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A new brittleness index for estimation of rock fracture toughness

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Abstract
Assessment of the correlation between rock brittleness and rock fracture toughness has been the subject of extensive research works in the recent years. Unfortunately, the brittleness measurement methods have not yet been standardized, and rock fracture toughness cannot be estimated satisfactorily by the proposed indices. In the present study, statistical analyses are performed on some data collected from the literature to develop two equations for estimation of modes I and II fracture toughness. Then a probabilistic sensitivity analysis is performed to determine the impact of the input parameters on the output ones. Based on the results obtained for the probabilistic analysis, a new empirical brittleness index including tensile strength, uniaxial compressive strength, and elastic modulus is suggested for estimating modes I and II fracture toughness. The analyses results reveal that the proposed index is capable of estimating rock fracture toughness with more satisfactory correlation compared to the previous indices.

Keywords: *Rock Fracture Toughness, Brittleness Index, Statistical Analysis, Probabilistic Analysis*.

1. Introduction

The ability of a rock to resist fracturing and propagation of the pre-existing cracks has been introduced as the rock fracture toughness or critical stress intensity factor (SIF). Rock fracture toughness is an intrinsic rock property that is used as an index for the fragmentation processes such as rock cutting, hydraulic fracturing, and explosive modeling [1-4].

Three types of crack propagation modes have been distinguished in the fundamental fracture process (Figure 1): mode I (tension, opening), mode II (shear, in-plain shear), and mode III (anti-plane shear, tearing). Based on the loading types, a crack can propagate to any of these modes, and three different values have been proposed as the fracture toughness of these modes.

Although several experimental testing methods have been developed for determination of rock fracture toughness, obtaining rock fracture toughness is comparatively more difficult than compressive and tensile strength of rocks in the laboratory [5]. In the recent years, several studies have been performed to develop an empirical relation between rock fracture toughness and other rock properties.

Zhixi et al. have proposed relationships between mode I fracture toughness and acoustic velocity of rocks, which can be used as a basis for an indirect evaluation of rock fracture toughness using the sonic log data from the field [6]. Brown and Reddisht [7] have shown that the fracture toughness of homogeneous rocks has a significant linear relationship with density. Whittaker et al. and Zhang have gathered the results of several laboratory tests in the literature, and have found that mode I fracture toughness and tensile strength of a rock could be empirically related to each other by a linear equation [2, 8].

Chang et al. have demonstrated that among the various physico-mechanical properties of rocks (density, porosity, P-wave velocity, elastic modulus, uniaxial compressive strength, and Poisson's ratio), P-wave velocity has the best relationship with mode I fracture toughness [9].

Kahraman and Altindag have studied the relation between mode I fracture toughness, K_{IC}, and

brittleness index (BI) of rocks. They used the area under the compressive strength line versus tensile strength as BI ($BI = \sigma_c \sigma_t / 2$), and found that there was a significant relation between K_{IC} and BI [5].
Wang et al. have performed an experimental study on a clay-stone, and suggested a linear correlation between mode I fracture toughness and tensile strength of the clay-stone [10].
However, most of the previous studies are concentrated on the estimation of mode I fracture toughness using rock properties, and there is no sufficient information about the empirical relationship for estimation of mode II fracture toughness. In other words, the major influence of tensile strength on the K_{IC} value has been demonstrated previously [2, 8, 10] but the impact of tensile and compressive strength on the K_{IIC} value has not been considered yet.
In the present study, correlation of modes I and II fracture toughness was considered to develop a new brittleness index for estimating fracture toughness for both modes.

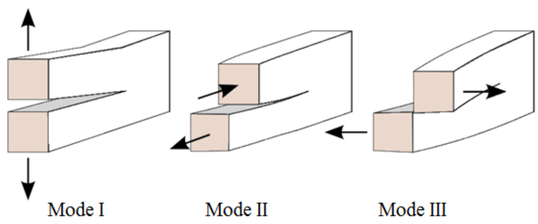

Figure 1. Three fundamental modes of crack propagation: mode I (tensile), mode II (in-plane shear), and mode III (anti-plane shear).

2. Brittleness index

The rock fracturing process is being affected, throughout the event, by brittleness property. A brittle fracture is characterized by a nil or minimum plastic deformation, whereas ductile fracture is accompanied by a significant amount of plastic deformation. Figure 2 schematically depicts the difference between the brittle and ductile fracturing. state of stress, and loading rate have substantial influences on the material brittleness, to a large extent, ductility and brittleness depend on the intrinsic characteristics such as mechanical composition and microstructure [11].
It should be mentioned that ductile fracturing hardly ever occurs in rocks. The ductile fracturing phenomenon is usually observed in metals, whereas most rocks behave as brittle under the normal conditions. However, not all rocks have the same brittleness value, and rocks can be categorized into different brittleness classes [12].

