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Comparison of strength-based rock brittleness indices with the brittleness index measured via Yagiz's approaches

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Abstract. Rock brittleness is one of the most significant properties of rock having a major impact not only on the failure process of intact rock but also on the response of rock mass to rock excavation. In fact, the brittleness is a combination of rock properties including not only the uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) but also density and porosity of rocks. Due to that, the brittleness should be examined very carefully for any excavation projects, i.e., mechanized excavation, drilling and blasting. The aim of this paper is to compare the strength-based brittleness indices with both the rock brittleness index (BI_o), directly obtained via punch penetration test (PPT) and also estimated via Yagiz's approach (BI_i) as a function of strengths and density of rocks. For the aim, database including more than 45 tunnel cases are used to compute common rock brittleness indices (BI_2 , BI_3 , BI_4), different combination of UCS and BTS. Further, these indices are compared with both BI_o and BI_i as well as each other. It is found that the BI_o and BI_i have a significant relations (ranging of determination coefficients (r^2) from 0.69 to 0.88 with strength-based brittleness indices commonly used in practice. Also, based on findings, several rock brittleness classifications are also revised herein.

1. Introduction

Brittleness is a key rock characteristic; it is pertinent to predicting rock fragmentation behavior, energy consumption in cutting rock, and the selection of proper cutting geometry considerations in mechanical excavation [1]. While brittleness is typically understood as a concept, there is no universally accepted measure for this rock characteristic; often a combination of rock properties is used define brittleness rather than a single test to make a direct measurement. Brittleness is a material property describing the material's loss of carrying capacity with a small deformation [2]. The brittleness is defined as a lack of ductility [3-4]. Ramsey [5] defined brittleness as the breakage of the internal cohesion of rocks. Obert and Duvall [6] defined brittleness as the fracture of materials at or only slightly beyond the yield stress. Hukka and Das [7] defined brittleness as follows: "with higher brittleness, the following facts are observed: low values of elongation, fracture failure, formation of fines, higher ratio of compressive to tensile strength, higher resilience, higher angle of internal friction, formation of cracks during indentation" [3-6].

Strength-based rock brittleness indices are commonly used as indirect tools to assess material brittleness. The rock brittleness indices can be quantified as the ration of the indirect Brazilian tensile



(BTS) to uniaxial compressive strength, (UCS) [7-9]. More, the brittleness can be estimated using UCS, BTS and density of rock [10-12]. The brittleness indices based on the rock strength parameters are widely used due to the relatively easy acquisition of the uniaxial compressive strength and splitting tensile strength, and these indices have wide use in the grade estimation of rock burst [7, 13, 14]. On the other hand, rock fragment size distribution [15] and indentation tests have been very useful to examine the rock behavior under the cutters [10-12]. Altindag [9] proposed the use of rock strengths to relate brittleness to drillability.

One of the tests that could be considered for the measurement of brittleness is an indentation test also called as punch penetration test (PPT). The PPT, originally intended to provide a direct method for estimating the normal load on disc cutters was developed in the late 1960s to provide a direct laboratory method to investigate rock behavior under the indenter [8]; however, the test has been used for evaluations of the hardness of rock, its drillability, and brittleness, and can be considered for predicting the performance of a Tunnel Boring Machine (TBM) [10, 17 and 18]. Szwedzicki [19] employed the test to measure rock hardness and stated that this test could be used for predicting the cuttability of rocks. Ozdemir [20] stated that the test could be utilized for quantifying the brittleness and toughness of rock by using test output.

In this paper, rock brittleness index measured using the PPT via Yagiz' method is compared with other well-known alternative strength based indices to be used for rock engineering and excavation purposes in practice.

2. Data development

The data collected from 48 mechanized tunnelling projects is examined to update data variables to compare the rock brittleness indices as summarized in table 1. The dataset includes 35% sedimentary rocks, 32% metamorphic and 35% igneous. In the dataset, rock brittleness can be classified from extremely low to very high brittleness based on the classification published by Yagiz [11, 12]. During the tests that was conducted by Yagiz (2009), entire intact rock specimens were observed and examined with naked eyes to make sure that those rock sample does not have any deformation related to discontinuities of rock mass. Each test is conducted at least five time to obtain the averaged values represented in table 1.

Table 1. Summary of dataset used to compute BI's for data analysis [11].

