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Comparative evaluation of Schmidt hammer test procedures for prediction of rock strength

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ABSTRACT

Uniaxial compressive and Brazilian tensile strengths (UCS and BTS) of rocks are considered as the most important properties in the design of most geotechnical projects, such as slope stability and underground excavation, which interact with rocks. Measuring UCS and BTS using standard laboratory tests is time consuming, tedious and expensive. Moreover, it requires a large number of well-prepared rock cores that is not often viable, particularly in soft or highly jointed rock masses. For these reasons, indirect tests such as Schmidt hammer hardness (SH) can be used for prediction of UCS and BTS of rocks. There is a wide variation in the recommended SH test procedures by institutions and researchers. The objective of this study is to evaluate the performance of SH testing procedures for prediction of UCS and BTS of rocks. Accordingly, 22 sandstone samples from Qum Province, Central Iran, were selected and their UCS, BTS and SH values were determined. Using data analysis, the correlation equations have been developed between UCS and BTS with SH. A t–test was performed to check the validity of the correlation equations. The results showed that the SH test procedures that are based on continuous impacts at a point reveal lower values than those based on single impacts. Further, it was found that SH test procedures have different performance for prediction of UCS and BTS of rocks.

Keywords : *Uniaxial compressive strength; Brazilian tensile strength; Schmidt hammer hardness; Correlation*

1. Introduction

Uniaxial compressive and Brazilian tensile strengths (UCS and BTS) of an intact rock are considered as the key properties in the design and construction of most geotechnical projects that interact with the rock, such as slope stability, underground excavation, dams, foundations on rock, as well as in the classification of rocks for engineering purposes. Commonly, these properties are determined directly by laboratory tests suggested by both the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM). However, UCS and BTS tests are time consuming, tedious and expensive. Moreover, these tests require a standard specimen that is not often feasible, particularly in soft or highly jointed rock masses. For these reasons, indirect tests are often used for prediction of UCS and BTS.

The Schmidt hammer hardness (SH) test is one of the most frequently used for indirect prediction of the rock strength [1-9]. This test is a quick, easy to apply and cheap in either site or the laboratory to provide preliminary information on the strength of rock materials. Many researchers developed different statistical relationships between UCS and BTS with SH (Table 1).

Also, some researchers have investigated the effect of various factors such as density, porosity, size, shape and spatial arrangement of grains, mineralogy, anisotropy, weathering grade, temperature, degree of surface smoothness, sample size, etc. on UCS, BTS and SH [3, 13, 27-34].

According to the literature review carried out for this research, there is a wide variation in the recommended testing procedures by institutions and researchers for determination of SH (Table 2). As can be followed from Table 2, the so far proposed SH test procedures are based on either single impacts or continuous impacts at a point. The International Society for Rock Mechanics (ISRM), American Society for Testing and Materials (ASTM) and a majority of other authors have recommended test procedures that are based on single impacts, while a number of authors have proposed the test procedures that are based on continuous impacts at a point. Moreover, some procedures consider the mean of the upper rebound values, while some take into account the peak rebound values from continuous impacts at a point.

Although the correlation between UCS and BTS with SH, and various other factors affecting on them have been intensively investigated for several decades, the effect of the SH test procedure on the correlation between UCS and BTS with SH is still unclear and it should be studied further. For this, one needs to understand better the correlation between UCS and BTS with SH, when the SH test procedure is considered as the affective factor on these parameters.

This study is an attempt to investigate the effect of the SH test procedure on the SH values of 22 sandstone samples. Moreover, the correlation equations were developed for the prediction of UCS and BTS values from SH by simple regression analyses. Finally, we compared the accuracy of the SH test procedures to predict the UCS and BTS values.

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Table 1. Previous researches on the relationships between UCS and BTS with SH.

