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Drillability Evaluation of Limestone Rock Quarries in Punjab and Khyber Pakhtunkhwa, Pakistan

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Abstract

The Compressive and Tensile Strengths of the rocks vis-a-vis Brittleness concepts (BCs) have often been used by various researchers to find empirical relations for the evaluation of drillability of the rocks. In this work the Uniaxial Compressive Strength (UCS), Brazilian Tensile Strength (BTS) and five BCs (B_1, B_2, B_3, B_4, and B_5) have been used to evaluate the drillability of the Limestone Rock quarries. For this purpose representative block samples of limestone rock were collected from the quarries of four Cement Factories which are operative in Sakesar and Samana Suk Formations of Punjab and Khyber Pakhtunkhwa (KPK), Pakistan. UCS and BTS tests were conducted for the determination of BCs (B_1, B_2, B_3, B_4, and B_5), whereas the Sievers' J- Miniature drill tests and Brittleness (S_{20}) Tests were conducted in the laboratory to find the Drilling Rate Index (DRI) of the rocks. The measured indices of the rocks were correlated with the rock strength parameters and BCs. Strong linear decreasing relations were found between DRI, UCS, BCs values B_3, B_4, and B_5, whereas weak relations were found between DRI, BTS, BCs values B_1 and B_2.

Key Words: Uniaxial Compressive Strength, Brazilian Tensile Strength, Limestone, Rock drillability, Sievers' J, Brittleness, Drilling Rate Index.

1. Introduction

The term of rock drillability is commonly used to explain the influence of a number of factors on the drilling rate and the wear of the drilling tool [19, 20 and 35] and is considered to be a standard factor for the progress of excavation. The rock drillability cannot be explained by a single parameter [4] and depends on the operational variables of the drilling machines and the corresponding rock characteristics. Studies conducted by Arthur [1] and Deketh [8] show that the drillability of rock and thereby the penetration rate of a drill are affected by rock hardness, rock texture and density, rock fractures and general structure of the rock mass. Moreover, the strength parameters of the rocks have prominent effects on the drillability of rock cutting tools. It has been found by Deketh [8] that the rock hardness and its strength may cause unexpectedly higher rates of wear to the cutting tools that usually increase the project cost.

Previous studies reveal that the drillability and boreability can be predicted from a combination of machine characteristics and rock properties. Many workers have used uniaxial compressive strength of the rock to predict the performance of tunnelling and drilling machines [7, 16 and 27]. However index tests like schmidt hammer, taber abrasion, point load, cone indenter and shore hardness have also been utilized to predict the performance of drilling or boring machines [13, 22, 24 and 25] Yarali and Soyer [38] stated that the strength of rock affects drillability and that decreasing linear relationships exist between DRI and UCS, Schmidt rebound hardness, Shore scleroscope hardness and diametric and axial point load strength. Yang et al. [39] examined that the characteristics of hardness and drillability are influenced by microstructure of the rock.

Various researchers have also studied the property of rock brittleness to develop empirical relationships with DRI and other drilling parameters of the rocks. Brittleness has been expressed by Hetenyi [11] and Morley [23] as being the lack of ductility. Obert and Duvall [28] are of the opinion that the materials such as cast iron and many rocks which usually terminate by fracture or only slightly beyond their yield stress are called brittle. Ramsay [30] describes that when the internal cohesion of rocks is broken, they are called brittle. The brittleness is a mechanical property and its definition varies from author to author. Singh [33] indicated that cuttability and penetrability of coal is strongly dependent on its brittleness. Singh [34] further found that a direct relationship exists between in situ specific energy and brittleness of three Utah coals. Hucka and Das [12] observed that a higher brittleness is a result of fracture failure with formations of fines and higher ratios of compressive strength to tensile strength.