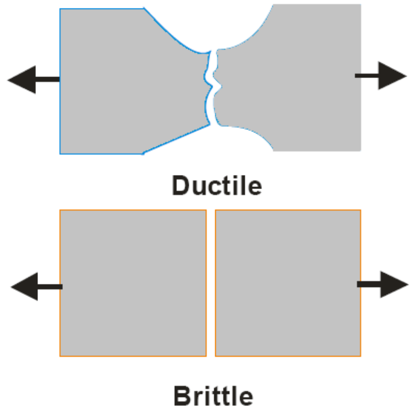

Figure 2. Brittle and ductile fracturings.

Although a large number of rock brittleness measurement methods have been suggested in the literature [13-17], still it has not yet been standardized. What follow, are the four common strength-based (compressive, σ_c , and tensile, σ_t) approaches to measure the brittleness index (BI_1, BI_2 , BI_3, and BI_4) of rocks:

$$BI_1 = \frac{\sigma_c}{\sigma_t} \tag{1}$$

$$BI_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \tag{2}$$

$$BI_3 = \frac{\sigma_c \cdot \sigma_t}{2} \tag{3}$$

$$BI_4 = (\sigma_c \cdot \sigma_t)^{0.72} \tag{4}$$

Equations (1) and (2) have been proposed by Hucka and Das [14], Equation (3) by Altindag [18], and Yarali and Soyer [19] have presented Equation (4).
In the recent years, the stress-strain curve has been analyzed for an estimation of rock brittleness [20, 21]. In the present work, it is intended to determine the correlations between σ_c , σ_t , and E with rock fracture toughness.

3. Evaluation of experimental data

A summary of modes II and I fracture toughness (K_{IIC} , K_{IC}) together with tensile strength (σ_t), uniaxial compressive strength (σ_c), and elastic modulus (E) of some rock types, gathered from the literature, is presented in Table 1. The values for tensile strength in this table 1 have been derived from the Brazilian tests on the basis of the ISRM standard. Also most data attributed to mode I fracture toughness was provided by the Chevron Bend test, and the Punch-Through Shear test was used for determination of the K_{IIC} value in most cases.

Table 1. Mechanical properties of some rocks.

Rock Type	K_{IIC} MPa.m[0.5]	K_{IC} MPa.m[0.5]	σ_t MPa	σ_c MPa	E GPa	BI1	BI2	BI3	BI4	Reference
Welsh limestone	1.0	0.9	8.5	144.9	33.2	17.1	0.9	615.1	167.8	[22]
Coarse-grained Sandstone	0.3	0.3	2.7	32.3	9.9	12.2	0.8	42.8	24.6	[22]
Fine-grained sandstone	0.4	0.4	3.3	58.4	14.6	17.5	0.9	97.4	44.5	[22]
Limestone	0.9	0.4	2.3	105.0	52.0	45.5	1.0	121.3	52.1	[23]
Marble	6.1	2.2	17.6	202.0	78.0	11.5	0.8	1777.6	360.3	[24]
Sandstone	5.0	1.7	15.7	194.0	69.0	12.4	0.9	1522.9	322.3	[24]
Granite	4.9	1.9	10.7	166.0	66.0	15.5	0.9	888.1	218.6	[24]
Aspo diorite	5.1	3.8	15.0	219.0	68.0	14.6	0.9	1642.5	340.3	[25]
Aue granite	4.1	1.6	8.0	134.0	48.0	16.8	0.9	536.0	152.0	[25]
Mizunami granite	4.9	2.4	9.0	166.0	50.0	18.4	0.9	747.0	193.0	[25]
Carrara marble	3.1	2.4	7.0	101.0	49.0	14.4	0.9	353.5	112.6	[25]
Flechtingen Sandstone	1.9	1.2	6.0	96.0	21.0	16.0	0.9	288.0	97.2	[25]
Rudersdorf limestone	2.3	1.1	5.0	40.0	22.0	8.0	0.8	100.0	45.4	[25]
Äspö diorite	4.4	3.8	14.9	211.0	76.0	14.2	0.9	1572.0	329.7	[26]
Lac du Bonnet Granite	6.4	2.5	14.8	165.0	68.0	11.1	0.8	1221.0	274.9	[27]
Äspö Diorite	2.0	1.0	10.0	224.0	60.0	22.4	0.9	1120.0	258.3	[27]
Crystalline rock	3.1	1.7	8.0	115.0	37.0	14.4	0.9	460.0	136.1	[27]
Äspö diorite	4.7	3.3	14.8	165.0	68.0	11.1	0.8	1221.0	274.9	[28]
Pegmatitic rock	3.3	2.0	12.0	115.0	55.0	9.6	0.8	690.0	182.3	[29]
Migmatitic gneiss	3.0	1.9	10.0	105.0	55.0	10.5	0.8	525.0	149.7	[29]
Migmatitic gneiss	3.9	3.1	14.0	123.0	55.0	8.8	0.8	861.0	213.8	[29]
Cement Mortar	0.28	0.15	2.00	16.00	4.00	8.00	0.78	16.00	12.13	-
Cement Mortar	0.8	0.5	5.0	68.0	28.0	13.6	0.9	170.0	66.5	-
Cement Mortar	1.1	0.6	2.2	54.0	10.7	24.1	0.9	60.5	31.6	-