Researchers	Rock type	Proposed equations	r/R^2
Aufmuth [1]	25 lithological units	$UCS = 0.33(SH\ \rho)^{1.35}$	0.80
Shorey et al. [2]	20 lithological units	$UCS = 0.4SH - 3.6$	0.94
Aydin and Basu [3]	Granite	$UCS = 1.45e^{0.07SH}$	0.92
Kilic and Teymen [4]	Sedimentary, metamorphic and igneous	$UCS = 0.0137SH^{2.2721}$	0.94
Gupta [5]	Granite	$UCS = 1.15SH - 15$	0.91
Torabi et al. [6]	Siltstone, sandstone, shale	$UCS = 0.0465SH^{2} - 0.176PLI + 27.68$	0.92
Minaeian and Ahangari [7]	Conglomerate	$UCS = 0.678SH$	0.93
Tandon and Gupta [8]	Quartzite, granite, gneiss, metabasics, dolomite	$UCS = 1.91SH - 10.3$	0.75
Jamshidi et al. [9]	Travertine	$UCS = 78.59 \ln(SH) - 239.2$	0.81
Jamshidi et al. [9]	Travertine	$BTS = 6.26 \ln(SH) - 17.99$	0.72
Singh *et al.* [10]	30 Sedimentary units	$UCS = 2SH$	0.72
Haramy and DeMarco [11]	10 different lithologies	$UCS = 0.99SH - 0.38$	0.70
Cargill and Shakoor [12]	Carbonates	$UCS = 18.17e^{(0.02\ SH\ \rho)}$	0.98
Katz et al. [13]	Chalk, limestone, marble, granite	$UCS = 2.21e^{(0.07SH)}$	0.96
Kahraman [14]	Carbonates	$UCS = 6.97e^{(0.014SH\ \rho)}$	0.78
Yimaz and Sendir [15]	Gypsum	$UCS = \exp(0.818 + 0.059SH)$	0.98
Yasar and Erdogan [16]	Limestone, marble, basalt, and sandstone	$UCS = 0.000004SH^{4.2917}$	0.89
Fener et al. [17]	11 different rock samples	$UCS = 4.24e^{0.059SH}$	0.66
Shalabi et al. [18]	Shale, anhydrite, dolomite	$UCS = 3.201SH - 46.59$	0.76
Cobanoglu and Celik [19]	Sandstone, limestone and cement mortar	$UCS = 6.59SH - 212.63$	0.65
Yagiz [20]	Carbonate, metamorphic	$UCS = 0.0028SH^{2.584}$	0.92
Karaman et al. [21]	Sedimentary, metamorphic and igneous	$UCS = 3.66\ SH - 63$	0.84
Bell [22]	Sandstones	BTS and SH	0.72
Bell [23]	Anhydrite and gypsum	BTS and SH	0.80
Bell and Lindsay [24]	Sandstones	BTS and SH	0.58
Kılıç and Teymen [25]	Igneous, sedimentary and metamorphic	$BTS = 0.0087\ SH^{1.7757}$	0.95
Karaman et al. [26]	Sedimentary, metamorphic and igneous	$BTS = 0.72\ SH - 16.6$	0.85

ρ: Density, PLI: Point Load Index

Table 2. Some recommended SH test procedures by various institutions and researchers.

Author (Institutions or Researchers)	Test procedure
Katz et al. [13]	Performed 32–40 individual impacts and average the upper 50%.
Hucka [27]	Selected the peak rebound value from 10 continuous impacts at a point. Averaged the peaks of three sets of tests conducted at three separated points.
Matthews and Shakesby [29]	15 measurements on any sample. The mean of the rebound values were calculated and five values deviating mostly from the mean were discarded.
Deere and Miller [35]	Recorded three readings along the length of an NX-size core for each 45° rotation. Averaged 24 readings, disregarding the erroneous readings.
Fowell and McFeat Smith [36]	Took the mean of at last five values from ten continuous impacts at a point.
Soiltest Inc [37]	Recorded 15 rebound values from single impacts and averaged the highest 10. The maximum deviation from the mean had to be less than 2.5.
Young and Fowell [38]	Divided the rock mass surface into grids and averaged the single impacts from each grid.
Kazi and Al-Mansour [39]	Recorded at least 35 rebound readings, dropped 10 lowest readings and averaged the remaining 25.
Pool And Farmer [40]	Selected the peak rebound value from five continuous impacts at a point. Averaged the peaks of the three sets of tests conducted at three separated points.
ISRM [41]	Recorded 20 rebound values from single impacts separated by at least a plunger diameter, and averaged the upper 10 values.
Goktan and Ayday [42]	Recorded 20 rebound values from single impacts separated by at least a plunger diameter. Rejected outlier values by using Chauvenet's criterion, and averaged the remaining readings.
USBR [43]	Ten readings at various locations on each surface. Discounted the five lowest readings, and averaged the highest five.
ASTM [44]	Recorded ten rebound values from single impacts separated by at least the diameter of the piston, and discarded the readings differing from the average of ten readings by more than seven units and determined the average of the remaining readings.
Summer and Nel [45]	Took 15 readings at different points and discarded five great outliers to obtain a mean value from the remaining 10 values.
Aydin [46]	20 Rebound values should be recorded from single impacts separated by at least a plunger diameter. The test may be stopped when any ten subsequent readings differ only by four (corresponding to R repeatability range of ±2).