	Density kN/m ³	UCS MPa	BTS MPa	BI ₀ kN/mm	BI ₁ kN/mm	BI ₂ Ratio	BI ₃ Ratio	BI ₄ MPa
Maximum	28.90	327.0	17.80	45.00	48.01	25.87	0.93	53.03
Minimum	20.50	9.50	2.30	10.00	11.79	4.13	0.76	3.31
Average	25.47	126.4	7.81	27.45	27.48	15.57	0.87	22.02
St-deviation	2.10	69.52	3.37	9.31	8.77	4.66	0.04	10.69

3. Strength based rock brittleness and Yagiz's approaches

The punch penetration test is one of the methods used for investigating various rock properties such as brittleness, toughness, hardness and drillability by using different evaluation approaches [10,17-19]. The first test apparatus was designed and the testing procedure given in a paper [21]. Since then, the test has been used for different purposes and does not specify certain rock properties; however it is known that the brittleness obtained from the PPT is a very significant input variables for estimating the excavatability and drillability of rocks [2, 10, 17, 20].

In the punch penetration test, a standard conical indenter is pressed into a rock sample that is cast in a confining steel ring [10]. The load-displacement measurements of the indenter are then acquired with a computer system and can be related to the mechanical cuttability (the energy required for efficient chipping). Yagiz [10] used the punch penetration test to develop a new approach of estimating rock

brittleness with force penetration curves, which could be also related to standard compressive and tensile rock strength and density of rocks:

$$BI_0 = \frac{F_{\max}}{P_{\max}} \quad (1)$$

$$BI_1 = 0.198 \cdot UCS - 2.174 \cdot BTS + 0.913 \cdot D + 3.807 \quad (2)$$

Where, BI_0 is the measured brittleness index in kN/mm, F_{\max} is the maximum applied force on a rock sample in kN, P_{\max} is the corresponding penetration at maximum force in mm, BI_1 is the predicted brittleness index in kN/mm. The UCS and BTS are in MPa, and D is the unit weight of rocks in kN/m³. More information related to Yagiz's method used for rock brittleness index can be found in the literature [11]. Since mid-1960's, dozens of different brittleness indices have been proposed to use for various applications especially in rock mechanics; however, well-known strength based rock brittleness indices are the subject herein to examine for rock engineering and excavation practice as follow.

$$BI_2 = \frac{UCS}{BTS} \quad (3)$$

$$BI_3 = \frac{(UCS-BTS)}{(UCS+BTS)} \quad (4)$$

$$BI_4 = \sqrt{\frac{UCS \cdot BTS}{2}} \quad (5)$$

Even though BI_2 and BI_3 are well known, these indices do not have and classification used in rock excavation and engineering practice. However, Equation 2 and 5 are examined and relatively well classified by proposed researchers [9,11-12] as shown in table 2 and 3. Besides that, Dhal et al., [15] classified rock brittleness based on rock fragment size distribution as shown table 4 which is given herein to pay attention to rock brittleness classifications in the current literature.

Table 2. Rock brittleness classification for excavatability [11-12].

BI_0 and BI_1	Description	Excavatability
>45.0	Extremely high brittle	Extremely difficult
40.0-45.0	Very high	Very difficult
35.0-39.0	High	Difficult
30.0-34.0	Medium	Medium
25.0-29.0	Low	Easy
20.0-24.0	Very low	Very easy
<20.0	Extremely low	Extremely easy

Table 3. Rock brittleness classification for drillability [9].

BI_4	Description	Drillability
>25.0	Extremely brittle	Extremely Difficult
20.0-25.0	Very brittle	Difficult
15.0-20.0	Brittle	Moderate
10.0-15.0	Moderately	Easy
<10.0	Low brittleness	Very easy

Table 4. Classification of rock brittleness [15].

S₂₀-value (%)	Classification
>66.0	Extremely high brittle
60.0–65.9	Very high
51.0–59.9	High
41.0–50.9	Medium
35.0–40.9	Low
29.1–34.9	Very low brittle
<29.0	Extremely low

4. Data Analyses

Several statistical correlations including simple linear and non-linear regressions are conducted to obtain the relations between the investigated rock brittleness indices. It should be mentioned that since the rock strengths ratios are the main variables for those indices except Yagiz's approaches [11], obtaining the high regression coefficient among some of them is likely. The rock brittleness is not only related to rock strength but the combination of rock properties including density, porosity, mineralogy, quartz content and strength of rock; however due to restriction of the dataset, only density and strength of rock is considered herein. More, rock density has very close relations with the porosity; so, simply either density or porosity should be taken consideration to examine the rock brittleness as possible. After the data examined and the brittleness indices was computed using the dataset in the literature [11], simple regression analysis is used for estimating the rock brittleness as a function of each other via linear and non-linear regressions based on coefficients of determination (R^2) as shown on table 5.

Table 5. The best relations among the rock brittleness indices in this study.