The correlations were evaluated for the K_{IIC} values with the existing strength-based brittleness indices. Figures 3-a through 3-d depict variations in the K_{IIC} values with the indicated brittleness indices.

The given figures illustrate that the indices have different correlations with mode II fracture toughness. It is evident that amongst the considered indices, BI_3 and BI_4 demonstrate better correlations with K_{IIC}. Evaluated correlations of K_{IC} with BI_3 and BI_4 are presented in Figures 4a and 4b.

Although BI_3 and BI_4 demonstrate better correlations with K_{IIC} compared to BI_1 and BI_2, they have not been not calibrated, and vary over a wide range. This could lead to an increased uncertainty in the predictions by BI3 and BI4. Also suggestion of a classification to determine the rock brittleness status is missing in the BI3 and BI4 indices.

Considering the aims of this research study, a statistical analysis was performed on the available data in Table 1 in an attempt to explore a more reliable empirical index for modes I and II rock fracture toughness.

4. Statistical analysis

The multivariate linear regression (MLR) analysis was performed to develop a linear relationship for estimation of mode I and mode II rock fracture toughness. A relationship was defined between the dependent variable K_{IC} and several other independent variables such as tensile strength, compressive strength, and elastic modulus. The MLR analysis was carried out to predict the values for the independent variable coefficients in the linear equation. The results of this regression analysis are presented in Table 2. Based on the MLR analysis, equation (5) can be suggested for the estimation of K_{IC}.

$$K_{IC} = 0.005 + 0.155\sigma_t - 0.00312\sigma_c + 0.0148E \quad (5)$$

A similar analysis was also carried out for estimation of K_{IIC}, the detailed results of which aregiven in Table 3. Hence, equation (6) can be proposed for the estimation of K_{IIC}.

$$K_{IIC} = -0.254 + 0.245\sigma_t - 0.00491\sigma_c + 0.0365E \quad (6)$$

"Significant", denoted in Table 3, determines the appropriateness of rejecting the null hypothesis in a hypothesis test, and varies in the range of 0-1. The difference between the observed statistic and its hypothesized population parameter in units of standard error was measured by the t-statistic. A t-test compares this observed t-value to a critical value on the t-distribution with (n–1) degrees of freedom to determine whether the difference between the estimated and hypothesized values for the population parameter is statistically significant. The correlation coefficients of the proposed equations are depicted in Figures 5a and 5b.

Comparisons between Figures 3, 4, and 5inferthatthe results deduced from the statistical analyses are more reliable in order to predict rock fracture toughness to compare with the existing brittleness indices. Therefore, it is a worthy contribution to propose a new brittleness index based on the statistical and probabilistic analysis results. On the other hand, the statistical analyses have been performed on a limited data, and generalization of the results to other data may result in unreliable predictions. However, the probabilistic analysis is an appropriate approach that overcomes the low accuracy caused by the inherent uncertainty in prediction.

