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# Evaluation of Relationships between Drilling Rate Index and Physical and Strength Properties of Selected Rock Units of Pakistan

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ABSTRACT

*Fifteen selected rock types collected from different formations of Pakistan were subjected to Drilling Rate Index (DRI) tests and various physical and strength properties tests including, porosity (n), density, primary wave velocity ($V_p$), uniaxial compressive strength ($\sigma_c$), Brazilian tensile strength ($\sigma_t$) and Schmidt hammer rebound number ($R_n$),. Prior knowledge of the drill ability of rocks and their physico-mechanical properties plays a decisive role in planning and design of rock drilling and excavation processes. DRI tests developed by NTNU/SINTEF are in use by the industry since 1960s and have proved very successful in estimation of the boreability of rocks, but no such work has been reported for Pakistani rocks to date. Reasonable correlations were found between the DRI and the properties of the tested rocks. The trends shown in this paper are of interest for the machine manufacturers and operators working on various projects involving the use of drilling machines and other mechanical excavators.*

## 1. Introduction

Over the past so many years the need for accurate prediction of drillability has proved necessary in drill and blast and mechanical tunneling activities. This is of utmost importance for planning, design and construction of underground projects in an optimized way. Drillability is found not only important for the wear prediction of the rock cutting tools and equipments but also for the expected drilling rate. Underground excavations using tunnel boring machines (TBMs), roadheaders, raise borers, continuous miners and several other excavators have become increasingly common in pastyears. Selection of these excavators without prior knowledge of physical, mechanical, petrographic and drillability properties of rock can cause unforeseen problems during their operation. The improper estimation of rock drillability can cause expensive and frequent tool replacement, which can significantly affect machine’s routine operation. Therefore, there is a need of improved prediction of drilling rate and rock properties for machine manufacturers and contractors involved in mining, tunneling, and underground construction industry.

Numerous geological and mechanical properties of the rocks affect the drillability. Several previous investigators [1-13] described $\sigma_c$ of rock as the most important parameter to affect a rock’ drillability. Many other rock strength parameters, such as $\sigma_t$, some index rock properties such as $R_n$, point load strength index (PLS), Shore scleroscope hardness (SH) have also been reported in the literature to define the ease or difficulty of a drilling operation [14-16]. A thorough discussion of the relevant parameters affecting the drilling performance can be found elsewhere [17-19].

The pioneering work to assess the drillability of rocks was conducted at the Norwegian University of Science and Technology (NTNU) in the early 1960s. Latest developments have concentrated on specifications and design of new tests, techniques and procedures [20-22].

NTNU found that drillability indices like the DRI, Vickers Hardness Number Rock (VHNR), Bit Wear Index (BWI) and Cutter Life Index (CLI) are indirect methods of calculating rock drillability. Numerous investigators have worked on drillability and investigated its relationships with other rock strength and physical parameters [23]. The term drillability is defined in construction industry to describe the effect of a numerous factors on the drilling rate (drilling velocity) and the wear encountered to the drilling tool as described by [19]. Jimeno et al.[25] correlated the penetration rate with different rock properties and found that $R_n$,$\sigma_c$, bulk density ($\rho_b$), $V_p$ and porosity (n)values reveal strong relationships with the penetration rate. Other researchers [7, 11, 25] used different rock properties like quartz content,$\sigma_t$, $V_p$ and porosityto calculate the drillability of rocks.

Kahraman et al. [26]proposed a new drillability index which he calculated from load-indentation plots of

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indentation tests and by using this new drillability index he established a penetration rate model for rotary drills. They also establish correlations of this drillability index with point load index, $\sigma_t$, $\sigma_c$, impact strength, elastic modulus, density, $R_n$ and $V_p$ and found noteworthy correlations. Kahraman et al.[10] investigated percussive blast hole drills in different rock types. The penetration rates were correlated with the physical and mechanical properties of the rocks estimated both in the laboratory and in the field. Impact strength showed a legitimate correlation with penetration rate. Moreover, the $\sigma_c$ and the $\sigma_t$, the PLS and the $R_n$ were the governing rock properties that effects the percussive drills penetration rate.

Yarali and Soyer [27] also examined the relationships between DRI and some mechanical properties of rocks in order to calculate the effect of strength and index properties of rocks on the drillability. DRI correlated very well with the $\sigma_c$, PLS, $R_n$ and Schmidt rebound hardness (SRH) with the exception of $\sigma_t$ which poorly correlated with DRI.

The drillability data of Pakistani rocks and its relationship with different rock properties is not documented as yet. Therefore, it was considered essential to establish a database of drillability rates along with the physical and mechanical properties of rocks in Pakistan. This data will be extremely beneficial for the on-going and proposed mega projects like dams, highways, tunnels and foundations for large structures in the country. The present study is also a part of a graduate level research conducted at the Geological Engineering Department, University of Engineering and Technology (UET), Lahore required for the completion of the M.Sc. degree of the principal author of the paper having registration # 2010-MS-GE-01.

