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A Study of Specific Fracture Energy at Percussion Drilling

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Abstract. The paper presents experimental studies of rock failure provided by percussion drilling. Quantification and qualitative analysis were carried out to estimate critical values of rock failure depending on the hammer pre-impact velocity, types of drill bits and cylindrical hammer parameters (weight, length, diameter), and turn angle of a drill bit. Obtained data in this work were compared with obtained results by other researchers. The particle-size distribution in granite-cutting sludge was analyzed in this paper. Statistical approach (Spearmen's rank-order correlation, multiple regression analysis with dummy variables, Kruskal-Wallis nonparametric test) was used to analyze the drilling process. Experimental data will be useful for specialists engaged in simulation and illustration of rock failure.

Notation accepted
A is the type of drill bits: *A*1 is the insert bit; *A*2 is the crosscut bit; *A*3 is the spade bit.
B is the hammer pre-impact velocity: *B*1 is 5 m/s; *B*2 is 7 m/s.
C is the type of hammers: *C*1 is the hammer with 0,350 m length, 0,035 mm diameter, and 2.5 kg weight; *C*2 is the hammer with 0.45 m length, 0.045 mm diameter, and 5,48 kg weight; *C*3 is the hammer with 0.70 m length, 0.035 mm diameter, and 5.48 kg weight; *C*4 is the hammer with 0.253 m length, 0.075 mm diameter, and 8.32 kg weight.
D is the turn angle angular rotation of a drill bit: *D*1 is 20°; *D*2 is 30°; *D*3 is 40°.

1. Introduction

All previous investigations conducted by the authors into wave actions associated with percussion drilling related to the drill string rather than the rock. Investigations included the principles of formation and propagation of power pulses via the drill string towards the drill bit [1].

This paper mainly focuses on estimation of the interaction between power pulses and rock, and the specific fracture energy produced by different types of drill bits.

The principles of percussion drilling were determined for coarse-grained granitic rock which is widely used in this type of research allowing to compare experimental results with obtained results by other researchers.

The efficient rock failure was studied in many works [3, 4, 5, 7, 10]. It is worth noting that some of them present conflicting data on results of rock failure affected by the above stated parameters. Thus, Ivanov et al. [2] suggest increasing the efficiency of rock disintegration up to 50% via changing the pulse configuration produced by the hammer. At the same time, Baron et al. [2] notes that the change of the pulse configuration cannot improve the efficiency of the dynamic rock failure. In works [2, 3] it was shown that at the critical percussive energy affecting the granitic rock (40 *J/cm* and higher), the hammer impact rate in the range of 5-9 m/s did not practically change the specific fracture energy.

Mavljutov [8] proved that the dependence between the specific fracture energy and the percussive energy was characterized by the existence of several extreme values. This, in turn, contradicts the results obtained by other researchers concerning the existence of critical percussive energy characterized by the optimum value of specific fracture energy.

Based on the above statements, the rock failure tests should be conducted to sort out the conflicting cases. The granitic rock workpiece was selected to define the degree of impact of a power pulse propagating along the drill string and that of a drill bit on the efficiency of rock failure.

2. Research Methodology

The impact testing machine was designed to study the specific fracture energy of coarse-grained granitic rock failure, permitting to transmit the impact and static loads to the rock. The cylindrical hammers with various parameters were used to apply impact loads to the drill string equipped with a drill bit. A static load was being constant during all tests that provided a close contact between the drill bit and the rock.

The percussive energy ranged between 31.25 – 207.35 *J*. The hammer pre-impact velocity was provided by the change of its drop height.

The dependence between the number of independent and dependent variables was established during this experiment. Herewith, independent variables were presented by the drill bit type (*A*), the hammer pre-impact velocity (*B*), the hammer type (*C*), and turn angle of the drill bit (*D*), while dependent variables included the amount of disintegrated granitic rock (weight ratio between average (per impact) and specific values), specific fracture energy, and drilling deeper per single impact (figure 1). The depth of the well was measured with a beam compass for ten times to find an average value.

The statistical approach was used to analyze the specific fracture energy. Reproducibility of test results was considered to be sufficient at values rather close to each other (±10%) obtained from 15 or 20 tests (each test included ten impacts). In some cases, the number of tests achieved 30 or 40.