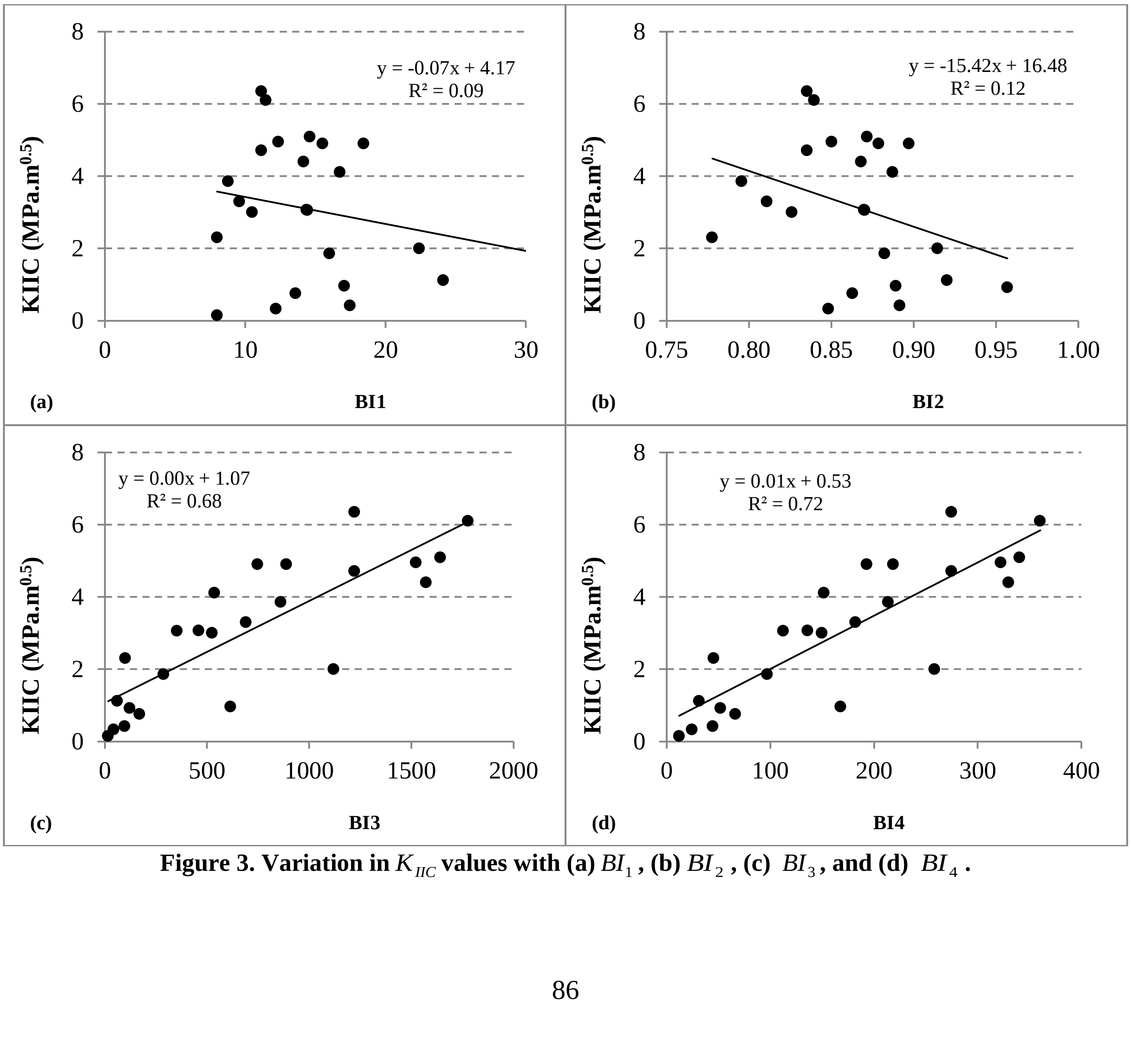

Figure 3. Variation in K_{IIC} values with (a) BI_1, (b) BI_2, (c) BI_3, and (d) BI_4.

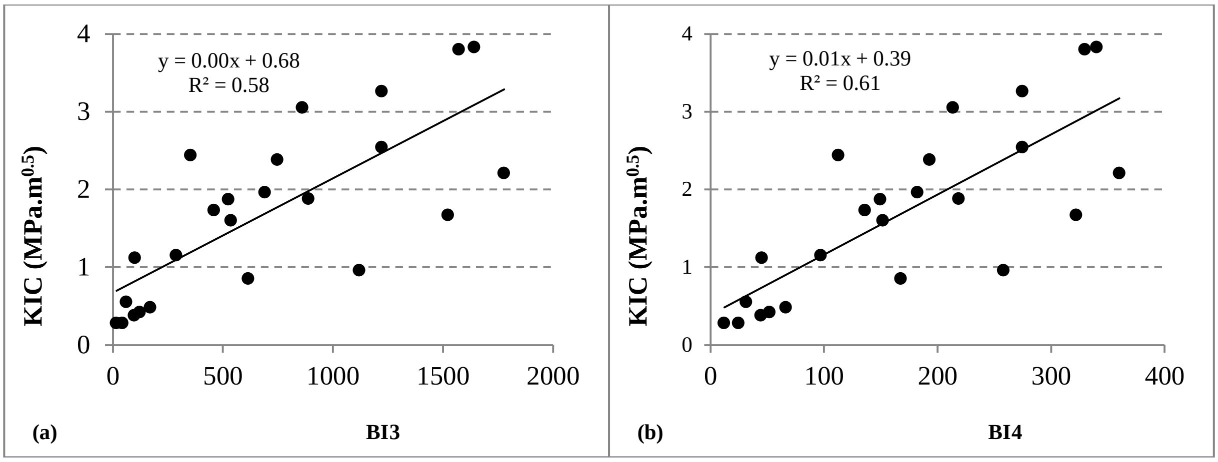

Figure 4. Variation in K_{IC} with (a) BI_3, and (b) BI_4.