## 2. Experimental Setup

### 2.1 Rock Samples

Fifteen rock samples including sedimentary, igneous and metamorphic rocks were collected from natural outcrops and formation contacts from different areas of Pakistan. Table 1 shows the names of the tested rock types alongwith their respective locations. Block samples were collected in order to have test samples free of macroscopic defects, fractures, partings or alteration zones.

Table 1: Names and formations of the rock samples used

| No. | Rock | Formation | Locality |
|---|---|---|---|
| 1 | Sandstone 1 | Warcha | Khewra Gorge, Salt Range, Punjab |
| 2 | Sandstone 2 | Kussak | Khewra Gorge, Salt Range, Punjab |
| 3 | Sandstone 3 | Khewra | Khewra Gorge, Salt Range, Punjab |
| 4 | Sandstone 4 | Murree | NJHPP* Muzaffarabad, Azad Kashmir, Pakistan |
| 5 | Siltstone | Murree | NJHPP Muzaffarabad, Azad Kashmir, Pakistan |
| 6 | Sandy Dolomite | Jutana | Khewra Gorge, Salt Range, Punjab |
| 7 | Dolomite (Pinkish) | Abbottabad | Mannu Di Bunn, Abbottabad Heights, Abbottabad, Khyber Pakhtunkhwa |
| 8 | Slate | Hazara | Mannu Di Bunn, Abbottabad Heights, Abbottabad, Khyber Pakhtunkhwa |
| 9 | Quartzite | Abbottabad | Mannu Di Bunn, Abbottabad Heights, Abbottabad, Khyber Pakhtunkhwa |
| 10 | Phyllite | Abbottabad | Mannu Di Bunn, Abbottabad Heights, Abbottabad, Khyber Pakhtunkhwa |
| 11 | Granitic Gneiss | Sharda | Neelum Valley, Azad Kashmir, Pakistan |
| 12 | Dolerite | Hadda | Sillanwali Sargodha, Punjab |
| 13 | Granite 1(Talcher Boulder) | Salt range | Khewra Gorge, Salt Range, Punjab |
| 14 | Granite 2 | Mansehra | Mansehra, Khyber Pakhtunkhwa |
| 15 | Andesite | Sharda | Neelum Valley, Azad Kashmir, Pakistan |

*NJHPP :-Neelum Jehlum Hydropower Project

### 2.2 Test Equipment for Rock's Drillability Determination

The drillability of rocks was determined by using the locally fabricated test equipment, made as per specifications of NTNU/SINTEF previously known as the NTH test developed at NTNU during 1958-1961. The Drilling Rate Index (DRI) is calculated by using two laboratory tests, the Brittleness Value ($S_{20}$) test [28] and the Sievers' J-Value (SJ) miniature drill test [23, 27-30].

#### 2.2.1 The Brittleness Test

The brittleness value ($S_{20}$) test gives a measure for the ability of the rock to resist crushing by repeated impacts. The sample volume used in the test corresponds to 500g of density 2.65 g/cm$^3$ from the fraction 16-11.2 mm. The

$S_{20}$ value is equal to the percentage passing the 11.2 mm mesh after the aggregate has been crushed by 20 impacts of a 14 kg hammer in the mortar. The $S_{20}$ value is the average value of 3-5 parallel tests as mentioned by [30]. The original schematic of the test apparatus to determine the $S_{20}$ is given in [23, 27, 30]. The locally fabricated test apparatus for $S_{20}$ test is available in UET, Lahore.

### *2.2.2 The Siever's J Miniature Drill Test*

The SJ value is the arithmetic mean of the measured drill hole depth in 1/10$^{th}$ mm of 4-8 drill holes after 200 revolutions of the 8.5 mm miniature drill bit. The usual procedure is to use the pre-cut surface of the sample cut perpendicular to the foliations of rock. The SJ value is measured along the foliations. A summary of the SJ test is given in [23, 27, 30].Locally manufactured test setup for SJ test is available in UET, Lahore.

### *2.2.3 Assessment of DRI*

The outcomes of the $S_{20}$ and SJ tests are used to assess the DRI graph mentioned in [23, 27, 30]. The classification of DRI as per [27, 30, 32] is given in Table 2.

Table 2: Classification categories of DRI adopted from [27, 30, 32]

| Category | DRI |
|---|---|
| Extremely low | $\leq$ 25 |
| Very low | 26—32 |
| Low | 33—42 |
| Medium | 43—57 |
| High | 58—69 |
| Very High | 70—82 |
| Extremely High | $\geq$ 83 |

### *2.3 Determination of Physical and Mechanical properties*

### *2.3.1 Density and Porosity*

Diamond saw cut core samples were used for the determination of bulk ($\rho_b$), dry ($\rho_d$), wet($\rho_{sat}$) densities and porosity (n). The density and porosity values were calculated using saturation and buoyancy technique as per ISRM [31] suggested methods.

