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Evaluation of the block punch index test for predicting the strength of sandstones

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Abstract
Strength measurement of rock requires testing that must be carried out on test specimens with particular sizes in order to fulfill testing standards or suggested methods. Often, the coring process breaks up the weaker core pieces, and they are too small to be used in either index tests or conventional strength tests such as point load index (Is) and Brazilian tensile strength (BTS). One of the index tests to indirectly determine the rock strength is the block punch index (BPI) test, which requires flat disc specimens without special treatment. This study aimed to evaluate the applicability of the BPI test for predicting the uniaxial compressive strength (UCS), BTS and I_S of the sandstones by empirical equations. Also, we have compared the performance of the BPI and I_S for predicting the UCS and BTS. It was experimentally shown that BPI is a reliable method for predicting the UCS, BTS and Is of the sandstones under study. Moreover, the results indicate that BPI could be utilized with same importance as Is for predicting the UCS, while predicting the BTS by Is appears to be more reliable than BPI.

Keywords: *Block punch index; Brazilian tensile strength; Point load index; Sandstone; Uniaxial compressive strength*

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1. Introduction

Strength measurement of rock is considered to be necessary in various rocks engineering design approaches as well as for the strength classification of rock materials. The UCS, BTS and I_S are among the important mechanical properties in strength measurements of rock that are determined in laboratory on core specimens according to test standards (ASTM) or suggested methods (ISRM). Measurement these properties require testing that must be undertaken on test specimens with particular sizes in order to fulfill testing standards or suggested methods. However, there are some of shortcomings associated with these conventional tests. For example, preparation of specimens with particular sizes in order to fulfill testing standards or suggested methods, the amount of time and labor necessary for specimen preparation, provisions for expensive testing equipment and testing durations may cause difficulties in strength measurement, particularly for weak or thinly stratified rocks. These difficulties motivated researchers to develop rock strength index tests that give reasonable results to determine directly and indirectly the rock strength using as small a specimen as possible (Ulusay and Gokceoglu, 1997).

One of the rock strength index tests to indirectly determine the UCS, BTS and I_S is the BPI test (Schrier, 1988; Ulusay and Gokceoglu, 1997; Gokceoglu and Aksoy, 2000; Sulukcu and Ulusay, 2001; Sonmez and Tunusluoglu, 2008; Karakul et al., 2010; Mishra and Basu, 2012; Kharaman et al., 2016; Jalali et al., 2019) that was accepted by ISRM as a suggested method. Table 1 provides the empirical equations by some researchers for predicting the rocks strength from BPI. Schrier (1988) established relationships between UCS and BTS with BPI and concluded that BPI is a good index for predicting the UCS and BTS, especially when only little rock material is available. Gokceoglu and Aksoy (2000) performed the UCS and BPI tests on the marl, mudstone, sandstone and schist. They used a linear regression equation to obtain the correlation between two tests with correlation coefficient of 0.95. Sulukcu and Ulusay (2001) reported a linear correlation between UCS and BTS with BPI, and those found correlation coefficients 0.90 and 0.81, respectively. Mishra and Basu (2012) based on experimental tests on the granite, schist and sandstone, found the reasonable correlations between UCS and BTS with BPI with determination coefficients 0.87 and 0.81, respectively. Roghanchi and Kallu (2014) described a power correlation between UCS and BPI with a determination coefficient 0.91 for basalt and rhyolite rocks. Kahraman et al. (2016) found a power relation between UCS and BPI with a regression coefficient 0.89 for pyroclastic rocks. Jalali et al. (2019) based on experimental tests on the different igneous and metamorphic rocks, found the reasonable correlations between UCS and BPI with a determination coefficient of 0.88.

The aim of this study is to provide more insight and to add more information to the correlation between BPI with UCS, BTS and Is of 15 different sandstones. Moreover, we have compared the performance of the BPI and I_S for predicting the UCS and BTS.

2. Apparatus and method of the Block Punch Test

There are no published standards for construction of the BPI test apparatus, and since this apparatus is not commercially available, it has to be fabricated in-house same as the one suggested by Ulusay et al. (2001) (Fig. 1e). There are three major parts in BPI test apparatus: a base support consisting of a punching block canal, a punching block and two steel bars on either side of the canal to clamp the specimen (Fig. 1a to 2d).

The thin disc specimen is placed at the center of the base support and clamped by the steel bars as shown in Fig. 2. After the placement of specimen into test, the load steady increased such that specimen failure occurs The compression loading of BPI test apparatus induces a double shear failure in the disc specimen, and the failure load is recorded for the calculation of BPI. When the compressive load on the specimen is gradually increased, the middle part of the specimen is punched out by the induced double shear failure as illustrated in Fig. 2 (Ulusay et al., 2001).

within 10–60 s as suggested by ISRM (1981). The corrected form of the BPI, considering the disc specimen having 50 mm diameter and 10 mm thickness is defined as (Ulusay et al., 2001);

$$BPI_C = 3499D^{-1.3926}t^{-1.1265}F_{t,\ D} \quad (1)$$

Where BPIc is the corrected form of BPI (MPa) considering dimension of the disc, D is the disc diameter (mm), t is the disc thickness (mm), and F is the failure load (kN).