R^2	BI ₀	BI ₁	BI ₂	BI ₃	BI ₄
BI ₀	1.0	-	-	-	-
BI ₁	0.88	1.0	-	-	-
BI ₂	0.70	0.76	1.0	-	-
BI ₃	0.71	0.78	0.97	1.0	-
BI ₄	0.69	0.72	0.46	0.45	1.0

As a result, every possible linear and non-linear regression is applied to the dataset and then the coefficient of determination (R^2) and equations are obtained as given here in from figures 1 and 2. As seen in table 5, the coefficient of determination between the BI₂ and BI₃ is likely ($r^2=0.97$) since both of them is the ration of UCS to BTS values of rocks. It is seen that the good correlations are also obtained among the BI₁ and BI₀ and BI₂, BI₃ and BI₄ with determination coefficient of more than around 0.70.

5. Conclusions

In this paper, common strength-based rock brittleness values are evaluated and the relations between those indices and the brittleness measured and estimated from the PPT is discussed. It is found that the strength based rock brittleness are practical and easy to obtain for early stage of rock engineering projects. However, rock brittleness is not only related to rock strength but it is also relevant with porosity, mineralogical content of rock, hardness and density of rocks. So, only the strength ratios of the rocks are not enough to compute the brittleness of rock.

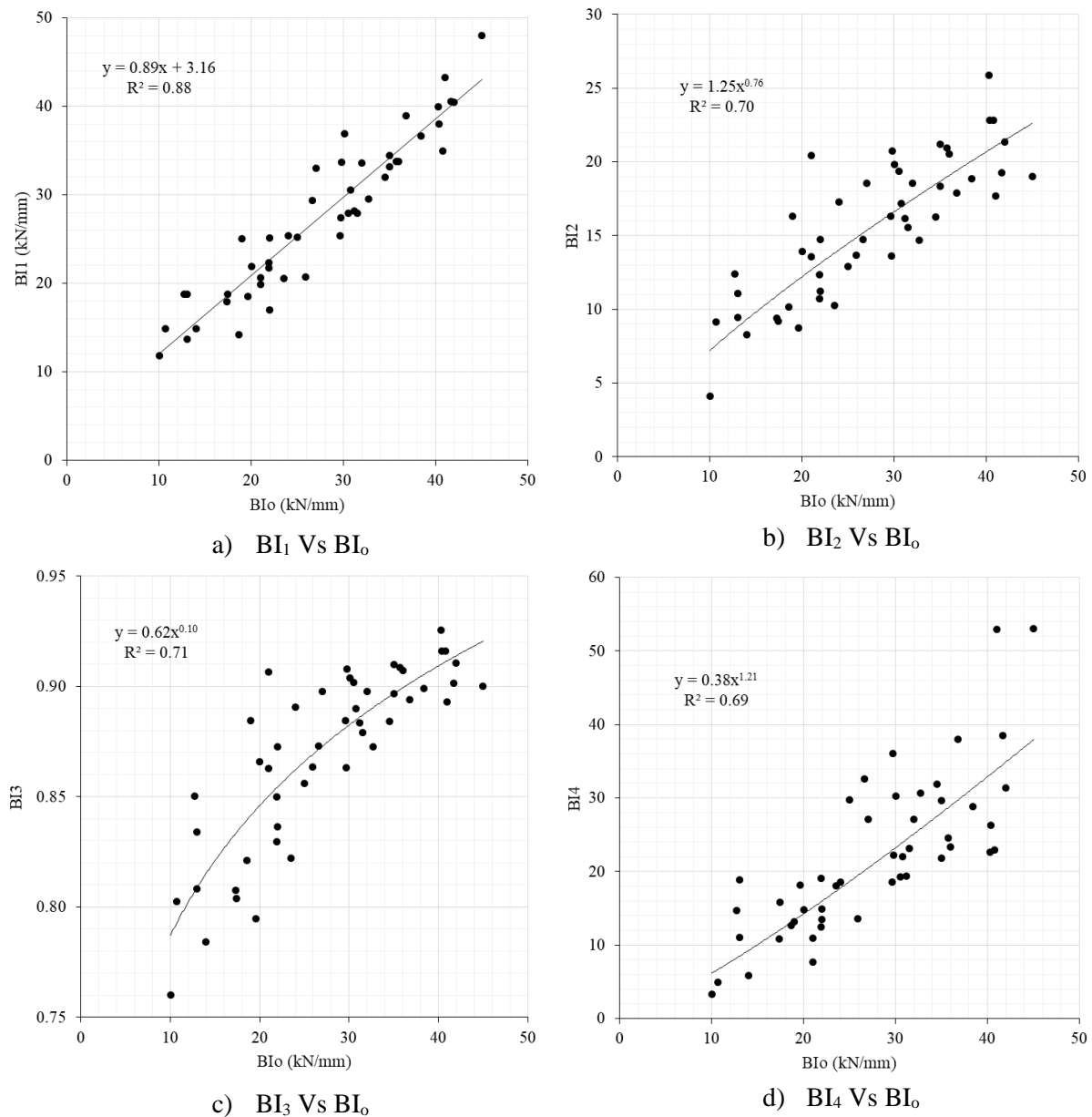


Figure 1. Relations between common strength based rock brittleness values and the brittleness measured via Yagiz' Method using the PPT.

