in rock samples depending on density was discussed in comparison with other estimated incubation times calculated from different rate dependences of strength.

On the basis of the proposed approach, the influence of hydrostatic pressure on the rate dependences of the fracture toughness of granite and marble was studied. Incubation time has been shown to increase with hydrostatic pressure and water saturation level. The linear dependence of incubation time on hydrostatic pressure was proposed. A relationship between hydrostatic pressure and saturation level for granite and marble was discussed. The dependences of incubation time on hydrostatic pressure were plotted.

Analysis of the incubation time depending on hydrostatic pressure and the level of water saturation showed that the hydrostatic pressure effects are opposite at low (acceleration of relaxation processes) and high (deceleration of relaxation processes) strain rates. The obtained estimates of incubation times can be used to determine the optimal strength properties of rocks, depending on the selected loading mode and the level of water saturation.

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