Table 2. Regression-analysis results for estimation of K_{IC}.

Predictor	Unstandardized coefficients	Standard error of coefficient	t-Statistic (T)	Significant (P)
Constant	0.005	0.316	0.02	0.99
Tensile strength	0.155	0.062	2.50	0.02
Compressive strength	-0.0031	0.005	-0.62	0.54
Elastic modulus	0.0148	0.016	0.93	0.37

Table 3. Regression-analysis results for estimation of K_{IIC}.

Predictor	Unstandardized coefficients	Standard error of coefficient	t-Statistic (T)	Significant (P)
Constant	–0.254	0.448	–0.57	0.58
Tensile strength	0.245	0.087	2.80	0.01
Compressive strength	–0.0049	0.007	–0.69	0.50
Elastic modulus	0.0365	0.023	1.61	0.12

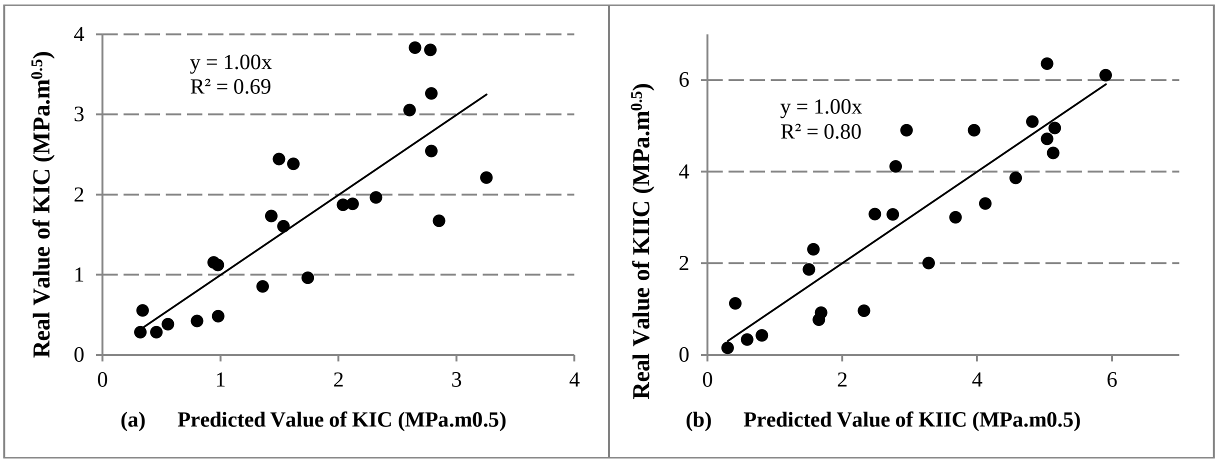

Figure 5. Comparison between real and predicted values for (a) K_{IC} by Eq. (5), and (b) K_{IIC} by Eq. (6).

5. Probabilistic analysis

The probabilistic analysis is based upon the generation of multiple trials to determine the expected values for a random variable [30]. The input and output of this approach are denoted by the distribution functions. The input distribution functions were obtained based on the variation in parameters, whereas the output distribution was calculated by the Monte Carlo simulation (MCS).

In the present study, three normal distribution functions were supposed for the three input parameters (tensile strength, compressive strength, and elastic modulus) as the input distribution function of analysis, and their impact on the output was considered using MCS. The distribution functions of the input parameters are depicted in Figures 6a-c.

As mentioned earlier, the probabilistic analysis is performed to assess the impacts of the input parameters on the outputs. Hence, considering equations (5) and (6), two probabilistic analyses were performed to evaluate the impacts of the input parameters on K_{IC} and K_{IIC}, respectively. Figures 7a and 7b illustrate these impacts on the K_{IC} and K_{IIC} values.

It has been demonstrated through Figure 7 that the major and minor influencing parameters on fracture toughness are the tensile and compressive strengths, respectively. Furthermore, it has been inferred that tensile strength and elastic modulus have direct effects on fracture toughness, while an inverse impact of compressive strength on the output is observed.