2. Materials and Methods

In this research, twenty-two different types of sandstone were obtained from different natural outcrops northwest of Qom (Central Iran) (Fig. 1). These sandstones generally commercialized as building stones and construction materials. For each sandstone, some block samples were selected varying in size from 20 × 35 × 35 cm³ to 30 × 40 × 40 cm³. The sandstones belonged to the Upper Red Formation, considered to date from the Middle to the Upper Miocene [47]. The core specimens were prepared from the sandstone blocks; they were 54 mm in diameter, and the edges of the specimens were cut parallel and smoothed to provide the ISRM standard size and shape [41]. The UCS and BTS tests were performed on the prepared core specimens from each sandstone type. An N-type Schmidt hammer (SH) was applied on specimens for determination of rebound numbers. To fulfill the aims of the research, the SH test was carried out based on the four most accepted test procedures recommended by institutions and researchers. Using dataset analyses, the correlation equations were developed for the prediction of UCS and BTS from SH.

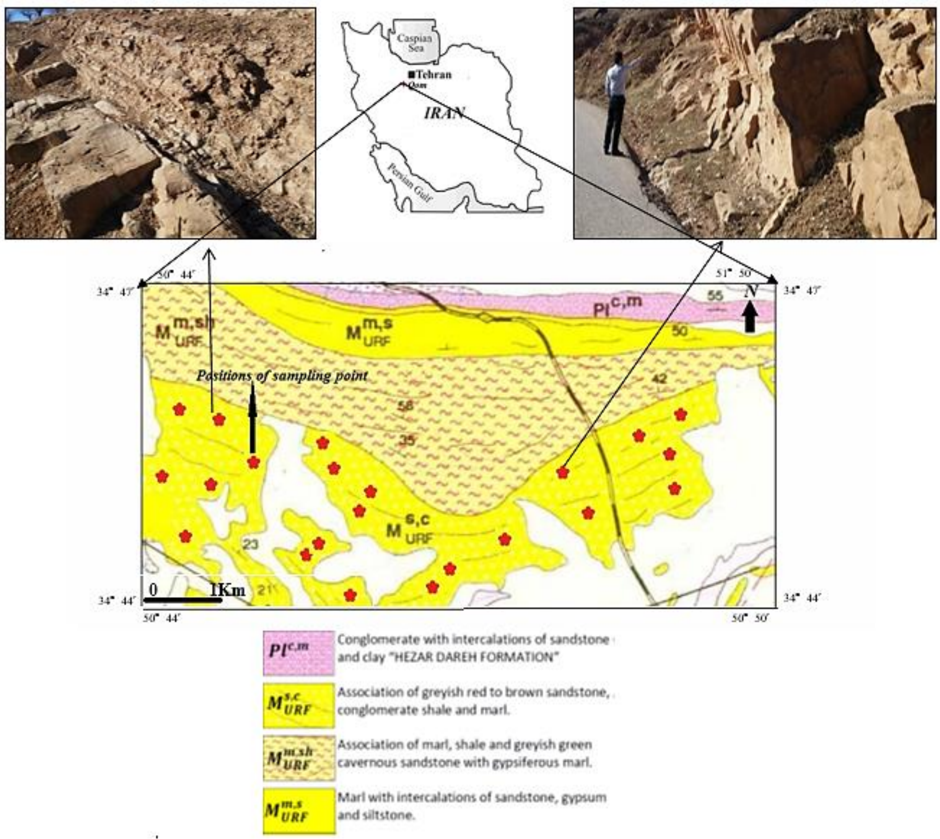

Fig. 1. Geological map of the study area (modified from the Qum geological map, 1:100,000, Iranian Oil Operating Companies (IOOC) [53].

3. Experimental studies

- UCS and BTS tests: The UCS value was determined in accordance with the method suggested by the ISRM [41]. The tests were carried out on trimmed core specimens that had a diameter of 54 mm and a length of about 135 mm. The stress rate on the core specimens was controlled at approximately 0.5–1 MPa/s. The maximum load at failure was used to calculate the uniaxial compressive strength of specimens. At least, five specimens of each sandstone type were tested, and the mean values were taken. The mean UCS values of sandstones are given in Table 3. As presented in this table, sandstone type 20 exhibits the highest UCS value (77.3 MPa), whereas sandstone type 16 indicates the lowest UCS equal to 46.6 MPa.