#### *2.3.1.1 P-wave velocity determination by (PUNDIT)*

$V_p$ of trimmed cores were found by using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) as per ISRM [31] suggested methods. For each rock type, the tests were conducted for five times and the averageof all five readings was taken as a final value.

#### *2.3.1.2 Uniaxial compressive strength ($\sigma_c$)*

Core samples for $\sigma_c$ tests were prepared to satisfy the requirements of ASTM D4543 having length to diameter ratio of 2.0 - 2.5. The $\sigma_c$ tests were performed in accordance with the method suggested by ASTM D7012-10.

#### *2.3.1.3 Brazilian tensile strength ($\sigma_t$)*

The samples for $\sigma_t$ tests were prepared in accordance with the requirements of ASTM D4543. The $\sigma_t$ tests were performed in conformance with ASTM D3967-08.

#### *2.3.1.4 Schmidt rebound hardness ($R_n$)*

Rn measurements were made on block samples using an L-type Schmidt hammer manufactured by ELE, England, with a impact energy of 0.74 Nm. All the measurements were performed in accordance with ASTM D-5873.

## 3. Evaluation of Test Results

The drilling rate index (DRI) values, mean and standard deviation of SJ and $S_{20}$ used to calculate DRI, alongwith the drillability classifications of all the tested rock units are given in Table 3. It can be noted that the DRI values of all the tested sedimentary rocks lie between the ranges of medium to extremely high. For metamorphic rocks the measured DRI values fall in the range of medium to high; whereas for the tested igneous rocks the DRI values were found between low to extremely low. Table 4 gives the values of the tested physical and strength properties of the rocks.

The DRI values of the tested rock samples were plotted against the measured physical properties of the rocks, with standard deviations of individual parameters by adding error bars to each of the data points in horizontal direction, to check for the existence of any meaningful correlation. The longer error bars show high variability and hence higher standard deviations of individual data points, whereas shorter error bars show low variability of the data point about the mean value. It is evident from Figure 1 that DRI values correspondents exponentially with $\sigma_c$ and Figure 2 shows DRI logarithmically corresponds to $\sigma_t$ with. From Figure (3-8), DRI values are corresponding in a linear manner with the $R_n$, $\rho_b$, $\rho_d$, $\rho_{sat}$, n, and $V_p$. From Figure 1, it can be seen that a reasonably good correlation exists between the DRI and the $\sigma_c$ values. The relationships between DRI and $\sigma_t$ and DRI and $R_n$ are although linear but their $R^2$ values are not very high (Figure 2 and Figure 3). Similar relationships between DRI and $\sigma_c$, $\sigma_t$ and $R_n$ have been noted elsewhere [27, 32].

A moderate correlation between DRI values and the dry density values can also be seen in Figures(4-6).The increase in DRI values with the corresponding increase in the porosity values (Figure 7) shows the ease with which the porous rocks can be drilled. Although the $R^2$ value of the relationship is not very high but still a general trend explains that a high DRI can be expected with the increasing porosity of the rocks. This shows that denser rocks are more difficult to bore through as compared to

Table 3: DRI values and their respective categories as per [30]

| No. | Rock Type | SJ | $S_{20}$ | DRI | Class |
|---|---|---|---|---|---|
| 1 | Sandstone 1 | 104 ± 2 | 43 ± 4 | 55 | Medium |
| 2 | Sandtone 2 | 104 ± 9 | 49 ± 4 | 62 | High |
| 3 | Sandstone 3 | 111 ± 1 | 78 ± 5 | 93 | Extremely High |
| 4 | Sandstone 4 | 73 ± 3 | 42 ± 8 | 51 | Medium |
| 5 | Siltstone | 121 ± 6 | 52 ± 3 | 68 | High |
| 6 | Sandy Dolomite | 47 ± 3 | 51 ± 4 | 58 | High |
| 7 | Dolomite (Pinkish) | 27 ± 2 | 56 ± 2 | 61 | High |
| 8 | Slate | 1.34 ± 0.10 | 57 ± 5 | 45 | Medium |
| 9 | Quartzite | 1.28 ± 0.17 | 54 ± 3 | 45 | Medium |
| 10 | Phyllite | 115 ± 3 | 46 ± 4 | 64 | High |
| 11 | Granitic Gneiss | 58 ± 6 | 60 ± 6 | 68 | High |
| 12 | Dolerite | 1.47 ± 1.92 | 40 ± 9 | 30 | Extremely Low |
| 13 | Granite 1 | 3.70 ± 0.86 | 43 ± 4 | 37 | