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An Experimental Study on Determination of Crack Propagation Energy of Rock Materials under Dynamic (Impact) and Static Loading Conditions

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ABSTRACT

The Charpy impact test, a widely applied impact strength determination test for various materials such as metals, polymers and cementitious materials was performed to evaluate the crack propagation energy of 13 different granite type rock materials under the impact load condition. Additionally, crack propagation energies of the granite materials were determined under the static load condition to compare the results with those of the Charpy impact test. The energy levels measured from static load tests were significantly lower than those obtained from the dynamic load test that the ratio of energy level under the dynamic loading to energy level under static loading condition was measured to change between 39 and 200 for different 13 type of granite materials tested in this study. The crack propagation time for the chevron-notched specimens under static loading was also measured using professional sound recording systems. As results of this study have not indicated that the crack propagation speed and energy values measured from different granite materials have a direct relationship, energy-dependent crack propagation speed was found to be an inherent property of rock materials. The Charpy impact test was assessed usable for being a sensitive crack propagation energy determination method for rock materials. In the context of improvement of the Charpy impact test for rock materials, some issues were pointed out in this study.

Keywords:
Crack propagation in rock materials; Impact strength of rock materials; Charpy test; Impact energy; Dynamic loading; Fracture toughness

INTRODUCTION

Determination of the fracture toughness of rock materials can be carried out under different conditions of static and dynamic loads, by following various testing methods suggested by different researchers, standards and International Society of Rock Mechanics and Rock Engineering [1-10]. Although there are numerous researches to get deeper to identify the fracture mechanics of rock materials under cyclic (dynamic) loading and better understand the differences in behaviour of fracturing under cyclic and static loads, it is still a need to focus on more and suggest a standard testing method for determination of fracture toughness of rock materials being exposed to impact load, another type of dynamic loading induced in various rock engineering applications. Rock fracture toughness values under the impact loading condition are key parameters for various rock engineering applications such as percussion drilling, use of various mechanical excavation machines, blasting operations, absorption of the rock bursting energy and etc. [11-15].

In this study, the Charpy impact test, a widely applied impact strength determination test for various materials such as metals, polymers, cementitious materials like concrete mixes and ceramics was performed to determine the fracture energy of 13 different granite type rock materials. Since it is practical and cheap for obtaining results quickly, the Charpy impact test was thought to be a potential test for being popular in impact strength determination of rock materials. In the Charpy impact test, notched beam specimens are hit by a hammer carried on a pendulum which is allowed to fall freely to supply impact energy. As the hammer hits to the opposite face directly behind the notch, an amount of energy is consumed for crack propa-

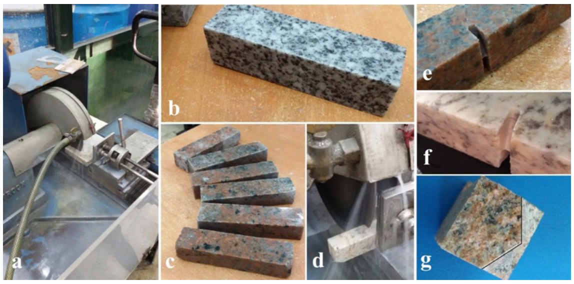

Figure 1. Block cutting (a, b, c), Chevron notch cutting and design (d, e, f, g)

gation. To measure the energy consumption amount, the height difference between the initial position and which the pendulum rises after failure is recorded by a pointer mounted on the dial.

Chevron notched granite specimens were prepared in this study to be applied both three-point flexural strength and Charpy impact tests for determination of the Mode I type fracture toughness and energy consumption for crack propagation values under different conditions of static and dynamic (impact) loading. The chevron-notches are artificial cracks and make initiation of the crack at the chevron tips. The chevron-notched geometry is made by the various machining operations, whose the simplest one is to use a rotating saw blade resulting in the sides of the notch, as done in this study.

MATERIALS AND METHODS

In this study, different Turkish granite blocks were cut into pieces to prepare specimens with dimensions of 25 mm x 25 mm x 80 mm. As seen in Fig. 1 which shows specimen preparation steps, the chevron notched artificial cracks were made using a circular saw with a diameter of 20 cm and a thickness of 1.3 mm. Because of the abrasion of rock samples during the cutting process, the notch width was mostly measured to vary between 2 mm and 3 mm, depending on the rock material. The chevron notch cutting depth was 8 mm for all specimens.