Hucka and Das [12]; and many other researchers [3, 18 and 37 have discussed the brittleness concepts of rocks in detail and have been using it for establishing empirical relationships with the drillability, boreability, penetration rates of percussive drills, specific energy in rock cutting, fracture toughness, Los Angeles abrasion loss, specific energy for drilling/cutting in rocks and the DRI. The brittleness concepts (BCs) which are derived from the compressive strength and tensile strength of the rocks are narrated below:

$$B1 = \frac{\sigma c}{\sigma t} \quad [12] \qquad (1)$$

$$B2 = \frac{\sigma c - \sigma t}{\sigma t} \quad [12] \qquad (2)$$

$$B3 = \frac{\sigma c \times \sigma t}{2} \quad [2] \qquad (3)$$

$$B4 = \sqrt{B3} \quad [6] \qquad (4)$$

$$B5 = (\sigma c \times \sigma)^{0.72} \quad [37] \qquad (5)$$

Where, B1, B2, B3, B4 and B5 denote brittleness; σc is UCS and σt is BTS of the rock(s).

In the current study the UCS, BTS and the above BCs are used to evaluate the drillability of the limestone rock quarries of Sakesar and Samana Suk formations in Punjab and Khyber Pakhtunkhwa (KPK), Pakistan. These quarries are selected on the basis of the economic importance of the limestone. Approximately eight cement factories are located in these areas and all the raw material for cement manufacturing is being produced from the above listed rock formations.

2. Sampling

Representative intact rock block samples of limestone, measuring at least one cubic foot in size, were collected from limestone quarries of M/s Bestway Cement Limited (Chakwal), M/s DG Cement Limited (Chakwal), M/s Bestway Cement Limited (Hattar) and M/s Mustehkum Cement Limited (Hattar), operative in Sakesar and Samana Suk limestone formations [14] of Punjab and Khyber Pakhtunkhwa (KPK) Pakistan respectively. The procured samples were ensured to be free from macroscopic defects and fractures. A total of fifty block samples of limestone were gathered from these sites. The location of the study areas is shown in Figure 1.

3. Experimental Work

3.1 Coring, Cutting and Lapping

Using a standard core drilling machine NX size core samples were taken from the rock blocks. A Japan made core cutting machine (Model 45 - D 536) and a standard grinding Machine have been used to obtain the correct size and smooth ends. The core sample preparation procedures conform to the International Society for Rock Mechanics (ISRM) standards [15].

3.2 Uniaxial Compressive Strength Test (UCS)

The UCS tests were carried out on a 200-Ton capacity Universal Testing Machine. NX size drill core samples were prepared with a length to diameter ratio of 2.5-3.0. The core specimen's ends were flattened within the range of 0.05 mm so that the loads could be applied uniformly and the loading rate was adjusted as mentioned in the ISRM test procedures [15]. The UCS tests were repeated three to five times so as to obtain the mean value.

3.3 Brazilian Tensile Strength test (BTS)

The BTS tests were conducted on core samples with a height to diameter ratio of 0.5. Standard loading rates were applied. The BTS tests were repeated from three to five times and the results were averaged. The tests were conducted according to the ISRM standards [15].