It should be noted that the traditional sensitivity analysis only examines the individual effect of the inputs on the output, whereas the probabilistic analysis considers the combined effects of all variable uncertainties on the output. Hence, the results of the probabilistic analysis are different from those for the traditional one.

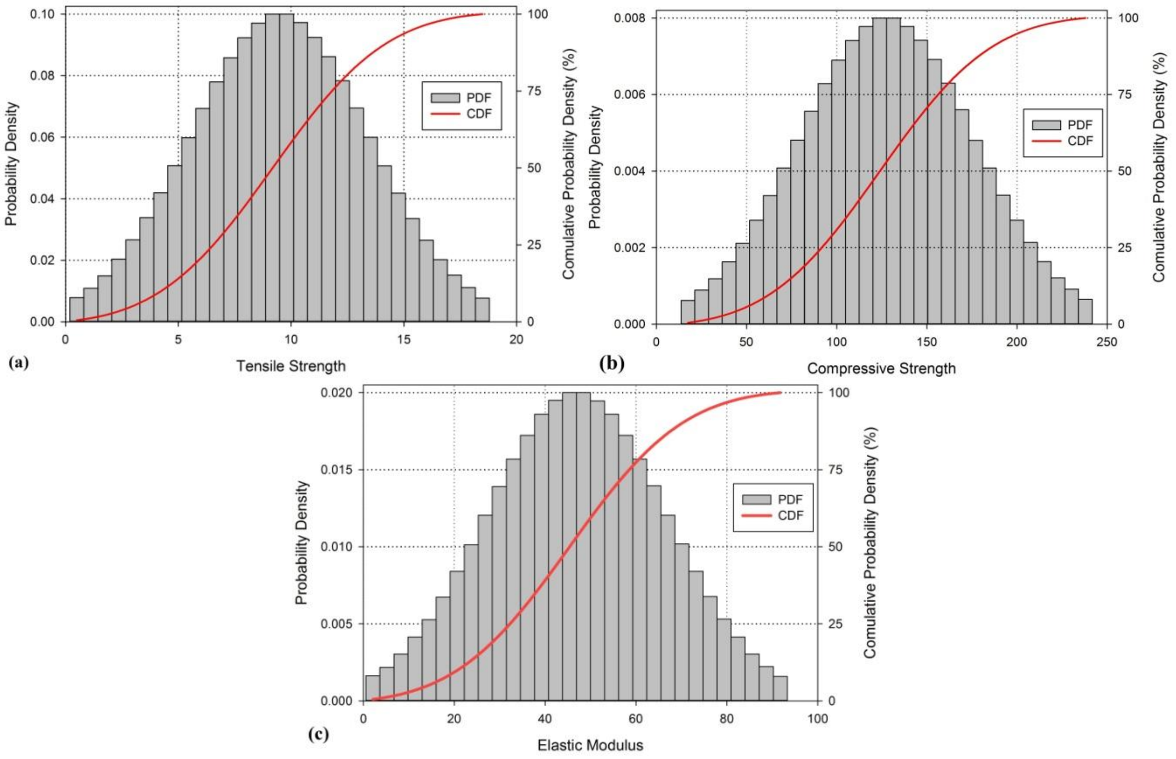

Figure 6. PDF and CDF of input parameters (a) tensile strength, (b) compressive strength, and (c) elastic modulus.

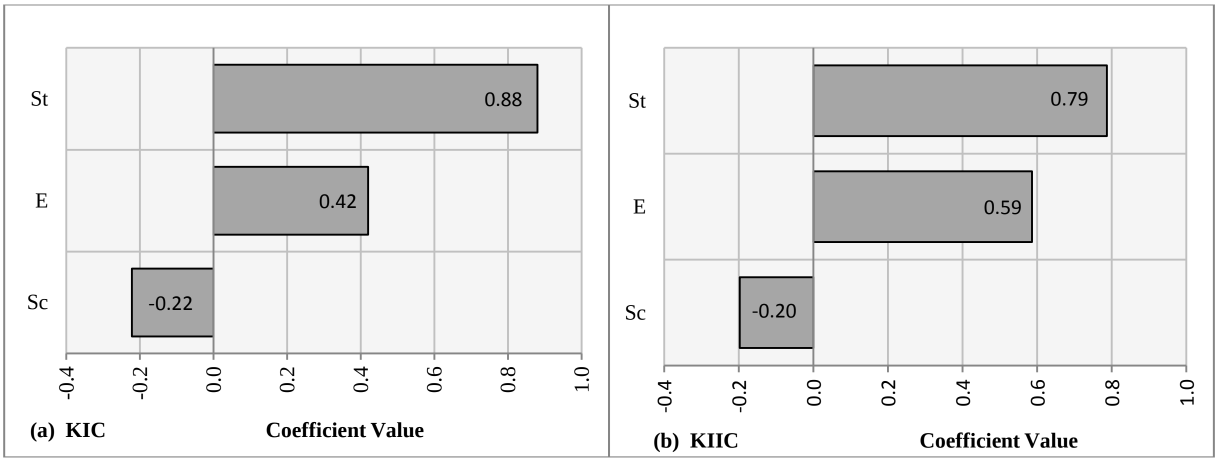

Figure 7. Impacts of input parameters of probabilistic analysis on (a) K_{IC} and (b) K_{IIC} .