To determine Mode I type fracture toughness of the chevron-notched specimens under static loading, three-point flexural strength test was applied using an electric motor press with a maximum load level of 50 kN, which is a sensitive loading equipment to be used for low strength materials. The loading rate of 1mm/min was

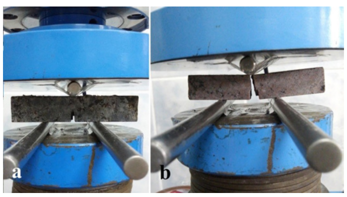

Figure 2. A three point flexural strength test specimen before loading (a) and after failure (b)

Figure 3. Charpy impact strength test: the test equipment (a), a specimen put in the abutments (b), lifting hammer (c, d), hammer dropped and determination of maximum hammer height after crack propagation (e), a failed specimen (f)

chosen to determine failure load in the three-point flexural strength test of the chevron notched specimens put on the abutments with a distance of 4 cm between each other (Fig.2). Similarly, Charpy impact test specimens had a gap dimension of 4 cm between the abutments where the specimens were put in (Fig. 3). As the hammer with the weight of 5 kg is dropped from 1 meter height, an energy level of 50 Joule was applied on the chevron notched specimens used in the Charpy impact test. As in the static load test, the bending effect was induced as the falling hammer applies load to the specimens used in the Charpy impact test. It should be noted herein that specimens of static and dynamic load tests were cut to have the same size of 25 mm x 25mm x 80 mm. In the Charpy test, differences in falling hammer height before and after the failure of specimens were read from the gage to define the energy consumption for crack propagation through the specimens.

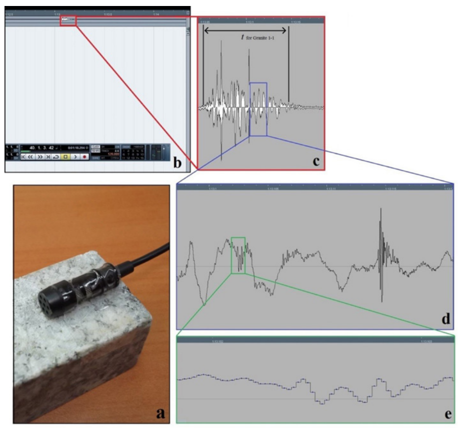

Figure 4. a) Contact microphone stuck on a specimen, b, c, d, e) recorded sound wave from a Granite 1 type specimen (t: crack propagation time)

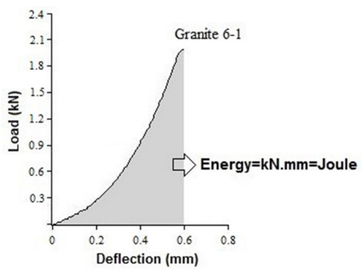

Figure 4. Logarithm of flow curves in rolling direction

A contact microphone was stuck on static load test specimens to record cracking sound for measuring the propagation time. The crack propagation time could be measured with a sensitivity of 0.01 millisecond, using a professional music production program and an external audio card for professional sound recording. An example of sound waves recorded during the crack propagation is given in Fig. 4. In addition to crack propagation time, deflections of the static load test specimens were measured by using the LVDT device. For 13 different granite materials named from Granite 1 to Granite 13, maximum loads, load-deflection graphs and crack propagation times were determined for static load specimens to investigate the relation between static load test results and energy consumption data obtained with the Charpy impact test.

RESULTS AND DISCUSSION

The maximum load and the area under the load-deflection curves of granite specimens tested in this study are respectively given in Table 1 and Table 2. Areas under the load-deflection curves were calculated to determine the energy level causing to break the resistance against the natural crack occurrence, as seen in Fig. 5. As another parameter measured during the static loading test, duration of the crack propagation data is given in Table 3. Depending on the crack propagation time, crack propagation distance and energy levels given in Table 2, time-dependent energy consumption for crack propagation rate in Watt unit (J/s), energy-dependent crack propagation speed (m/Js=1/Ns) and energy consumption per a unit crack surface area occurrence (J/m^2=N/m) are given in Table 4. The crack propagation distance was 23 mm from the tip of the notch to the specimen end. Because all the specimens tested in this study has the same crack surface area and same specimen dimensions, energy consumption per unit crack surface area is directly proportional to the crack propagation energy. Two-sided cracking surface cross-section area of 10 cm^2 (5 cm2x2) was considered to calculate values in Table 4. The energy consumption values determined by applying the Charpy impact test for crack propagation under the dynamic load are given in Table 5.