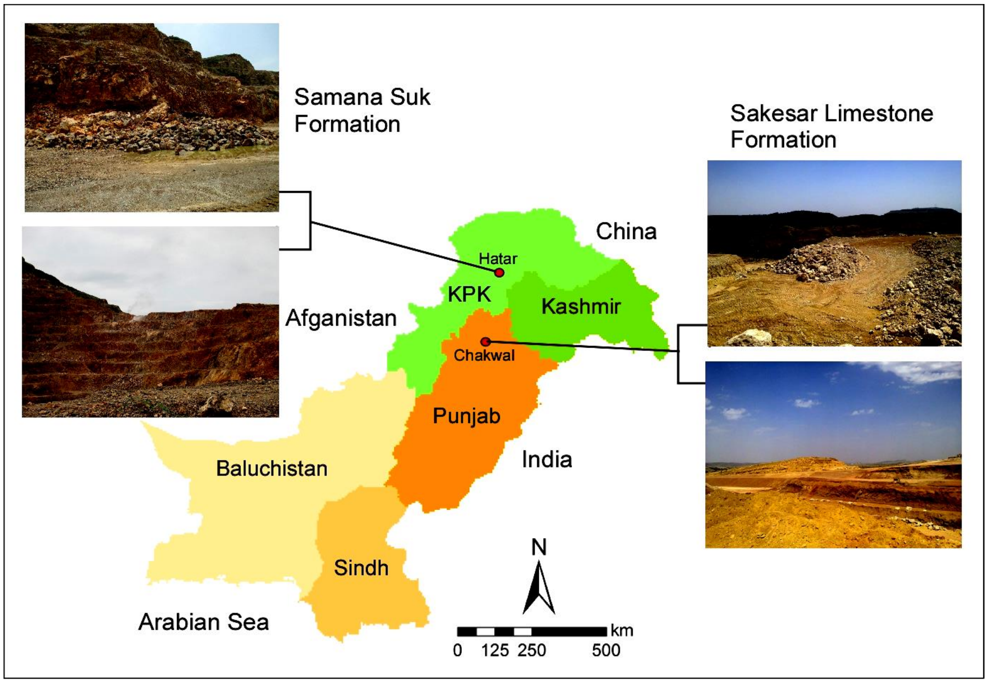

Fig. 1 Location map of the study areas

3.4 Drillability of Rocks

The drillability of the limestone rocks was evaluated on the basis of the Drilling Rate Index (DRI) and the procedures and standards prescribed by the NTNU (Norwegian University of Science and Technology) [10, 21 and 26]. The DRI is noted from a graph (Figure 4) which is between the Sievers' J- (SJ) Value and the Brittleness Value (S_{20}). The lesser value of DRI specifies that there is more difficulty in boring the rock [9].

3.4.1 The Sievers' J (SJ) miniature drill test

The SJ drill test is widely used to measure the surface hardness of rock samples. Its value is measured as the mean value of the drill hole depth to 1/10 mm of 4 to 8 drill holes after 200 revolutions of the 8.5 mm miniature drill test bit. As prescribed in the standard procedures, the pre-cut surface of the sample is kept perpendicular to the foliation of the rock. The SJ-value is therefore measured parallel to the foliation. After the test the drill hole depth is measured by use of a slide calliper [10]. An outline of the SJ test and the local laboratory set up in the Department is shown in Figures 2 and 3.

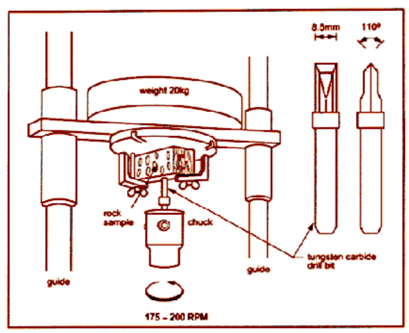

Fig. 2 Outlines of principles for the Sieves' J miniature drill test [13].

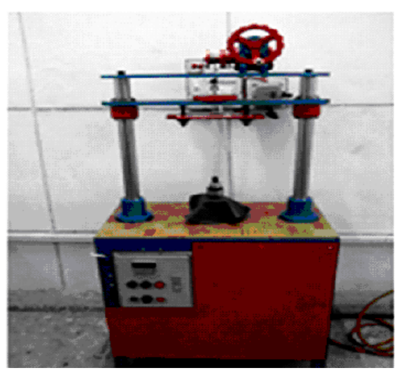

Fig. 3 Sieves' J miniature Drill Test setup at Rock Mechanics Laboratory of Mining Engg. Dept.

3.4.2 The Brittleness Test (S20).

The brittleness test gives a good measure of the ability of rock to resist crushing by repeated impacts. The test method was developed in Sweden by N. Von Matern and A. Hjelmer in 1943. Several modifications of the test have so far been developed. The sample weight corresponds to 500 grams of density 2.65 g/cm^3 taken from the sieved fraction of 16 to 11.2 mm. The brittleness value S_{20} is calculated as the percentage of material that passes the sieve size of 11.2 mm mesh after the aggregate has been crushed by 20 impacts in the mortar. According to the procedures, 3 to 5 parallel tests are run to obtain the mean for the Brittleness value (S_{20}) [10]. An outline of the test and the local laboratory testing set up in the Department is shown in Figs. 4 and 5.