6. Suggestion of brittleness index

Tensile and uniaxial compressive strength have been utilized in several research works to determine some strength-based brittleness indices. In the present study, in addition to the tensile and compressive strengths, elastic modulus was also considered in the suggested brittleness index.

Equation (7) represents the proposed index, where σ_t, σ_c, and E are the tensile strength (MPa), uniaxial compressive strength (MPa), and elastic modulus of rock (GPa), respectively.

$$BI = \sigma_t^{\,a} \sigma_c^{\,b} E^c \tag{7}$$

The constants a, b and, c were obtained on the basis of the probabilistic analysis results. These constants are proportional to the coefficient values illustrated in Figure 7. They can be calculated as follow:

$$a = \frac{0.88 + 0.79}{2} = 0.84$$

$$b = \frac{-0.22 - 0.20}{2} = -0.21$$

$$c = \frac{0.42 + 0.59}{2} = 0.51$$

After substituting these constants in equation (7), the proposed brittleness index, equation (8) was achieved as:

$$BI = \frac{\sigma_t^{\,0.84} E^{0.51}}{\sigma_c^{\,0.21}} \tag{8}$$

The proposed index can be used to estimate mode I and mode II rock fracture toughness. Figure 8 a-b illustrate the correlations between the BI values and the K_{IC} and K_{IIC} values, respectively.

The correlation coefficients obtained (Figure 8) were higher than those for the already existing strength based indices and rock fracture toughness, and are valid for any data in the range of the considered distributions (Figure 6). Based on the developed index, the rocks were categorized in five distinct classes, presented in Table 4.

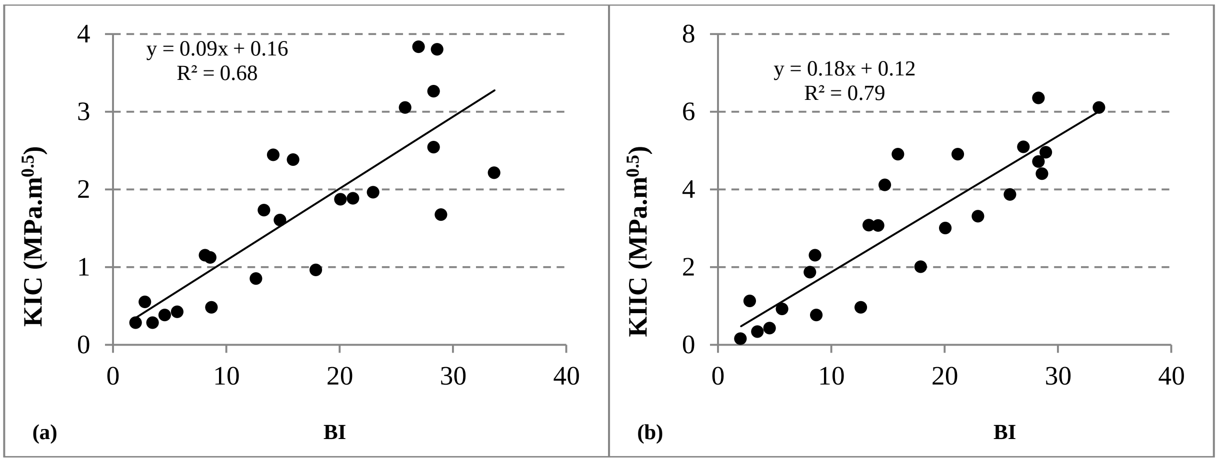

Figure 8. Variation in (a) mode I and (b) mode II fracture toughness with the suggested brittleness index.

Table 4. Suggested classification of rocks based on brittleness index.