Arithmetical averages were determined for the following parameters: the amount of disintegrated granitic rock, drilling deeper per single impact, and specific fracture energy. Coefficients of variations made up 6 – 9 %.

Obtained results during the experiment were analyzed using methods of mathematical statistics with probability belief of 0.95. This analysis showed that the distribution of obtained random values did not exactly conform to the normal law of distribution that required conducting nonparametric tests, namely: Spearmen's rank-order correlation, multiple regression analysis with dummy variables, and Kruskal-Wallis nonparametric test.

3. Results and Discussion

Table 1 presents the summary of experimental results that have proved the insignificant difference between specific fracture energy values at impact rates of 5 and 7 m/s, and types of dependencies were also identical. However, the hammer weight had a substantial effect on the specific fracture energy and drilling deeper per single impact.

At the same time, a substantial impact of load application rate on the specific fracture energy and drilling deeper per single impact is obvious.

Hammers *C*2 and *C*3 both having 5.48 kg weight but different length, showed unexpected results. Thus, a widely spread opinion that longer hammers provide a longer power pulse duration and are 1,4 – 1,9 times energy efficient than that shorter and thicker ones [2] was proved only for the insert bit (figure 3 *a*). The increase of the hammer length from 450 to 700 mm resulted in 6–10% decrease of the specific fracture energy.

Another situation was observed, however, for crosscut and spade bits. For crosscut and spade bits the increase of the hammer length from 450 to 700 mm resulted in 9–16% and 5% increase of the specific fracture energy, respectively. It was assumed that the hammer length of 700 mm leads to the increase of the reflected power pulse energy.

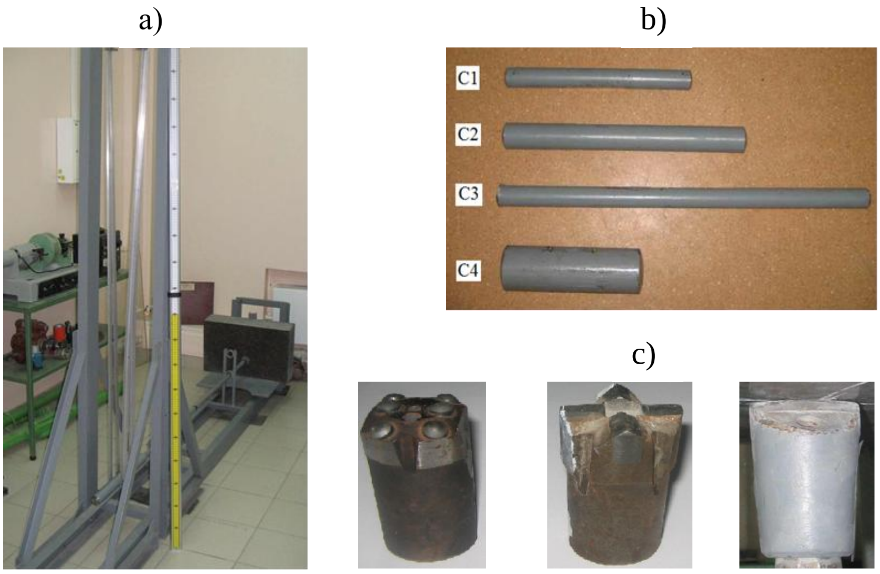

Figure 1. Test bench: *a)* – impact testing machine; *b)* – cylindrical hammers; *c)* – drill bits (43 mm diameter).