Studied sandstones were also classified according to their UCS values as suggested in the ISRM [48] (Fig 2). This Figure shows that most of sandstones were classified as having a medium strength (50–100 MPa), except the sandstones type 10 and type 16 that fall into the rock classes with low strength (25–50 MPa).

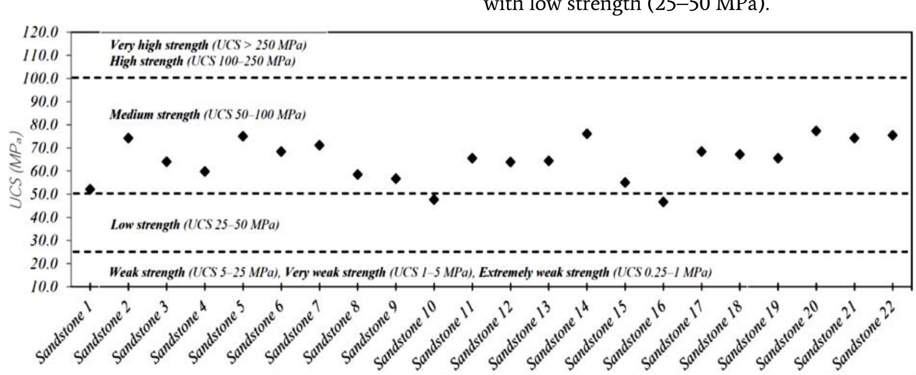

Fig. 2. The UCS classification of sandstones [48].

For the Brazilian test, disc specimens with a diameter of 54 mm and a thickness-to-diameter ratio of 0.5 were obtained from cylindrical cores. The tensile load was applied continuously on the specimens at a constant stress rate of 200 N/s until samples' failures [41]. The BTS values were found out by the following equation:

$$BTS = (2P/\pi Dt) \quad (1)$$

Where P is the peak load, and D and t are the disc's diameter and thickness, respectively.

Five specimens were used to determine the BTS of each sandstone type and their mean values were obtained afterward. The results of these determinations are presented in Table 3. As shown in this Table, the BTS of the sandstones varies from 5.1 to 9.4 MPa. Sandstone type 10 shows the lowest BTS with 5.1 MPa, while the highest BTS is 9.4 MPa and belongs to sandstone type 22.

- SH tests: Considering the wide procedural variations reported in the literature, four most common approaches wree used for the determination of SH in this study. The Schmidt hardness test was performed with an N-type hammer according to the test procedures of Hucka [27], Pool and Farmer [40], ISRM [41] and ASTM [44] (Table 2). Each test procedure was performed on all sandstone specimens with the hammer held vertically downwards and at right angles to horizontal faces of the cylindrical cores in a steel V-block having a weight of approximate 23 kg, defined by the ISRM (1981). Hammer readings were determined on specimens with a diameter of 54 mm. In should be noted that each specimen was inspected for macroscopic defects to eliminate any anisotropy effects on the measurement. In order to avoid the edge effects, the recordings were made at least two plunger diameters away from the edges of the cores. Three cylindrically formed specimens from each sandstone type were used for determination of SH and then, the average value was recorded as the rebound number according to each test procedure. The results of these determinations are presented in Table 3.

Table 3. UCS, BTS and SH values of the tested sandstones.

Rock code	UCS (MPa)	BTS (MPa)	SH			
			*Hucka (SH_1) [27]	Pool and Farmer (SH_2) [40]	ISRM (SH_3) [41]	ASTM (SH_4)[44]
Sandstone 1	52.1	5.7	35	37	40	41
Sandstone 2	74.2	8.4	46	45	51	50
Sandstone 3	64.0	6.2	38	42	44	46
Sandstone 4	59.8	7.6	40	43	46	44
Sandstone 5	75.0	7.7	52	54	55	56
Sandstone 6	68.4	8.9	47	48	52	53
Sandstone 7	71.1	6.7	44	42	48	47
Sandstone 8	58.5	6.5	36	39	43	41
Sandstone 9	56.7	6.0	39	40	43	42
Sandstone 10	47.6	5.1	39	38	41	40
Sandstone 11	65.5	7.0	41	40	47	43
Sandstone 12	63.9	6.0	38	39	43	42
Sandstone 13	64.4	7.4	42	43	46	45
Sandstone 14	76.1	7.7	48	45	53	52
Sandstone 15	55.0	5.7	35	37	39	39
Sandstone 16	46.6	5.2	36	32	38	38
Sandstone 17	68.4	8.0	49	50	52	51
Sandstone 18	67.2	5.9	41	42	46	45
Sandstone 19	65.5	6.9	43	44	45	46
Sandstone 20	77.3	8.6	55	56	57	57
Sandstone 21	74.2	9.1	50	51	56	53
Sandstone 22	75.4	9.4	50	47	53	54