Table 1. Empirical equations for predicting the rocks strength from BPI

References	Rock type	Equations	R or R^2
Schrier (1988)	Breccia, calcarenite, calcilutite, dunite, gneiss, limestone, marble, mudstone and sandstone	UCS= 6.1BPI–3.3 BTS= 0.4BPI–0.4	R=0.86 R=0.82
Ulusay and Gokceoglu (1997)	23 rock types including igneous, sedimentary and metamorphic rocks	UCS= $5.5BPI_C$ UCS= $5.29BPI_C^{1.01}$ UCS= $9.82e^{-0.108BPIC}$ UCS= 40.48ln (BPI_C) –13.4	R=0.94 R=0.91 R=0.83 R=0.82
Gokceoglu and Aksoy (2000)	Marl, mudstone, sandstone and schist	UCS= $5.25BPI_C$	R=0.95
Sulukcu and Ulusay (2001)	23 different rock types	UCS= $5.1BPI_C$ BTS= $0.68BPI_C$	R=0.90 R=0.81
Sonmez and Tunusluoglu (2008)	Limestone, travertine, andesite, sandstone, marl and schist	UCS= $0.8 \times 2.266(m_i)^{0.3824} \times BPI_C$	R^2=0.86
Karakul et al. (2010)	Limestone, sandstone, mica schist, shale and travertine	UCS_{C90}= $5.1 \times 1.47^{-0.00456\alpha}BPI_C\alpha$	R= not available
Mishra and Basu (2012)	Granite, schist and sandstone	UCS= $4.93BPI_C$ BTS= $0.35BPI_C$+3.69	R^2=0.87 R^2=0.81
Yesiloglu-Gultekin et al. (2013)	6 different granitic rocks	UCS=47.106 ln (BPIc) – 17.14	R=0.52
Roghanchi and Kallu (2014)	Basalt and rhyolite	UCS=$23.49BPI^{0.68}$	R^2=0.91
Kahraman et al. (2016)	Pyroclastic rocks	UCS=2:8 $BPI^{1.02}$	R=0.89
Jalali et al. (2019)	7 different igneous and metamorphic rocks	UCS=139.91ln(BPIc) - 297.26	R^2=0.88

Notes: BPI_C: Corrected BPI, UCS: Uniaxial compressive strength, BTS: Brazilian tensile strength, m_i: Hoek–Brown constant, α: Angle between the core axis and foliations, R^2: Determination coefficient, R: Regression coefficient

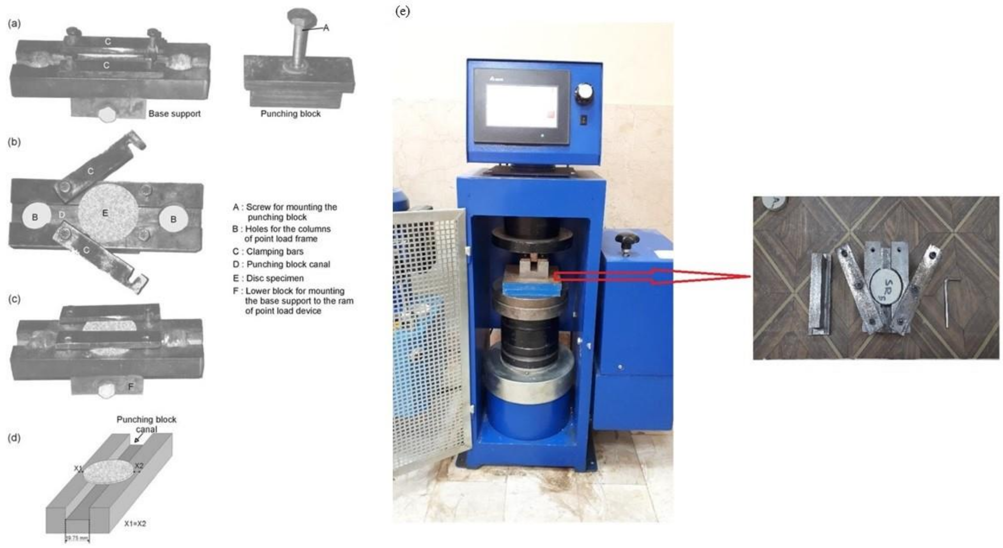


Figure 1. (a) A general view of the BPI test apparatus consisting of base support, steel bars (clamping bars) and punching block; **(b)** a plan view of the base support before clamping of the specimen; **(c)** a perspective view of the base support after the specimen is fixed; **(d)** a schematic view of the punching canal of the base support (After Ulusay et al., 2001), and **(e)** the BPI test apparatus used in this study

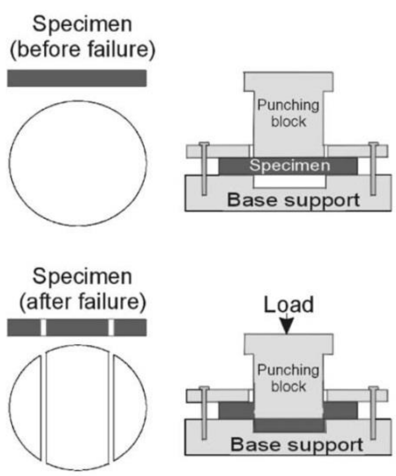


Figure 2. Schematic illustrations of the BPI test specimens before and after failure (After Ulusay et al., 2001)

3. Experimental studies

3.1. Rock sampling

To carry out the research, sandstone different outcrops in the city surroundings of Khoramabad were visited and a great number of block samples from 15 different sandstones were collected. These sandstones are similar in mineralogical composition but different in strength. Fig. 3 shows geological map of study area and the location of sampling. The block samples varied from 20×35×35 to 30×40×40 cm^3 in size were collected to fulfill the purpose of this research. Each block sample was inspected to ensure that it would provide standard testing specimens. During the sampling, rock types free from alteration zones, bedding planes and fracture were selected to eliminate any anisotropy effects on the measurement.

