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The Estimation of the Mode I Fracture Toughness of Rocks Using Brittleness Index

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ABSTRACT: Mode I fracture toughness is a significant parameter for investigating the failure behavior of rocks. This parameter has several applications in many different fields, such as mining and tunneling. As the determination of fracture toughness by conducting tests is very time consuming and expensive, using empirical relationships is recommended in this regard. In this study, uniaxial compression, the Brazilian and three-point bending tests were conducted on the specimens of limestone, sandstone, tuffite, lithic tuffs, andesite and travertine. This study aims to determine an empirical relation that enables us to estimate mode I fracture toughness of rock using the brittleness index. The study indicates that of the three brittleness indices (B_1, B_2 and B_3), mode I fracture toughness only has a relationship with brittleness index B1 which has the coefficient of determination R^2= 0.995. This relationship, which is an exponential one, reveals that as the brittleness index increases, the magnitude of mode I fracture toughness increases non-linearly. The proposed relationship equivalent was compared with that of Kahraman and Altindag, and the root-mean-square error was calculated in two equations. Given this calculation, it can be said that the proposed equation, with higher precision than the one proposed by Kahraman and Altindag, can be used to estimate mode I fracture toughness of rocks.

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1- Introduction

Griffith was the first who carried out works on fracture mechanics. He began his pioneering studies around 1920. Griffith discovered that there were many microscopic cracks in every material and hypothesized that these small cracks altogether lowered the overall strength of the material when loading and stress concentration occurs. Stress concentration means that the stress is concentrated around the crack tip or joint, and theses cracks grow rapidly. Therefore, the material breaks long before it reaches its theoretical strength. Although Griffith's theory was very important, but there were some shortcomings in his theory. He considered only elastic materials while not considering brittle and fragile materials which have plastic deformation range. Next, in 1952 to 1954, Irvine introduced a factor called the stress intensity factor which denotes the amount of local stress around the crack tip. Preliminary research in the field of rocks dates back to the works initiated by Hoek and Bieniawski in 1965 in South Africa.

The classification of fractures based on the fracture mode is of old terms of fracture mechanics. Three primary fracture modes are possible in fracture mechanics, which are called mode I, mode II and mode III (Figure 1) [1].

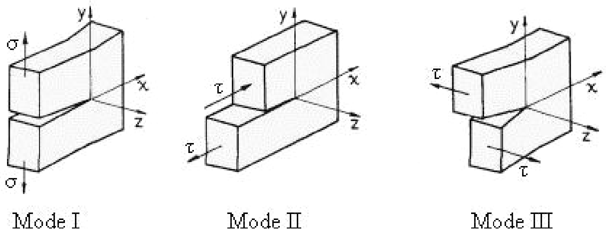

Figure 1. Fracture modes

Rock is a brittle material and as all brittle materials are weak in terms of tension, mode I (tensile mode) is generally considered to be the most critical loading mode in rock mechanics applications. Given that the determination of mode I fracture toughness by conducting experiments is time-consuming, expensive and has operational-specific problems of its own, researchers have attempted to provide empirical equation in the past. Gunsallus [2] and Bhagat et al. [3] experimentally found that the mode I fracture toughness is associated with tensile strength. Whittaker et al. [4] also offered relationships between the mode I fracture toughness and tensile strength, point-load index, compressive strength and the velocity of longitudinal waves. Barman [5] found an empirical relationship between the mode I fracture toughness and point-load index while Brown et al. also found an empirical relationship between this parameter and density [6]. Zhang et al. [7] also offered an empirical equation between the mode I fracture toughness and tensile strength, which is obtained using the Brazilian test. However, a review

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of previous literature reveals that a survey was conducted by Kaharman and Altindag regarding the estimation of the mode I fracture toughness using brittleness index [8]. However, no integrated studies were conducted in Iran to propose empirical equations.

2- Results and Discussion

The Brazilian, uniaxial compression and three-point bending tests (on cylindrical specimens with straight crack) are done on specimens. The data obtained from toughness, the Brazilian and uniaxial compression tests lead to Equations 1 to 3 which show the relationship between the mode I fracture toughness and the brittleness index.

$$K_{IC}=0.0512B_1^{0.5206} \qquad R^2=0.9955 \tag{1}$$

$$K_{IC}=0.8154B_2^{(-0.801)} \qquad R^2=0.0171 \tag{2}$$

$$K_{IC}=1.7772B_3^{(-0.266)} \qquad R^2=0.0458 \tag{3}$$

As can be seen, Equation 1 (Figure 2) has the highest coefficient of determination, and thus is recommended to be the proper equation to estimate the mode I fracture toughness. To verify the accuracy of the obtained equation, the proposed equation is compared with that of Kahraman and Altindag. The statistical studies indicate that the accuracy of the proposed equation lies in estimating the mode I fracture toughness.

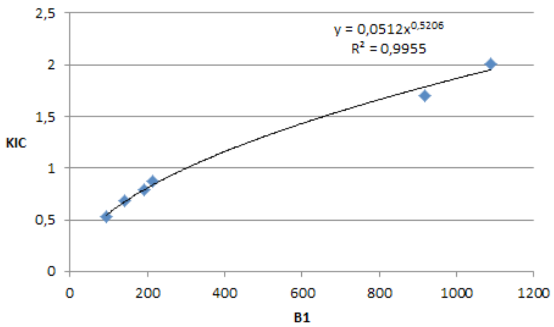

Figure 2. Relationship between the mode I fracture toughness and B_1

3- Conclusion

In this study, uniaxial compression, Brazilian and three-point bending tests were conducted on a specimen of rocks. The objective of this study is to obtain an empirical equation to estimate the mode I fracture toughness of rocks by using the brittleness index. The study showed that for the three brittleness indices (B_1, B_2 and B_3), the mode I fracture toughness only has a relationship with B1 brittleness index with the coefficient of determination R^2=0.995. This equation shows that as the brittleness index increases, the mode I fracture toughness value increases non-linearly too. The reason for the increase of mode I fracture toughness with brittleness index of B_1 can also be explained so that the higher the tensile strength is, the higher the mode I fracture toughness will be, which actually is the rock strength against the crack propagation due to tensile force. Moreover, as the uniaxial compressive strength increases, based on the fracture mechanics relationships, the mode I fracture toughness increases too, whereas its effect on the mode I fracture toughness is less compared with that of the tensile strength. Based on the literature published, the library-based studies conducted until 2016 show that only Altindag et al. have proposed an equation to estimate the mode I fracture toughness by using the brittleness index. To investigate the efficiency of the proposed equation, the equation is compared with Kahraman and Altindag's equation and the root-mean-square error is calculated in both equations. According to this calculation, it can be stated that the proposed equation can estimate the mode I fracture toughness of rocks with higher precision than that of Kahraman and Altindag's equation. This approves the advantage of this study over that one proposed by Kahraman and Altindag.

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