Table 1. Results obtained with static load test

Specimen name	Fmax (kN)	S.D. in Fmax (kN)	Specimen number
Granite 1	1.26	0.07	3
Granite 2	1.20	0.11	3
Granite 3	0.92	0.10	3
Granite 4	1.17	0.11	3
Granite 5	1.02	0.08	3
Granite 6	1.95	0.06	3
Granite 7	0.41	0.09	3
Granite 8	0.54	0.07	3
Granite 9	0.63	0.05	3
Granite 10	0.35	0.02	3
Granite 11	1.34	0.10	3
Granite 12	1.26	0.13	3
Granite 13	0.38	0.05	3

Table 2. Areas under load-deflection curves (E: Energy, S.D: Standard Deviation)

Specimen name	E (milliJoule)	S.D. in E (milliJoule)	Specimen number
Granite 1	441	20	3
Granite 2	399	34	3
Granite 3	93	10	3
Granite 4	357	36	3
Granite 5	219	19	3
Granite 6	486	27	3
Granite 7	204	15	3
Granite 8	90	7	3
Granite 9	126	23	3
Granite 10	105	11	3
Granite 11	204	12	3
Granite 12	354	10	3
Granite 13	60	7	3

Table 3. Crack propagation durations

Specimen name	t (millisecond)	S.D. in t (millisecond)	Specimen number
Granite 1	90	8	3
Granite 2	65	7	3
Granite 3	105	7	3
Granite 4	157	10	3
Granite 5	119	5	3
Granite 6	18	2	3
Granite 7	29	4	3
Granite 8	26	2	3
Granite 9	323	34	3
Granite 10	305	23	3
Granite 11	40	3	3
Granite 12	61	9	3
Granite 13	246	16	3

Table 4. Energy consumption rate and crack propagation speed under static load

Specimen name	Energy Consumption rate (Watt)	Crack propagation speed (m/s)	Energy dependent crack propagation speed (1/Ns)	Energy consumption per crack surface area (mJ/cm²)
Granite 1	4.90	0.26	0.59	44.1
Granite 2	6.14	0.35	0.88	39.9
Granite 3	0.89	0.22	2.37	9.3
Granite 4	2.27	0.15	0.42	35.7
Granite 5	1.84	0.19	0.87	21.9
Granite 6	27.00	1.28	2.63	48.6
Granite 7	7.03	0.79	3.87	20.4
Granite 8	3.46	0.88	9.78	9.0
Granite 9	0.39	0.07	0.56	12.6
Granite 10	0.34	0.08	0.76	10.5
Granite 11	5.10	0.58	2.84	20.4
Granite 12	5.80	0.38	1.07	35.4
Granite 13	0.24	0.09	1.50	6.0

It was seen that crack propagation characteristic of rock materials significantly differ depending on loading under static or dynamic conditions. As an example, specimens of Granite 6 having high fracture toughness and energy consumption level for crack propagation under the static load condition had significantly less fracture propagation energy under the impact load condition in comparison with that of Granite 11 with relatively low energy capacity under static loading condition. The relation between crack propagation energy and fracture toughness values was found to be dependent on rock material and not convenient for a generalization. Also, the energy levels measured from static load tests were not found related to the crack propagation energy in dynamic load test that the ratio of energy level under the dynamic loading to energy level under static loading condition was measured to change between 39 and 200 for different 13 type of granite samples tested in this study. The energy level under the static load and deflection graphs which was found to be lower than energy levels obtained with the Charpy impact test for all rock materials tested in this study confirms that energy consumption for crack propagation increases with an increase in loading rate [16-19]. The crack propagation time increasing with a decrease in the loading rate is accepted to be a reason for the issue of measuring energy level under static load to be lower than those obtained from the impact test [20-22].