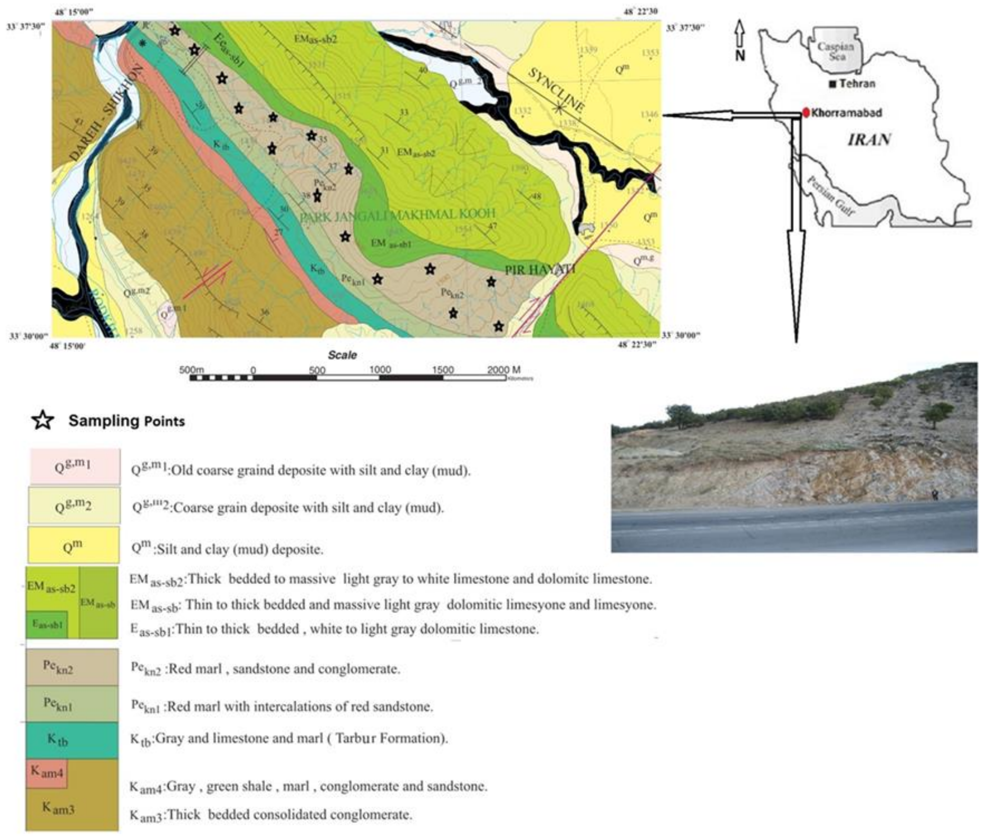


Figure 3. Geological map of study area and the location of sampling

3.2. Sandstones strength

To fulfill the aims of the research, the strength tests including the BPI, UCS, BTS and I_S were carried out in Damghan and Lorestan universities, Iran. Five specimens in the form of cylindrical were used to perform each test and then their mean values were obtained. The details of the each test are explained briefly herein and results are summarized in Table 2.

The BPI values were determined on disc specimens having a diameter of 54 mm and a disc thickness of 10 mm. The test apparatus fabricated in-house was used in this study (Fig. 1e). The tests were performed in accordance with method suggested by Ulusay et al. (2001). The load was applied such that the failure would occur within 10-60 s loading as suggested by ISRM (1981). Then, BPI values of the specimens were determined using Eq. (1). Some of specimens of BPI test before and after failure are shown in Fig. 4.

The UCS was determined in accordance with method suggested by the ISRM (1981) and tests were carried out on trimmed core specimens that had a diameter of 54 mm and a length to diameter 2.5. With the help of a polishing and lapping machine, the ends of the specimens were made flat and perpendicular to the axis of the specimens and their sides were smoothed and polished within 0.02 mm, ensuring that the load could be applied uniformly.

The BTS test procedure was followed in accordance with ISRM (1981). This test conducted on core specimens having a diameter of 54 mm and a diameter to thickness ratio of 2. The tensile load on the specimen was applied continuously at a constant stress rate such that failure took place within 2 minutes of loading. The BTS was found out by the following equation:

$$BTS = (2P/\pi Dt \qquad (2)$$

Where P is peak load, and D and t are diameter and thickness of the disc, respectively.

The Is test has been considered among the cheap and useful testing method for predicting the strength of rocks due to its testing ease, simplicity of specimen preparation and field applications (Broch and Franklin, 1972; Bieniawski, 1975; Kahraman and Gunaydin, 2009; Basu and Kamran, 2010; Azimian and Ajalloeian, 2015; Jamshidi et al., 2016). It is also frequently been reported as an indirect measure of the compressive and tensile strengths of rock (Broch and Franklin, 1972; Bieniawski et al., 1975; Fener et al., 2005; Cobanglu and Celik, 2008; Heidari et al., 2012; Singh et al., 2012; Li et al., 2013). In this study only axial Is test was performed on the cylindrical specimens that had a diameter of 54 mm and a diameter to thickness of 1 according to ISRM (1981). The Is $_{(50)}$ (referred to a standard size of 50 mm) was calculated as follows:

$$Is_{(50)} = F \times Is = (D_e/50)^{0.45} \times (P/D_e^2) \quad (3)$$

Where P is peak load, D_e is equivalent core diameter ($D_e^2 = 4A/\pi$ where A= WD, W= diameter of the specimen, and D= distance between the platens at failure for axial Is test), and F is size correction factor = $(D_e/50)^{0.45}$.