Class	*BI*	Brittleness description	Example
I	>20	Very high	Marble, Granite, Diorite, Gneiss, Basalt, Ceramic
II	15-20	High	Marble, Sandstone, Granite, Chert, Ceramic
II	10-15	Medium	Sandstone, Limestone, Tuff, concrete,
III	5-10	Moderate	Limestone, Tuff, concrete, Shale, Siltstone, Chalk, coal
IV	<5	Low	Rock-salt, Clay-stone, Chalk

7. Discussion

The ability of a material to absorb energy and plastically deform without fracturing is known as the toughness modulus. Elastic modulus and ultimate strength of rocks are the predominant parameters influencing the toughness of materials. Elasticity has a major effect on the rock deformation and failure pattern, although it has seldom been considered as an effective parameter on rock brittleness in the previous studies. Although the tensile and compressive rock strengths are relevant to the elastic modulus, the effects of elastic modulus on brittleness and toughness cannot be ignored. As shown in the Tornado diagram (Figure 7), the impacts of elastic modulus on both modes I and II fracture toughness are larger than compressive strength.

Furthermore, from a fracture mechanics viewpoint, elastic energy is a fundamental part of the energy required for crack propagation in brittle materials such as rocks. Indeed, Irwin has shown that if the plastic zone around the crack tip is very small compared to the crack size, the energy required to grow the crack is not dependent on the state of stress at the crack tip, and it is computable with a purely elastic solution [31].

The major effect of tensile strength on the mode I fracture toughness is easily explainable and logical due to the same loading mode. Accordingly, it is expected that shear or compressive strength should be the main effective parameter on the shear fracture toughness, although the results obtained for the probabilistic analyses confirm that tensile strength is the most important effective parameter on K_{IIC}. This finding has been established by the results of the works of several researches on the direct shear test of the rock joints. Grasselli, Zhang et al., Ghazvinian et al. and Sarfarazi et al. have emphasized that, generally, the failure in rock asperities is due to tensile fracture instead of compressive fracture [32-35]. Also Park and Song have modeled a number of natural joints by PFC3D, and have carried out several shear tests [36]. This study showed that during the shear tests, the number of tensile cracks was much greater than the number of shear cracks. Furthermore, the total number of tensile cracks increased with increase in the normal stress in shear tests.

As shown in Figure 7, the impact of tensile strength on the shear fracture toughness (K_{IIC}) is less than its impact on K_{IC}, although the most significant parameter on K_{IIC} is still the tensile strength.

8. Conclusions

The present study yielded a new brittleness index, suggested for the estimation of rock fracture toughness. Tensile strength, uniaxial compressive strength, and elastic modulus were the three parameters employed for the development of the said brittleness index.

The analysis results revealed that tensile strength was the major influencing parameter on both mode I and mode II rock fracture toughness. However, the impacts of tensile strength on the shear fracture toughness (K_{IIC}) were less than those on the tensile one (K_{IC}). Among the input parameters, elastic modulus and uniaxial compressive strength were the second and third effective parameters on the rock fracture toughness value, respectively.

The correlation coefficients for the suggested brittleness index with K_{IC} and K_{IIC} were 0.68 and 0.79, respectively, which are higher than those for the already-existing strength-based indices and rock fracture toughness.

Rocks were categorized into five different classes from the low-brittle rocks (BI<5) to the very high-brittle ones (BI>20) based on the developed index.

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ارائه شاخص شکنندگی جدید برای تخمین چقرمگی شکست سنگ

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چکیده:

طی سال‌های اخیر ارزیابی همبستگی بین شاخص شکنندگی و چقرمگی شکست سنگ مورد توجه بسیاری از محققان قرار گرفته است. با این حال روش‌های اندازه‌گیری شکنندگی سنگ به صورت استاندارد ارائه نشده و چقرمگی شکست را نمی‌توان توسط شاخص‌های پیشنهادی با دقت مناسبی پیش‌بینی کرد. در این مطالعه، تحلیل‌های آماری بر روی داده‌های مستخرج از منابع مختلف به منظور تخمین مُدهای I و II چقرمگی شکست صورت گرفته است. سپس با استفاده از شبیه‌سازی مونت‌کارلو تأثیر تغییرات همزمان مقاومت تک‌محوری فشاری، مقاومت کششی و مدول الاستیسیته بر چقرمگی شکست سنگ تعیین شده است. بررسی‌های انجام شده نشان داده شد که از بین پارامترهای مذکور، مقاومت کششی سنگ بیشترین تأثیر را بر چقرمگی شکست دارد. در نهایت با استفاده از نتایج تحلیل‌های انجام شده شاخص شکنندگی جدیدی پیشنهاد شده است که چقرمگی شکست سنگ را به صورت کارآمدتری نسبت به شاخص‌های پیشین تخمین می‌زند.

کلمات کلیدی: چقرمگی شکست سنگ، شاخص شکنندگی، تحلیل آماری، تحلیل احتمالاتی.