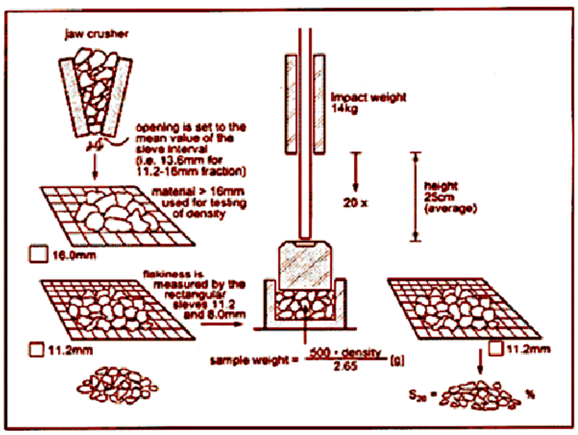

Fig.4 Outlines of the brittleness test [13]

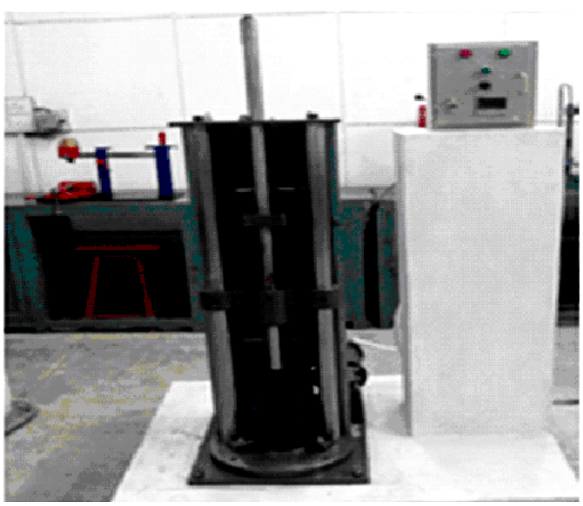

Fig.5 Brittleness Test set up at Rock Mechanics Laboratory of Mining Engg. Department

3.4.3 Assessment of Drilling Rate Index (DRI)

The DRI is assessed from Figure 6 which is based on the Brittleness (S20) and the Sievers'J-value of the tested rocks. The classification of DRI is presented in Table 1.

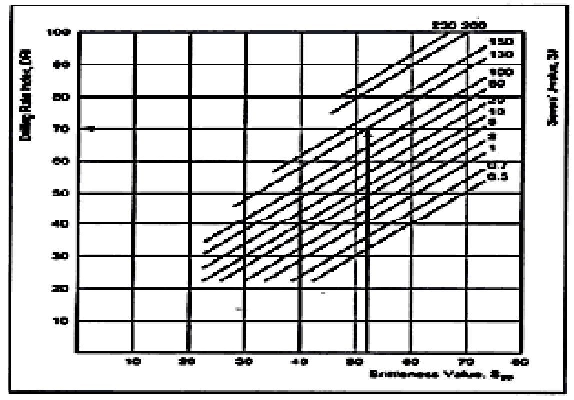

Fig.6 Diagram for Assessment of DRI [13]

Table 1 Classification Categories of DRI [13]

Category	DRI
Extremely low	≤25
Very low	26 – 32
Low	33 – 42
Medium	43 – 57
High	58 – 69
Very high	70 – 82
Extremely high	≥82

4. Results and Discussion

In this study limestone rock from four different locations of quarries operating in Punjab and KPK were tested for their strength tests, BCs and DRI evaluations. The average results of the tests are given in MPa in Table 2 and Table 3 respectively.

Table 2 shows that the UCS of the limestone rock ranges from 24.62 MPa to 133.60 MPa and BTS ranges from 2.39 MPa to 8.31 MPa. BCs values (B_1, B_2, B_3, B_4, and B_5) determined from UCS and BTS displays a narrow range variation of values for B_1, B_2 and B4 while B_3 and B_5 have a wide range. Test results of SJ, S_{20}, DRI and classification of DRI of limestone rock are given in Table 3. It was found that the DRI values change from 38.00 to 57.50 showing a low to medium drillability of the limestone rocks of the selected sites.