Table 2. The mechanical properties of the samples under study

Rock code	BPI_C (MPa)	UCS (MPa)	BTS (MPa)	$I_{S(50)}$ (MPa)
Sandstone 1	9.40	54.5	5.80	4.74
Sandstone 2	11.31	61.4	6.49	5.41
Sandstone 3	7.92	42.3	4.32	3.60
Sandstone 4	9.33	49.3	4.80	4.22
Sandstone 5	12.52	65.7	6.31	5.33
Sandstone 6	10.35	61.7	5.67	4.75
Sandstone 7	7.37	43.7	4.43	4.21
Sandstone 8	12.69	64.6	5.88	5.24
Sandstone 9	8.99	52.4	5.33	4.71
Sandstone 10	6.94	37.4	3.80	3.35
Sandstone 11	6.71	42.5	4.52	3.66
Sandstone 12	8.38	45.3	4.69	4.06
Sandstone 13	6.00	32.6	3.79	3.62
Sandstone 14	11.37	60.9	5.92	5.13
Sandstone 15	9.91	50.0	5.30	4.38

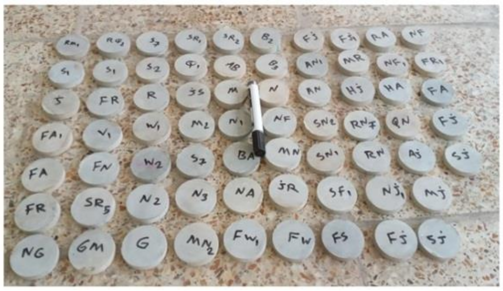
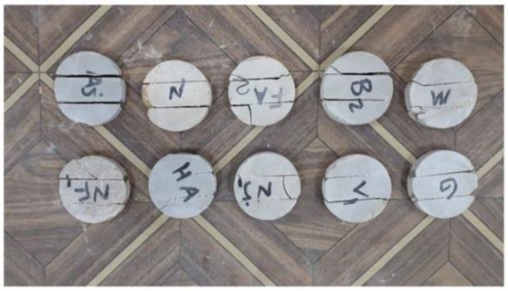



Figure 4. Some of specimens before and after failure in the BPI test

4. Results and discussion

4.1. Predicting the UCS, BTS and Is $_{(50)}$ by BPI_C

Using the simple or multiple regression analyses for predicting the rock properties are commonly encountered in the literature (Cargill and Shakoor, 1990; Kahraman, 2001; Yasar and Erdogan, 2004; Sharma and Singh, 2007; Kilic and Teymen, 2008; Yagiz, 2011;

Kurtulus et al., 2012; Mishra and Basu, 2012; Abdi et al., 2018; Jamshidi et al., 2018; Jamshidi, 2019).

In this study, we have used from the simple regression analyses to develop the sets of empirical equations among the BPI_C, UCS, BTS and $Is_{(50)}$.The data presented in Table 2 are used for the analyses. For this purpose, linear (y = ax + b), power ($y = ax^b$), exponential ($y = ae^x$) and logarithmic (y = a + ln x) regressions were undertaken with 95% confidence limits. Authors attempted to develop best correlation between different variable for to attain the most reliable empirical equation. The results of the regression analyses are given in Table 3.

As seen in Table 3, a logarithmic, power and linear correlations between UCS and BPI_C, BTS and BPI_C and $Is_{(50)}$ and BPI_C, respectively, were considered as the best fits, based on the highest R^2. In general, better correlation has a higher R^2. Since the values of the determination coefficients between different types of correlations (exponential, linear, logarithmic, and power) are very small (Table 3), and on the other hand, for simplicity, we have considered linear correlations between different strength parameters.

In Fig. 5 the correlations between UCS, BTS and $Is_{(50)}$ with BPI_C are presented for samples. It can be seen from Fig.5a that UCS increases linear with value of BPI_C. The equation for the curve is:

$UCS = 4.7469\ BPI_C + 6.905$, ($R^2$=0.92) (for 32.6<UCS<65.7 and 6.00< BPI_C <12.69) (4)

A linear relationship was observed between BTS and BPI_C with lower determination coefficient using the following equation (Fig. 5b):

$BTS = 0.381BPI_C - 62.782$, ($R^2$=0.84) (for 3.79<BTS<6.49 and 6.00< BPI_C <12.69) (5)

It can be seen from Fig. 5c that best-fitted correlation between $Is_{(50)}$ and BPI_C was found to be represented by linear regression curve using the following equation:

$Is_{(50)} = 0.3002\ BPI_C + 1.6419$, ($R^2$=0.85) (for 3.35<$Is_{(50)}$<5.41and 6.00< BPI_C <12.69) (6)