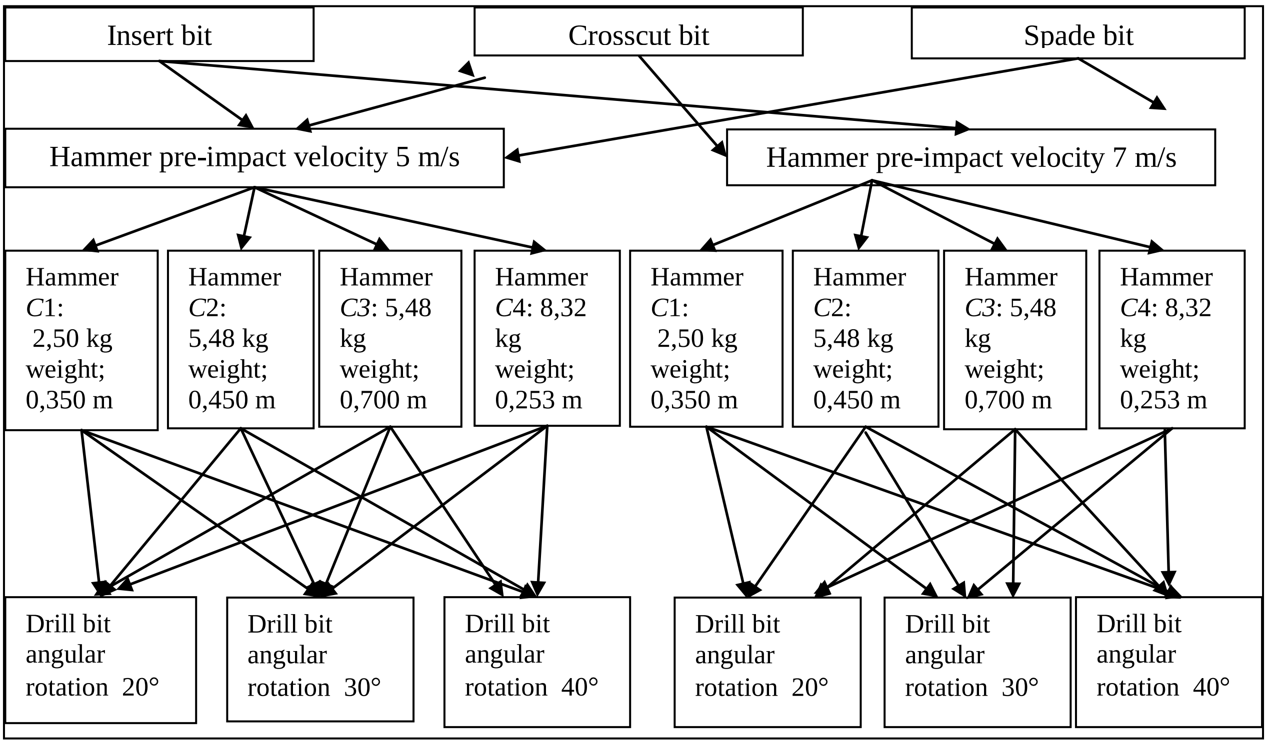

Figure 2. Range of independent variables.

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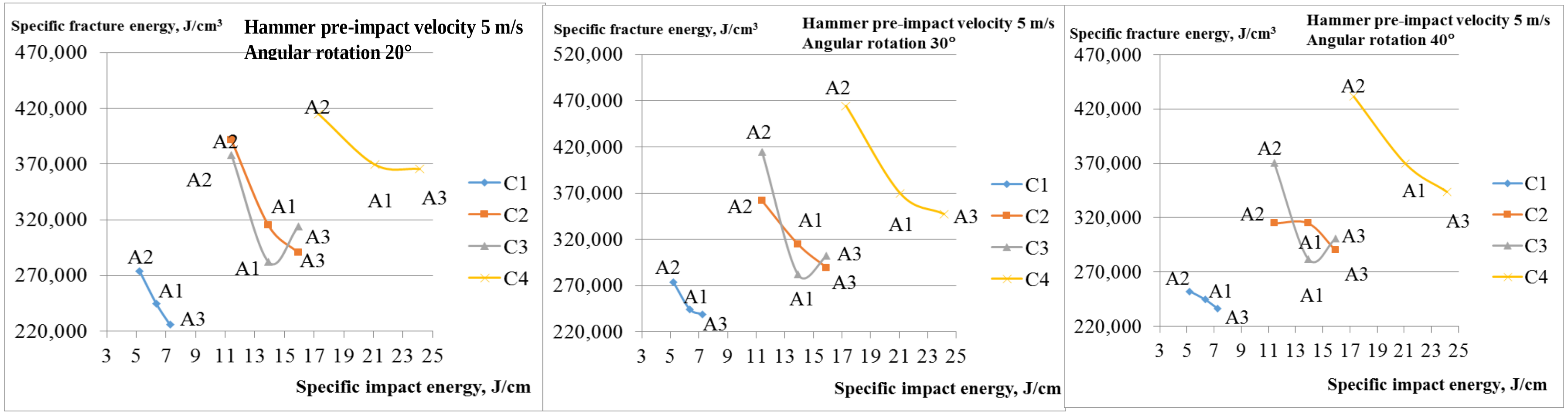
Table 1. Summary of experimental results for drill bits (insert A1, crosscut A2, spade A3) [9]