Due to that, rock brittleness obtained as a function of rock strength and density of rock using the output of the PPT is more reliable than others which are only the strength ratios. The brittleness measured and estimated via Yagiz's approaches are more realistic, since rock density that is also directly related to porosity and abrasivity of the rocks is used as one of input variables to estimate the rock brittleness; More, there is a space to update the obtained rock brittleness values using other rock properties as an input such as quartz content of rocks. According to the findings, rock brittleness classification and indices developed/estimated based on the PPT is reasonable and acceptable for pre-investigation stage of rock engineering project to examine the brittleness and excavatability.

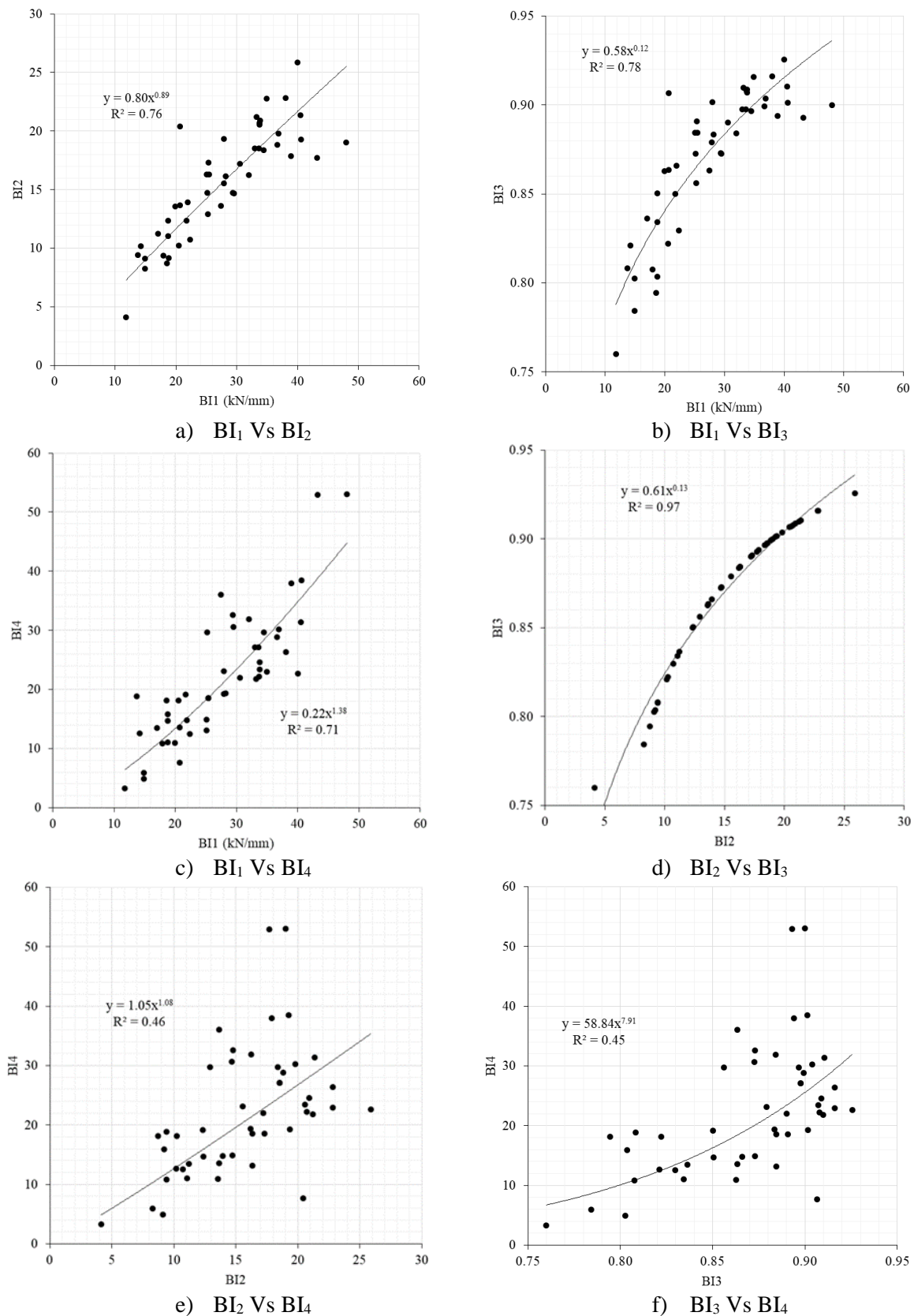


Figure 2. The relations among the studied brittleness indices from BI_1 to B_4 .

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