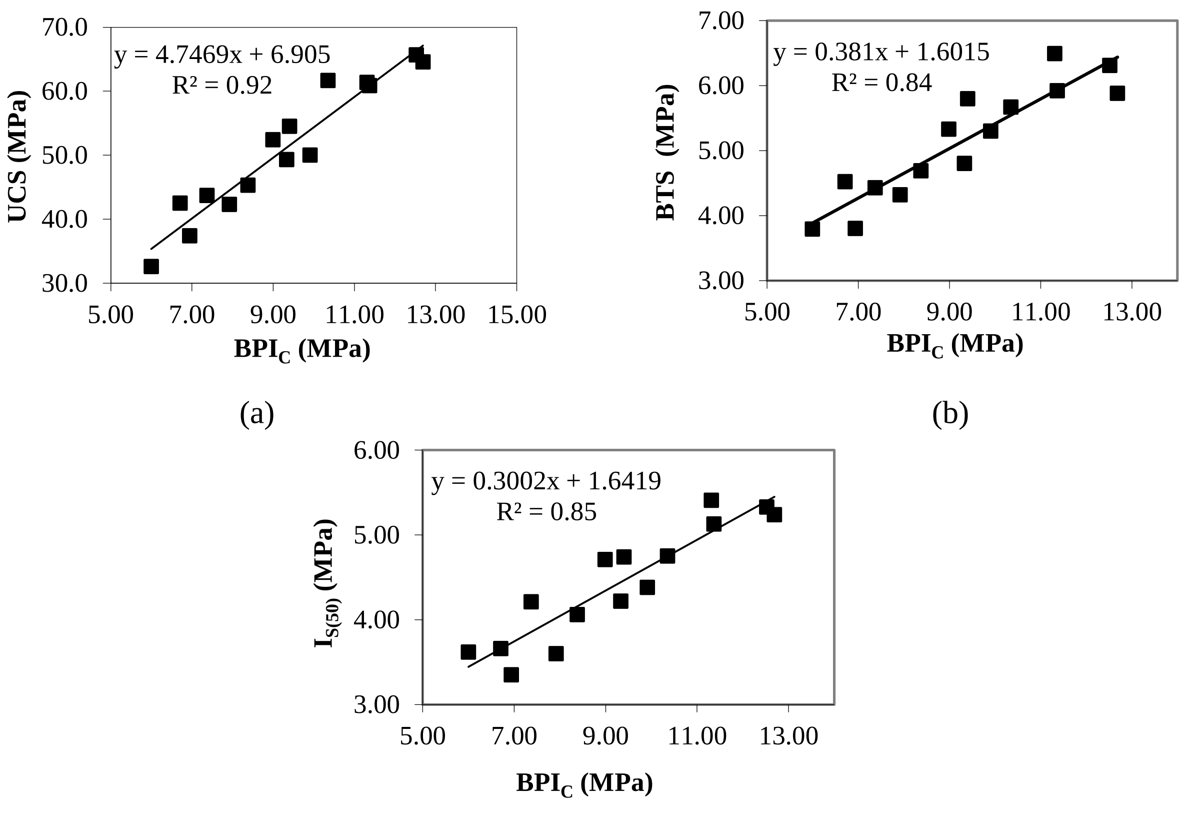
The Eqs.4–6 indicates that UCS, BTS and $Is_{(50)}$ have good correlations with BPI_C. However, UCS showed stronger correlation with BPI_C (R^2=0.93) when compare with correlations between BTS and BPI_C (R^2=0.85), and $I_{S(50)}$ and BPI_C (R^2=0.85).

A comparative study with the previous researchers was done to verify the limitations of the earlier equations proposed by various authors that have correlated UCS and BTS with BPI_C. For this, we have put our observed BPI_C in the equations proposed by various researchers and plotted it versus observed UCS and BTS. It can be seen from Fig. 6a that the predicted UCS data by Ulusay and Gokceoglu's (1997) equation are in good agreement with those observed in this study, while there are differences between our observed UCS data and the predicted UCS data by the equations of Schrier (1988), Sulukcu and Ulusay (2001) and Mishra and Basu (2012).

Fig.6b shows the predicted BTS from BPI_C using the equations of Schrier (1988), Sulukcu and Ulusay (2001) and Mishra and Basu (2012) versus the observed dataset. It can be seen that Schrier's (1988) equation, predicts BTS with lower values than observed BTS. However, predicted BTS data from equations proposed by Sulukcu and Ulusay (2001) and Mishra and Basu (2012), gives higher values than our observed BTS data. The differences found between results of this study with previous researches could be related to tested limited rock types in this study that only concentrated on the sandstones, while the other researchers used from a wide range of rock types.

Table 3. Summarized the simple regression analyses results

Parameters	Regression equations	Equation type	Determination coefficient (R^2)
$UCS–BPI_C$	$UCS= 20.528e^{0.0958BPI}$	Exponential	0.90
	$UCS= 4.7469\ BPI_C + 6.905$	Linear	0.92
	$UCS = 43.201 \ln (BPI_C) – 44.235$	Logarithmic	0.93
	$UCS= 7.1747BPI_C^{0.8805}$	Power	0.92
$BTS–BPI_C$	$BTS= 2.5067e^{0.0758BPI}$	Exponential	0.83
	$BTS= 0.381BPI_C – 62.782$	Linear	0.84
	$BTS= 3.482 \ln (BPI_C) – 1048$	Logarithmic	0.85
	$BTS = 1.0904\ BPI_C^{0.6971}$	Power	0.85
$Is_{(50)}– BPI_C$	$Is_{(50)}= 2.3188e^{0.0685BPI}$	Exponential	0.83
	$Is_{(50)} = 0.3002\ BPI_C + 1.6419$	Linear	0.85
	$Is_{(50)} = 2.7126 \ln (BPI_C) – 1.5495$	Logarithmic	0.84
	$Is_{(50)} = 1.1124BPI_C^{0.6217}$	Power	0.83



(c)

Figure 5. The correlation between (**a**) UCS and BPI_C (**b**) BTS and BPI_C, and (**c**) $I_{S(50)}$ and BPI_C