Set of tests				Average amount of disintegrated granitic rock per impact, cm^3	Specific fracture energy, J/cm^3	Drilling deeper per single impact, mm		Average amount of disintegrated granitic rock per impact, cm^3	Specific fracture energy, J/cm^3	Drilling deeper per single impact, mm		Average amount of disintegrated granitic rock per impact, cm^3	Specific fracture energy, J/cm^3	Drilling deeper per single impact, mm
B1	**C1**	**D1**	**A1**	0,130	242,978	0,09	**A2**	0,115	274,022	0,08	**A3**	0,139	225,671	0,08
B1	**C1**	**D2**	**A1**	0,130	241,107	0,09	**A2**	0,115	273,821	0,08	**A3**	0,132	239,162	0,08
B1	**C1**	**D3**	**A1**	0,126	249,552	0,09	**A2**	0,125	252,207	0,08	**A3**	0,127	236,146	0,08
B2	**C1**	**D1**	**A1**	0,255	242,029	0,15	**A2**	0,241	255,189	0,15	**A3**	0,253	242,306	0,11
B2	**C1**	**D2**	**A1**	0,225	273,948	0,15	**A2**	0,236	260,109	0,14	**A3**	0,261	235,108	0,15
B2	**C1**	**D3**	**A1**	0,237	259,258	0,15	**A2**	0,258	238,406	0,16	**A3**	0,257	239,588	0,16
B1	**C2**	**D1**	**A1**	0,212	328,403	0,14	**A2**	0,178	391,335	0,10	**A3**	0,238	290,467	0,14
B1	**C2**	**D2**	**A1**	0,212	325,949	0,14	**A2**	0,191	361,556	0,11	**A3**	0,237	289,361	0,13
B1	**C2**	**D3**	**A1**	0,237	290,315	0,16	**A2**	0,219	314,817	0,13	**A3**	0,236	290,034	0,15
B2	**C2**	**D1**	**A1**	0,432	312,814	0,30	**A2**	0,401	336,304	0,21	**A3**	0,401	336,187	0,23
B2	**C2**	**D2**	**A1**	0,409	328,942	0,29	**A2**	0,430	312,739	0,25	**A3**	0,483	276,518	0,27
B2	**C2**	**D3**	**A1**	0,455	295,113	0,25	**A2**	0,437	309,166	0,26	**A3**	0,488	311,798	0,25
B1	**C3**	**D1**	**A1**	0,231	297,082	0,16	**A2**	0,183	378,152	0,11	**A3**	0,218	313,909	0,13
B1	**C3**	**D2**	**A1**	0,240	287,519	0,17	**A2**	0,167	414,392	0,10	**A3**	0,227	302,077	0,14
B1	**C3**	**D3**	**A1**	0,259	264,772	0,16	**A2**	0,187	370,255	0,11	**A3**	0,229	300,487	0,13
B2	**C3**	**D1**	**A1**	0,460	292,465	0,29	**A2**	0,370	370,372	0,25	**A3**	0,376	357,278	0,20
B2	**C3**	**D2**	**A1**	0,456	295,051	0,29	**A2**	0,366	367,909	0,23	**A3**	0,453	296,905	0,25
B2	**C3**	**D3**	**A1**	0,455	295,659	0,3	**A2**	0,366	370,510	0,19	**A3**	0,487	277,132	0,25
B1	**C4**	**D1**	**A1**	0,289	361,199	0,19	**A2**	0,251	415,054	0,15	**A3**	0,284	365,519	0,17
B1	**C4**	**D2**	**A1**	0,278	374,564	0,19	**A2**	0,224	464,383	0,13	**A3**	0,299	347,567	0,17
B1	**C4**	**D3**	**A1**	0,282	373,081	0,16	**A2**	0,241	431,340	0,16	**A3**	0,302	343,850	0,18
B2	**C4**	**D1**	**A1**	0,479	427,043	0,31	**A2**	0,471	432,805	0,27	**A3**	0,513	397,168	0,29
B2	**C4**	**D2**	**A1**	0,519	392,444	0,34	**A2**	0,478	428,141	0,27	**A3**	0,523	390,644	0,30
B2	**C4**	**D3**	**A1**	0,499	408,313	0,37	**A2**	0,467	438,524	0,28	**A3**	0,517	394,356	0,30

a)



b)