Table 2: UCS, BTS and BCs Values of Limestone rock formations

Sr.No.	Rock Code	UCS (Mean values) (Mpa)	BTs (Mean Values) (Mpa)	$B1 = \frac{\sigma c}{\sigma t}$	$B2 = \frac{\sigma c - \sigma t}{\sigma c + \sigma t}$	$B3 = \frac{\sigma c \times \sigma t}{2}$	$B4 = \sqrt{B3}$	$B5 = (\sigma c \times \sigma t)^{0.72}$
1	BWC1	24.62	3.84	6.42	0.73	47.23	6.87	26.44
2	BWC2	30.54	4.74	6.44	0.73	72.42	8.51	35.96
3	BWC3	133.60	8.31	16.07	0.88	555.32	23.57	155.89
4	BWC4	50.71	5.81	8.73	0.79	147.32	12.14	59.96
5	BWC5	76.43	7.20	10.62	0.83	275.12	16.59	94.02
6	BWC6	37.90	5.18	7.32	0.76	98.15	9.91	44.76
7	DGC1	121.56	7.70	15.79	0.88	468.00	21.63	137.82
8	DGC2	110.04	6.54	16.83	0.89	359.84	18.97	114.06
9	DGC3	110.04	7.79	14.13	0.87	428.62	20.70	129.37
10	DGC4	97.67	3.37	28.98	0.93	164.58	12.83	64.94
11	MCH1	42.57	2.56	16.63	0.89	54.49	7.38	29.30
12	MCH2	81.68	2.39	34.18	0.94	97.61	9.88	44.58
13	BCH1	46.04	3.72	12.38	0.85	85.63	9.25	40.57
14	BCH2	29.76	4.77	6.24	0.72	70.98	8.43	35.45
15	BCH3	25.78	6.17	4.18	0.61	79.53	8.92	38.47

UCS=Uniaxial compressive Strength, BTS = Brazilian Tensile Strength, B1, B2, B3, B4, B5 = BCs,BWC = BestwAy Cement Chakwal, DGC = DG Cement Chakwal, MCH = Mustehkum Cement Hattar, BCH = Bestway Cement Hattar.

Table 3: DRI Values of the Limestone rock formations and their classifications.

Sr.No.	Rock Code	Rock Type	Rock Formation	SJ (Mean Value)	S_{10} (Mean Value)	DRI	Class
1.	BWC1	Limestone	Sakesar Limestone	9.93	57.64	57.50	Medium
2.	BWC2	Limestone	Sakesar Limestone	8.89	54.20	55.00	Medium
3.	BWC3	Limestone	Sakesar Limestone	5.07	39.65	39.50	Low
4.	BWC4	Limestone	Sakesar Limestone	8.26	51.55	51.00	Medium
5.	BWC5	Limestone	Sakesar Limestone	7.76	50.17	49.00	Medium
6.	BWC6	Limestone	Sakesar Limestone	8.32	52.94	53.00	Medium
7.	DGC1	Limestone	Sakesar Limestone	7.49	39.85	38.00	Low
8.	DGC2	Limestone	Sakesar Limestone	7.77	41.89	41.00	Low
9.	DGC3	Limestone	Sakesar Limestone	8.07	43.86	41.00	Low
10.	DGC4	Limestone	Sakesar Limestone	9.16	46.53	46.00	Medium
11.	MCH1	Limestone	Samana Suk	6.75	53.99	53.50	Medium
12.	MCH2	Limestone	Samana Suk	6.76	47.80	46.00	Medium
13.	BCH1	Limestone	Samana Suk	5.36	52.57	52.50	Medium
14.	BCH2	Limestone	Samana Suk	4.24	54.23	51.50	Medium
15.	BCH3	Limestone	Samana Suk	6.04	52.75	51.00	Medium

DRI: Drilling Rate Index, SJ: Sievers's J Miniature Drill Test, S_{20}: Brittleness Test Value, BWC: Bestway Cement Chakwal, DGC: DG Cement Chakwal, MCH: Mustehkum Cement Hattar, BCH: Bestway Cement Hattar.