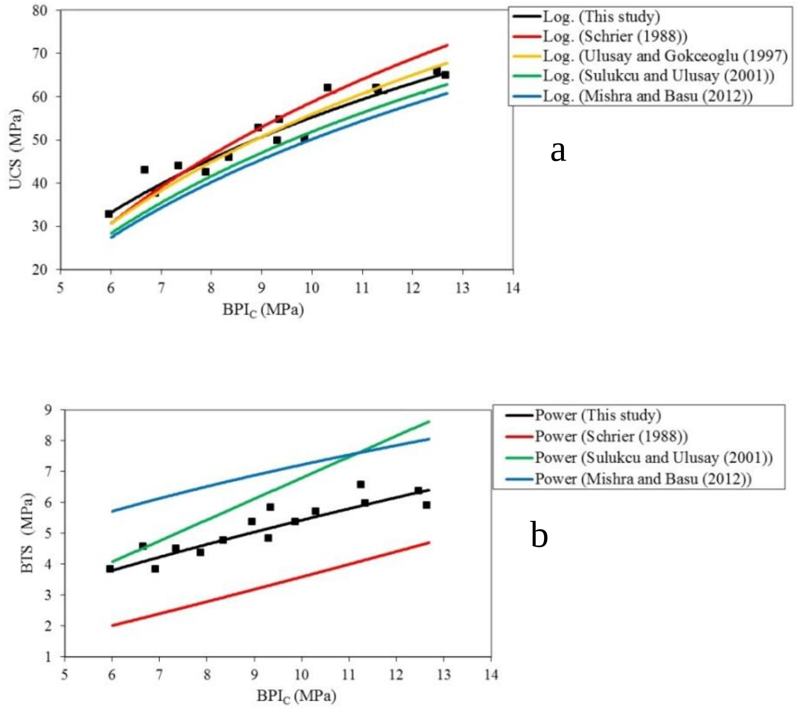


Figure 6. The comparison of the derived equations in this study and those obtained by other researchers (**a**) UCS versus BPI_C, (**b**) BTS versus BPI_C

4.2. Comparative study between performance of the BPI_C and $Is_{(50)}$ for predicting the UCS and BTS

UCS and BTS were correlated with the $Is_{(50)}$ as shown in Fig. 7. In this Fig, it can be seen that the trend of data shows an increase in UCS and BTS with increase in the $Is_{(50)}$. Also, it can be seen that best-fitted correlations between UCS and BTS with $Is_{(50)}$ were found to be represented by linear regressions. The equations for the correlation between UCS and BTS with $Is_{(50)}$ are, respectively:

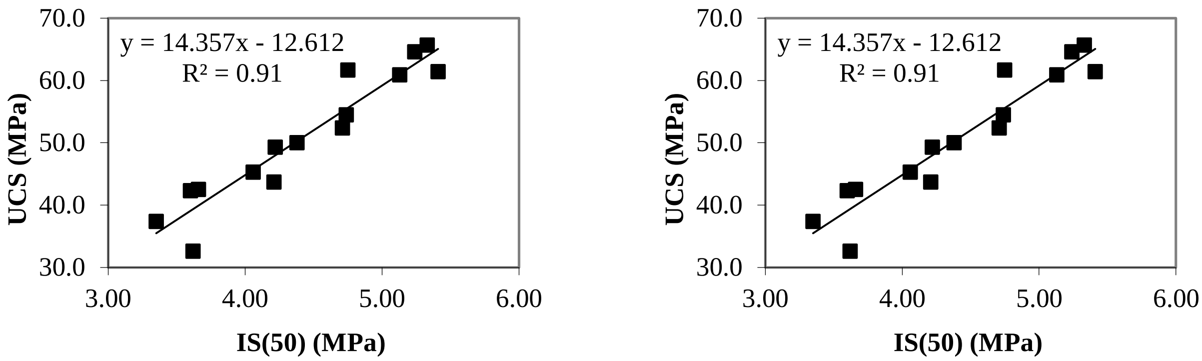
$$UCS = 14.357\, Is_{(50)} - 12.612, \ (R^2=0.91) \ (\text{for } 32.6<UCS<65.7 \text{ and } 3.35<Is_{(50)}<5.41) \quad (7)$$

$$BTS = 1.2303 Is_{(50)} - 0.3104, \ (R^2=0.93) \ (\text{for } 3.79<BTS<6.49 \text{ and } 3.35<Is_{(50)}<5.41) \quad (8)$$

Comparison of correlation between UCS with BPI_C (Eq. 4) and $Is_{(50)}$ (Eq. 7) shows approximately the same determination coefficients (i.e. 0.93 and 0.91, respectively). As that seen from Figs. 5b and 7b, the correlation data between BTS and BPI_C is the more scattered than it that is between BTS and $Is_{(50)}$. As a result, determination coefficient between BTS and BPI_C (R^2= 0.85) is significantly lower than that between BTS and $Is_{(50)}$ (R^2= 0.93). This shows that $Is_{(50)}$ than BPI_C is the more accurate for predicting the BTS of samples.

The derived results in this study were compared with those available in the literature (Table 4). Sulukcu and Ulusay (2001), based on the experimental tests results on the different rock types for predicting the UCS and BTS, show that BPI_C could be more preferable to $I_{S(50)}$, because the BPI test led to considerably lower errors in determining the UCS and BTS when compared with those obtained from Is test. Mishra and Basu (2012) reported the different relationships between UCS and BTS with BPIc for granite, schist and sandstone. Their results shows that when predicting the UCS of rocks, the BPI_C is as useful as the $Is_{(50)}$. Moreover, the results of these researchers revealed correlation between BTS and BPI_C is considerably stronger than the correlation between BTS and $Is_{(50)}$ when all rocks are considering in the correlations. On other hand, it is worth to noting that Mishra and Basu (2012) showed the BTS and BPI_C are in a stronger correlation than that BTS and $Is_{(50)}$ in case granite. However, when schist and sandstone are considered, the BTS and $Is_{(50)}$ provides a stronger correlation than that BTS and BPI_C.