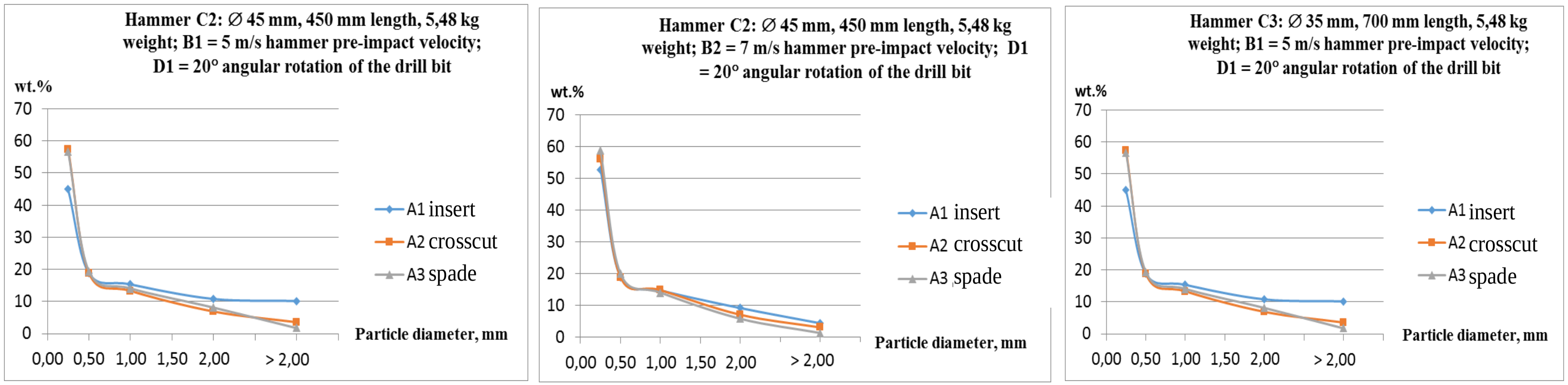


Figure 3. Empirical relations between the specific fracture energy and specific impact energy and the particle-size distribution in granite-cutting sludge:
a) – relation between the specific fracture energy and the specific impact energy. Hammer C2. Impact rate 5 m/s. Angular rotation 20°, 30°, 40°
b) – particle-size distribution in granite-cutting sludge (hammers C2 and C3)

As shown in figure 3 *b*, the percentage of particles having 0.25 mm diameter is maximum (40–60 wt.%). Particles having 0.5 and 1,0 mm diameter make up 10–20 wt.%; and particles with 2.0 mm diameter and larger are 5-10 wt.% and 2–14 wt.%, respectively.

With increase of the percussive energy the insert bit (see table 1 and figure 3 *b*) has the advantage over other drill bit types. The insert bit produced granite-cutting sludge of larger size in all cases and showed perfect results at different impact rates. Thus, at 5 m/s impact rate of the hammer the percentage of particles having the diameter over 2 mm is about 10 wt.%, while that of particles with diameter less than 0.25 mm does not exceed 49 wt.%. Results obtained at 7 m/s impact rate of the hammer are comparable with those of the crosscut and spade drill bits.

The lowest specific fracture energy is observed at 20° turn angle angular rotation of the spade drill bit and the load applied by hammer *C*1. With the increase of the percussive energy from 68.5 to 103.7 *J*, 30° and 40° angular rotations show practically identical results in relation to the specific fracture energy.

The crosscut bit is characterized by the best specific fracture energy value at 40° turn angle at the percussive energy of 30-70 *J*. At higher values of percussive energy the difference between the specific fracture energy values is substantially reduced at 30° and 40° turn angle angular rotations.

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