***Test procedure (Table 2)**

As seen from Table 3, the SH values of sandstones determined from the SH test procedures are different. For instance, the SH values from Hucka's test procedure [27] range from 35 for sandstones 1, and 15 to 55 for sandstone 20, whereas based on the ISRM test procedure [41], it is from 38 for sandstone 16 to 57 for sandstone 20.

As can be followed from Table 3, the SH results based on continuous impacts (Hucka [27] and Pool and Farmer [40] procedures) reveal the lower values than those based on single impacts (ISRM [41] and ASTM [44] procedures). The SH test procedures based on continuous impacts at a point will be resulted in initiation and propagation of new microfractures and the development in the exxisting ones due to repeating the impact at a point; these in turn, influence the quality of samples and causing lower SH values than those based on single impacts. The results from this study were compared with those available in the literature. The difference in the SH values obtained from continuous impacts and single impacts in this study are in a good agreement with the findings of Goktan and Gunes [49], Buyuksagisa and Goktan [50] and Karaman and Kesimal [51].

The studied sandstones were also classified according to their SH values as suggested in the ISRM [52] (Fig. 3) (dashed lines). Fig. 3 shows that sandstones with respect to the SH test procedures fall into different rock classes with slightly strong, strong or very strong strength. For instance, based on the SH test procedures of Hucka [27] and Pool and Farmer [40], sandstone 8fall into the class with slightly strong rock (20–40), whereas according to the procedures of ISRM [41] and ASTM [44], it falls into the class with strong rock (40–50).

Furthermore, it is worth noting that based on test procedures of Hucka [27] and Pool and Farmer [40], the results of SH values generally fall into classes with "slightly strong rock" and "strong rock", whereas the SH values by the ISRM and ASTM test procedures [41] and [44] mostly fall into the "strong rock" and "very strong rock" classes.

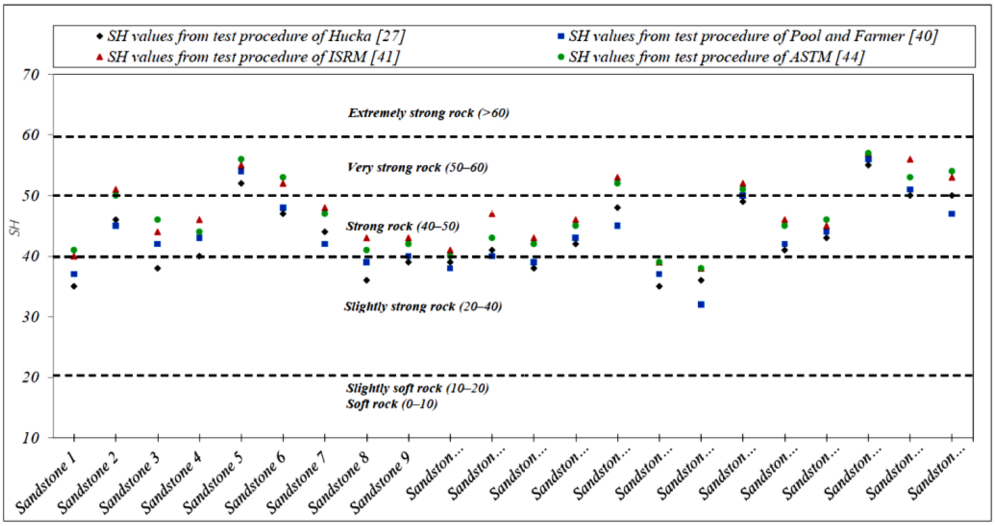

Fig. 3. SH classification of sandstones based on all SH test procedures [52].