The results of this study indicates that BPI_C have approximately the same importance as $I_{S(50)}$ for predicting the UCS, while predicting the BTS by $I_{S(50)}$ appears to be more precise than by BPI_C. Difference in the results obtained in this study and those from previous studies is probably due to the fact that tested rocks in each study were not consistent.



(a) (b)

Figure 7. The correlation between (**a**) UCS and $I_{S(50)}$, and (**b**) BTS and $I_{S(50)}$

Table 4. Equations among the UCS, BTS, $I_{S(50)}$ and BPI_C derived in this study and those obtained by other researchers

References	Rock type	Equations	R or R^2
Sulukcu and Ulusay (2001)	23 different rock types	UCS= $5.1BPI_C$	R=0.90
		UCS= 15.31 $I_{S(50)}$*	R= 0.83
		BTS= $0.68BPI_C$	R=0.81
		BTS= $2.30I_{S(50)}$*	R=0.80
Mishra and Basu (2012)	Granite, schist and sandstone	UCS= $4.93BPI_C$	R^2=0.87
		UCS = $14.63I_{S(50)}$ *	R^2=0.88
		BTS= $0.35BPI_C$ +3.69	R^2=0.81
		BTS= 1.06 $I_{S(50)}$ +5.34*	R^2=0.49
This study	Sandstone	UCS= 4.7469 BPI_C + 6.905	R^2=0.92
		UCS = 14.357 $I_{S(50)}$ – 12.612	R^2=0.91
		BTS= $0.381BPI_C$ – 62.782	R^2=0.84
		BTS = $1.2303I_{S(50)}$ – 0.3104	R^2=0.93

*Calculated by the author

4.3. The validity of the proposed regression equations

To investigate the validity of the proposed regression equations, t-test was conducted among the achieved equations using the statistical software package of SPSS version 21.0. The test compares the computed t-value with a tabulated t-value using the null hypothesis. In this test, a 95% level of confidence was chosen. If the computed t value is greater than the tabulated t-value, the null hypothesis is rejected. This means that R^2 is significant. If the computed t-value is less than the tabulated t-value, the null hypothesis is not rejected. In this case, R^2 is not significant. Since a 95% confidence level was chosen in this test, a corresponding critical t-value ±2.145 is obtained from the related tables. It can be seen from Table 5 which all the computed t-values are greater than the tabulated t-values. So, it is concluded that there are a real correlations among the BPIc, UCS, BTS and $Is_{(50)}$, and can be used in the early stages of rock engineering works.

Although, the determination coefficients of the equations are between 0.85 and 0.93 and these are in approximately good levels, it is not identifies the valid equations necessarily. Therefore, for validating the equations, the predicted production values were plotted versus the observed production values as shown in Figs. 8 and 9. The error in the predicted value is represented by the distance that each data point has from the 1:1 diagonal line. A point lying on the line indicates an exact prediction. Since, the observed versus predicted data plots in are scattered uniformly around the diagonal line (Figs. 8 and 9), it indicates that proposed regression equations are good correlations.

Table 5. t-test results

Regression equations	Determination coefficient (R^2)	t-test	
		Calculated value	Tabulated value
UCS= 4.7469 BPI_C + 6.905	0.92	17.336	±2.145
BTS= 0.381BPI_C – 62.782	0.84	–10.949	±2.145
$I_{S(50)}$ = 0.3002 BPI_C + 1.6419	0.85	–12.614	±2.145
UCS = 14.357 $I_{S(50)}$ – 12.612	0.91	18.585	±2.145
BTS = 1.2303$I_{S(50)}$ – 0.3104	0.93	9.868	±2.145

Conclusions

The BPI_C, UCS, BTS and $I_{S(50)}$ for 15 different sandstones were determined in the laboratory. By analyzing the results of laboratory tests, the following regression equations have been developed as follows;

*UCS = 4.7469 BPI_C + 6.905, (R^2=0.92) (for 32.6<UCS<65.7 and 6.00< BPI_C <12.69)

*BTS = 0.381BPI_C – 62.782, (R^2=0.84) (for 3.79<BTS<6.49 and 6.00< BPI_C <12.69)