Regression analyses were undertaken on the obtained data to find the relationship of DRI with strength properties and B_1, B_2, B_3, B_4, and B_5. Various graphical relations are displayed in Figure 7 to Figure 13. As seen in these figures there are decreasing linear relationships between DRI and UCS, DRI and BTS, DRI and different BCs (B_1, B_2, B_3, B_4, and B_5). There were strong linear relations for DRI versus UCS; and DRI versus B3, B_4, and B_5, however, very weak relations were found for DRI versus BTS; and DRI versus B_1 and B_2.

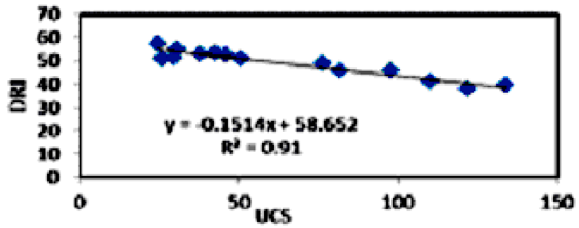

Fig.7 DRI of the rock correlated with UCS.

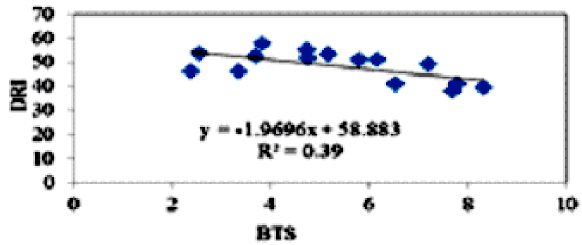

Fig.8 Relationship between DRI and BTS.