4. Results and discussion

4.1. Correlation between UCS and SH

In order to be able to determine the best correlation equations between UCS and SH, regression analysis was done. The equation of the best fit line and the determination coefficient (R^2) were obtained for each regression. The plot of the UCS as a function of SH, for different test procedures are shown in Fig. 4. As can be followed from Fig. 4, the highest (R^2 = 0.856) and lowest (R^2 = 0.727) coefficients of determination, between UCS and SH, was obtained based on the ISRM [41] and Pool and Farmer [40] test procedures, respectively. The equations of these correlations are as follows:

$$UCS = 58.35 \ln (SH_2) - 154.6, (R^2=0.727) \quad (2)$$

$$UCS = 70.417 \ln (SH_3) - 206.04, (R^2=0.856) \quad (3)$$

The results of regression analyses shown in Fig. 4 reveal that the prediction performance of UCS by the SH test procedures that are based on single impacts at a point (ISRM [41] and ASTM [44]) are better than those of continuous impacts (Hucka [27] and Pool and Farmer [40]). On other hand, among the SH test procedures that are based on single impacts, the ISRM procedure [41] gives a better prediction, for which the determination coefficient is 0.856, while for the ASTM [44] test procedure, the determination coefficient is 0.829. These results are in conflict with the findings of Buyuksagis and Goktan [49]. These researchers studied the correlation between the SH test procedures and UCS of some rock types. Their results showed that the SH test procedures that are based on continuous impacts at a point provide a more reliable and accurate predictions of the UCS than those that are based on single impacts.

The literature reports many equations for prediction of the UCS of rocks using the SH, which give various relationships (linear and non–linear). Some of these equations are listed in Table 1. However, as can be seen from Fig. 4, the logarithmic relationship gives the best correlation between UCS and SH.

The derived correlations in this study were compared with those available in the literature. There is a significant difference in coefficients of determination between UCS and SH of this study and those of other studies. For example, Karaman and kesimal [51] reported different relationships for the SH test procedures and UCS with coefficients of determination of 0.838 to 0.945; Tandon and Gupta [8] and Cobanoglu and Celik [19], based on the experimental tests results on sedimentary and igneous rocks, obtained linear relationships between UCS and SH with a coefficients of determination of 0.75 and 0.65, respectively.

4.2. Correlation between BTS and SH

The plot of BTS as a function of SH is shown in Fig. 5. It can be seen from this figure that as the SH increases, the BTS increases, as well. The relation between BTS and SH test procedures are as follows:

$$BTS = 8.0554 \ln(SH_1) - 23.132, \ R^2 = 0.720 \quad (4)$$

$$BTS = 0.1816\, SH_2 - 0.7995, R^2 = 0.678 \quad (5)$$

$$BTS = 0.0347 SH_3^{1.3783}, R^2 = 0.820 \quad (6)$$

$$BTS = 9.2313 \ln(SH_4) - 28.317, R^2 = 0.770 \quad (7)$$

There is a coefficient of determination of 0.720 to 0.820 between BTS with SH. The comparison of coefficients of determination showed that the correlation between BTS and SH based on single impacts (Eqs. 6 and 7) are the most reliable for prediction of BTS than those based on continuous impacts at a point (Eqs. 4 and 5).

There are many equations for prediction of UCS from SH, whereas there are very few studies in the literature on the relationship between BTS and SH (see Table 1). The equation proposed by Karaman et al. (2015) exhibit a linear relationship between BTS and SH with a coefficient of determination of 0.85. However, non–linear relationships between these parameters were obtained by Kılıç and Teymen (2008) and Jamshidi et al. (2016a) with coefficients of determination of 0.95 and 0.72, respectively. In this study, linear and non–linear relationships between BTS and SH with coefficients of determination of 0.678 to 0.820 was found (Eqs. 4–7). To investigate the validity of the proposed correlation equations, the t–test was conducted among the achieved equations using the SPSS statistical software package version 21.0.

The significance of the r–values can be determined by the t–test, assuming that both variables are normally distributed and the observations are chosen randomly. The test compares the computed t–value with a tabulated t–value using a null hypothesis. In this test, a 95% level of confidence was chosen. If the computed t value was greater than the tabulated t–value, the null hypothesis was rejected, meaning that r is significant. If the computed t value was less than the tabulated t–value, the null hypothesis was not rejected. In such a case, r was not significant. Since a 95% confidence level was chosen in this test, a corresponding critical t–value ±2.08 was obtained from the related tables. It can be seen from Table 4 in which all the computed t values are greater than the tabulated t values. Therefore, it is concluded that there are real correlations between the UCS and BTS with SH. However, regarding the values of coefficients of determination (R^2) in Table 4, equations 4 and 8 gave the highest degree of accuracy for prediction of UCS and BTS, respectively, whilst in other equations, this degree was found to be somewhat lower, nevertheless statistically acceptable. Therefore, the established regression equations can be used in the early stages of geotechnical projects that interact with rock.