Table 5. Energy consumption values determined by the Charpy test (E: Energy)

Specimen name	E (Joule)	S.D. in E (Joule)	Specimen number
Granite 1	26	1.5	3
Granite 2	29	1.7	3
Granite 3	14	0.6	3
Granite 4	23	1.0	3
Granite 5	16	2.1	3
Granite 6	19	1.2	3
Granite 7	20	1.5	3
Granite 8	12	1.5	3
Granite 9	11	1.0	3
Granite 10	21	2.5	3
Granite 11	33	2.7	3
Granite 12	24	3.1	3
Granite 13	10	1.2	3

In fracture toughness tests, the load level for start of crack propagation is reached step by step under static loading condition. On the other hand, the load level for the start of crack propagation is immediately applied on the material under impact effect. In case of the crack propagation under the static load condition, a stress level applies on the crack boundaries as a dependent on the energy absorbed during the increase of static load [23-29].

Because the load level needed for crack propagation increases with an increase in the loading rate, higher load levels than those in the static loading condition are expected to reach in Charpy impact tests, which can be accepted as another reason for having higher energy absorption capacity under impact effect [30,31]. Because the crack propagation mode varies by a transition from a dominant main crack at the low load rates to one resulting from both main crack and micro-cracking ahead of the main crack at the high loading rates, the plastic dissipation in the fracture process zone increases with increasing loading rate as an issue that causes to increase the load level and energy consumption for cracking under impact load condition [32,33].

Energy consumption rate during crack propagation and crack propagation speed per energy level are some significant parameters in different Rock Engineering applications with immediate loading such in blasting operations. As an outcome of this study, time-dependent energy consumption rate (Watt) was not found related with fracture toughness value and energy consumption values measured in both dynamic loading and static loading conditions. Results of this study have not indicated that the crack propagation speed and fracture toughness values measured from different granite materials have a direct relationship. The energy-dependent crack propagation speed was found to be an inherent property of rock materials.

The crack propagation speed should be focussed on as an important parameter for bettering in different applications such as the determination of delaying time between blasting holes to improve excavation performance [34-38]. According to the results, energy level dependent crack propagation speed was assessed to be an inherent material property with the unit of 1/Ns. As crack propagation speed and energy level to break the resistance against the start of crack propagation are known to vary with a change in initial impact energy of the falling hammer, a definite energy level to be applied in the Charpy impact test is suggested to investigate in the standardization studies [39-41].

The Charpy impact test, a popular test carried out to determine the impact strength of many different materials such as ceramics, concrete, steel materials is suggested to be also used for evaluation of crack propagation energy of rock materials under impact load condition. A standard Charpy impact test equipment development for the core specimens with widely used diameter dimensions like the NX core size is thought to be a significant contribution in the field of rock testing.

As a very basic assumption by considering the energy transformation, 1 meter height of drop makes the hammer to have 4.4 m/s speed when it contacts to the Charpy impact test specimen. In case of lower speed of crack propagation resulting from the response of rock materials to the impact energy than that of the impact hammer motion, crack propagation speed is expected to be artificially increased by the motion of the hammer. In different applications, crack propagation speed is varied due to the motion of tools such in the applications of various mechanical excavation machines. In addition to the impact energy level, tool speed is an individual effect on crack propagation energy [42-45]. For improvement of a new Charpy test equipment, the hammer fall velocity effect is found to be investigated for evaluation of crack propagation energies. Therefore, some modified versions of the test equipment would be used for different testing conditions considering hammer fall energy and speed differences. For instance, natural crack propagation speed can be determined under an immediate energy loading with a very slow hammer motion. To decrease the speed of hammer motion without having no decrease in the impact energy, it is suggested to use a weighty hammer and short drop heights. On the other hand, a high height of the fall and low weight hammers can be used for having relatively high velocities without an increase in the energy level applied in the Charpy impact test.

For the aim of making an advanced Charpy test equipment, high speed cameras are usable to measure crack propagation time and follow the crack propagation steps taking a time as short as microseconds [46-50].

CONCLUSION

The crack propagation resistivity of the rock materials was determined to significantly change depending on testing under static or impact (dynamic) loading condition. Therefore, it is the proper way to determine fracture toughness values and crack propagation energy levels under the relevant load condition. The Charpy impact test is suggested to use for sensitive determination of the crack propagation energies of rock specimens and improve for being applied as an advanced impact test for rock materials.

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