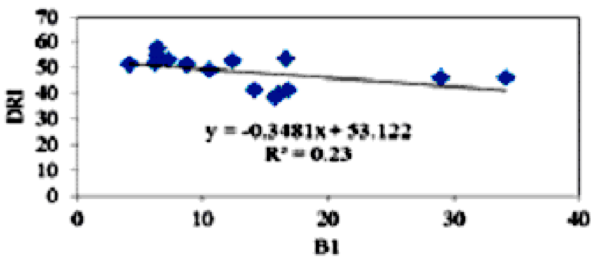

Fig.9 Relationship of brittleness (B4) with DRI

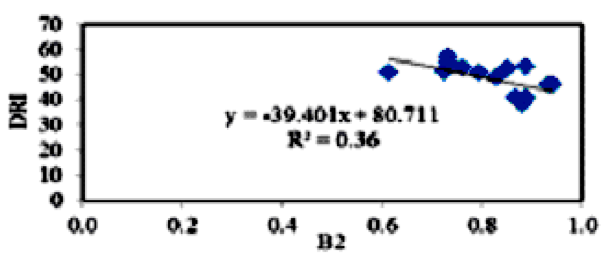

Fig.10 Relationship of Brittleness (B2) with DRI

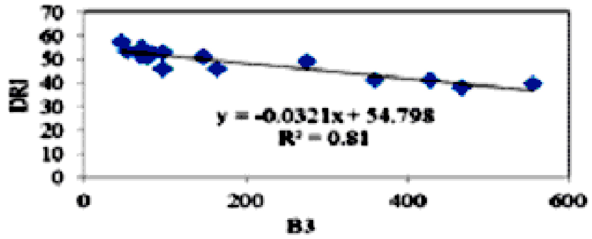

Fig.11 Relationship of Brittleness (B3) with DRI

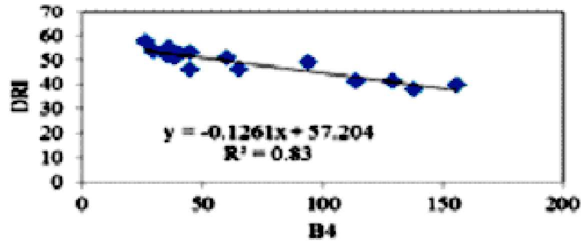

Fig.12 Relationship of Brittleness (B4) with DRI

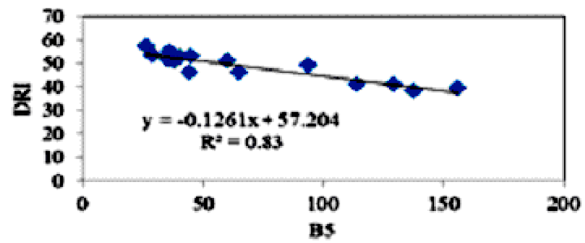

Fig.13 The relationship of Brittleness (B5) with DRI

Strong coefficients of determination (R^2) were found among DRI, UCS and BCs (B_3, B_4, and B_5) and weak values of R^2 were observed among DRI, BTS and BCs (B_1 and B_2) with 95 % confidence interval and 5 % significance level (α-value). The validity of the relationships/equations was verified by statistical t -test and F- test; and the strength of R^2. The t and F- test values were calculated and compared with the tabulated values. At this step it was checked whether the computed t and F values were greater than the tabulated values or not; and the strength of R^2 is weak or strong. The equations were accepted as valid if the computed t and F values were greater than the tabulated values; and the strength of R^2 was strong. An overall summary of all the developed relationships/equations and coefficients of determination (R^2); computed and tabulated t and F values with significance levels are shown in Table 4 below:

Table 4: Summary of the Relationships/Equations, R^2, t and F Values (Computed and Tabulated) with significance levels

Sr. No.	Relationship/Equations	Coefficient of Determination (R^2)	Computed t abs. Values	Computed f Values	Tabulated t Values	Tabulated F Values	Significance Level (α-value)
1.	DRI–58.652–0.1514*UCS	0.91	| –11.40 |	129.968	2.048	4.67	0.000
2.	DRI–58.883–1.9696*BTS	0.39	| –2.815 |	8.208	2.048	4.67	0.013
3.	DRI–53.122–0.3481*B1	0.23	| –1.995 |	3.981	2.048	4.67	0.067
4.	DRI–80.711–39.401*B2	0.36	| –2.660 |	7.076	2.048	4.67	0.020
5.	DRI–54.798–0.0321*B3	0.81	| –7.497 |	56.201	2.048	4.67	0.000
6.	DRI–57.204–0.1261*B4	0.83	| –8.131 |	66.108	2.048	4.67	0.000
7.	DRI–57.204–0.1261*B5	0.83	| –7.895 |	62.339	2.048	4.67	0.000

The above summary reveals that meaningful relationships are seen between DRI and UCS, B3, B4 and B5. It reflects that the DRI and thus the drillability of the cited rock formations are dependent on the UCS and brittleness values of the rocks.

The results of the study were compared with the findings of the different previous researchers which show a good agreement of decreasing linear relationship of drillability (penetration rate) i.e., DRI with UCS [17, 37, 38]. However, the relationships of DRI with brittleness values found by various researchers appeared to be exponential [5, 36, 37] whereas current study shows decreasing linear relationships.

5. Conclusion

Fifty representative blocks of limestone rock were brought to the laboratory from four different locations of quarries in Punjab and KPK regions to evaluate drillability of rocks by relating the DRI to the strength parameters and brittleness concepts (BCs) of the rocks. The DRI indices were statistically correlated with UCS, BTS and BCs (B_1, B_2, B_3, B_4, and B_5).It was found that there are strong decreasing linear relationships of DRI with UCS, brittleness B_3, B_4, and B_5. However weak correlations were explored between DRI, BTS and brittleness B_1 and B_2. The developed relationships show that increased rate of both UCS and brittleness decreases the DRI of the rock.

The established relationships were verified by employing the Student T-Tests, F- Tests and strength of coefficients of determination (R^2). The statistical analysis reveals that the UCS and brittleness B_3, B_4, and B_5 can be used for the evaluation of the drillability of the Limestone rock quarries in the Sekasar and Samana Suk Formations. This study is also in good agreement with the results of the previous researchers and reflects that the strength parameters and rock brittleness are important parameters for drillabillity evaluation of the cited rock. Therefore, understanding the drillability, strength parameters and brittleness characteristics will be useful for the quarry and mine operators to check the likely response of rock to drilling and excavation.

6. Acknowledgements

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