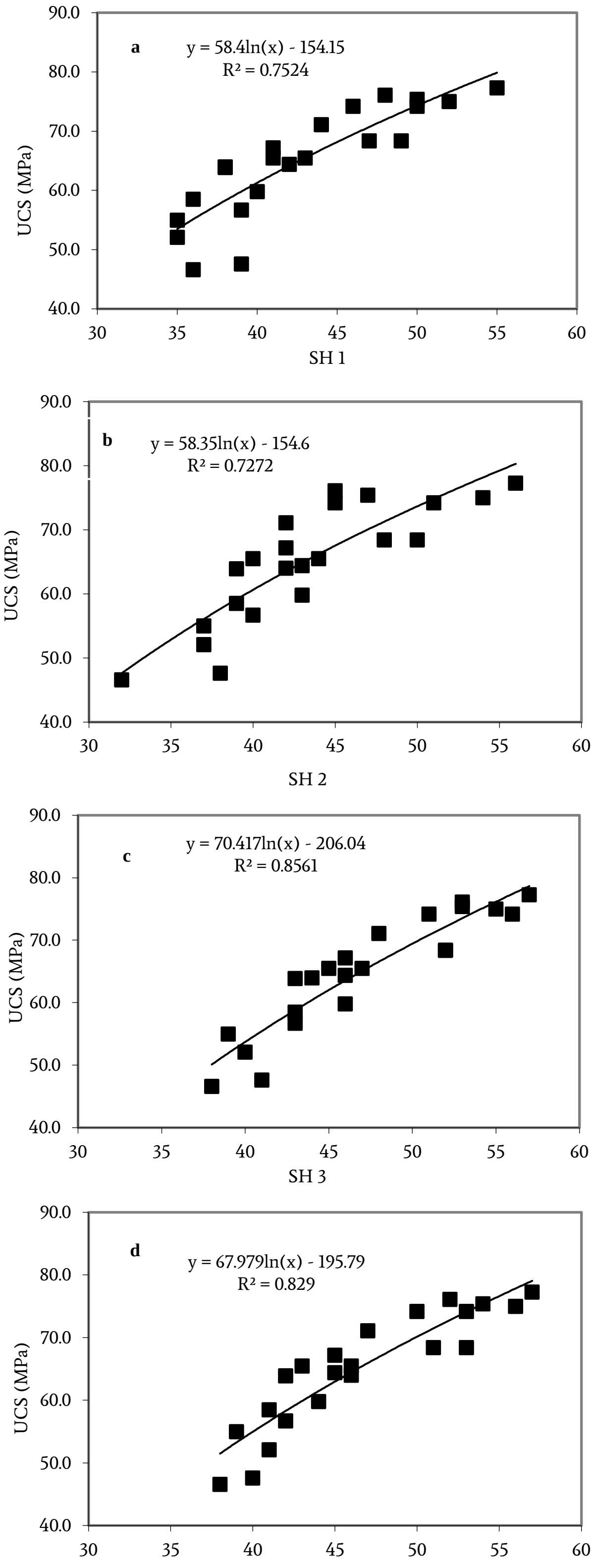

Fig. 4. UCS versus a SH_1 (Hucka [27]) b SH_2 (Pool and Farmer [40]) c SH_3 (ISRM [41]) d SH_4 (ASTM [44]).