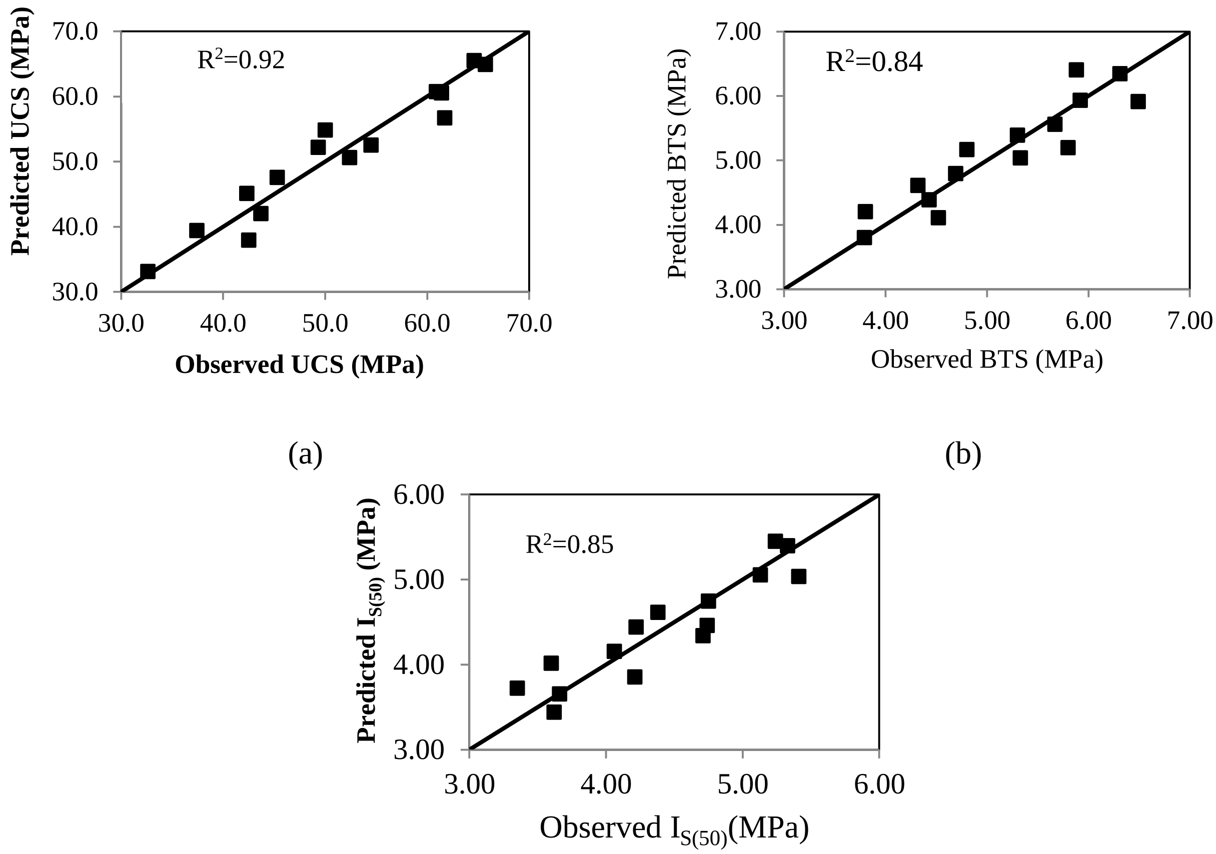
*$Is_{(50)}$ = 0.3002 BPI_C + 1.6419, (R^2=0.85) (for 3.35<$Is_{(50)}$<5.41and 6.00< BPI_C <12.69)

*UCS = 14.357 $Is_{(50)}$ – 12.612, (R^2=0.91) (for 32.6<UCS<65.7 and 3.35<$Is_{(50)}$<5.41)

*BTS = 1.2303 $Is_{(50)}$ – 0.3104, (R^2=0.93) (for 3.79<BTS<6.49 and 3.35<$Is_{(50)}$<5.41)

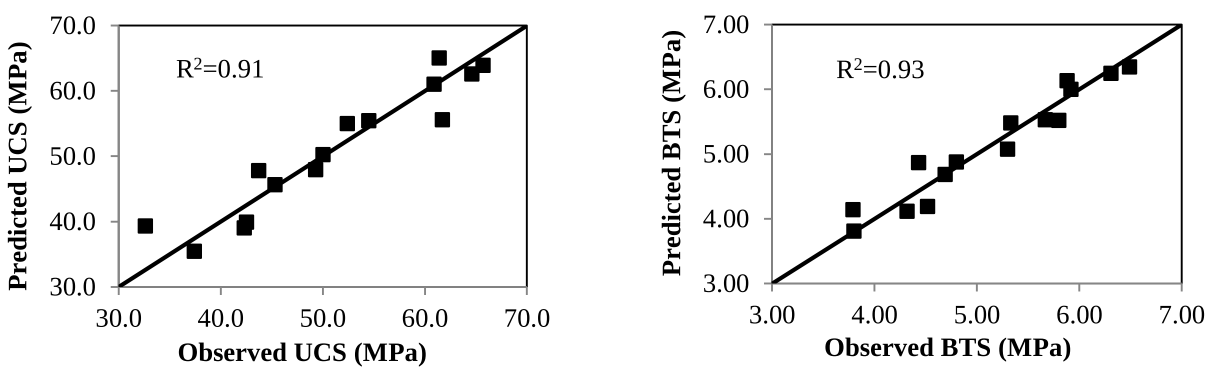
Proposed regression equations were compared with those available in the literature as well as were validated by the t-test and the 1:1 diagonal line. The results showed that UCS, BTS and Is $_{(50)}$ can be predicted using BPI_C with good accuracy. Moreover, the results indicated that BPI_C could be used with similar importance as $Is_{(50)}$ for predicting the UCS; while $Is_{(50)}$ is the more reliable than BPI_C for predicting the BTS.

Due to specimen preparation without special treatment and performing the test with a simple apparatus, the BPI test can be offer a quick, easy and cheap means for predicting the mechanical properties of different rock types, particularly the heavily jointed rock and/or thinly stratified rock masses. However, further researches are necessary to investigating the performance and accuracy of the BPI_C for predicting the strength of rocks as well as to check the validity of the proposed equations for the other rock types.



(c)

Figure 8. Observed the mechanical properties values versus the mechanical properties values predicted: (a) Observed the UCS values versus the UCS values predicted from Eq. 4 (b) Observed the BTS values versus the BTS values predicted from Eq. 5, and (c) Observed the $I_{S(50)}$ values versus the $I_{S(50)}$ values predicted from Eq. 6



(a) (b)

Figure 9. Observed the mechanical properties values versus the mechanical properties values predicted: (**a**) Observed the UCS values versus the UCS values predicted from Eq. 7, and (**b**) Observed the BTS values versus the BTS values predicted from Eq. 8

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