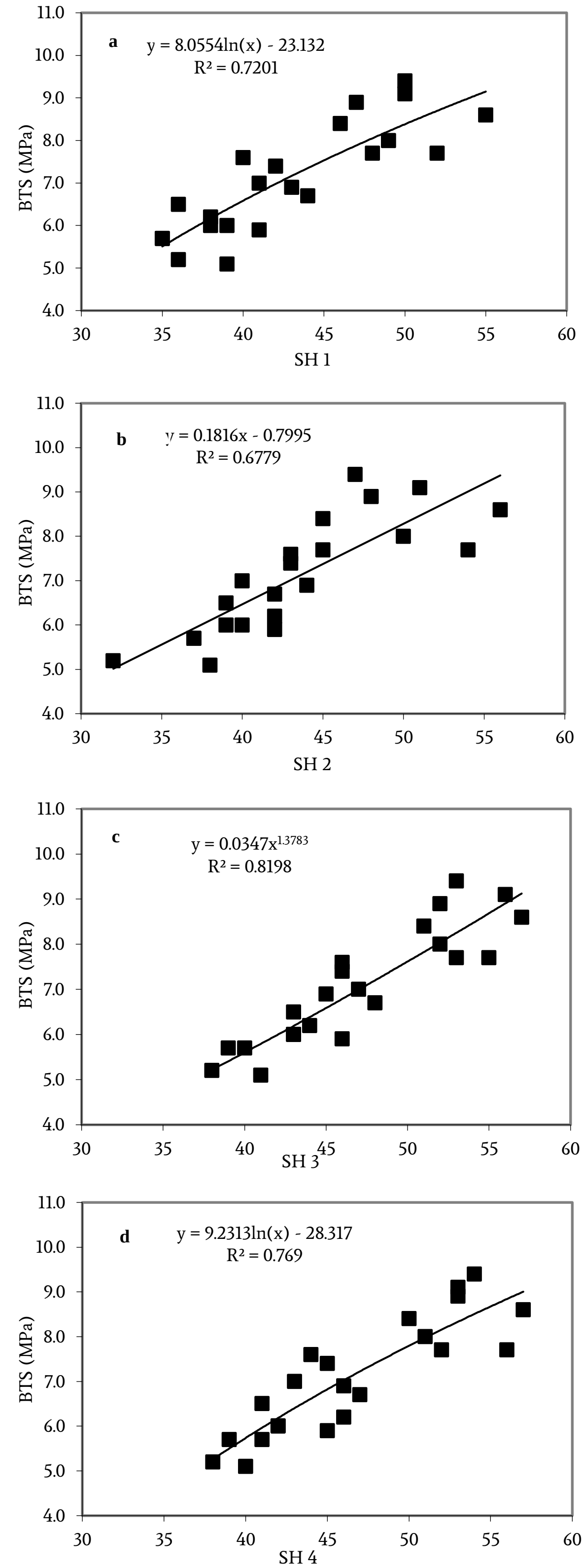

Fig. 5. BTS versus a SH_1 (Hucka [27]) b SH_2 (Pool and Farmer [40]) c SH_3 (ISRM [41]) d SH_4 (ASTM [44]).

Table 4. Summarized regression analytical results.

Equation number	Correlation equations	Determination coefficient (R^2)	t test	
			Calculated value	Tabulated value
2	UCS = 58.4 ln (SH_1) – 154.15	0.752	20.25	±2.08
3	UCS = 58.35 ln (SH_2) – 154.6	0.727	18.80	±2.08
4	UCS = 70.417 ln (SH_3) – 206.04	0.856	18.13	±2.08
5	UCS = 67.979 ln (SH_4) – 195.79	0.830	18.15	±2.08
6	BTS = 8.0554 ln(SH_1) – 23.132	0.720	–34.46	±2.08
7	BTS = 0.1816 SH_2 – 0.7995	0.678	–35.08	±2.08
8	BTS = 0.0347$SH_3^{1.3783}$	0.820	–41.30	±2.08
9	BTS = 9.2313 ln(SH_4) – 28.317	0.770	–39.56	±2.08

UCS: Uniaxial compressive strength, BTS: Brazilian tensile strength, $SH_{1\ to\ 4}$: Schmidt hammer hardness based on Hucka (SH_1) [27], Pool and Farmer (SH_2) [40], ISRM (SH_3) [41] and ASTM (SH_4) [44]

5. Conclusions

In this study, a comprehensive laboratory program was performed to compare the performance of the four most accepted test procedures of SH for prediction of UCS and BTS of 22 sandstone samples. By analyzing the data of laboratory tests, the major results obtained from this study can be summarized as follow:

a) SH results of sandstone samples based on continuous impacts at a point reveals the lower values than that based on single impacts at a point. Lower SH values obtained from continuous impacts procedures can be attributed to an increase in inherent weakness agents such as porosity, microfissure, etc. due to the repetition of the impact at the point; this in turn influences the quality of sandstone samples and reduces their SH values.

b) By statistical analyses, the linear and non–linear equations were developed between the SH test procedures with UCS and BTS, coefficients of determination between 0.678 and 0.856. Equations were validated by the t–test and for prediction of UCS and BTS, the results show that the SH test procedures that are based on single impacts at a point are more appropriate and reliable than those that are based on continuous impacts at a point. Moreover, it was found that the best correlation between UCS and BTS with SH obtained for the SH test procedure based on the ISRM approach.

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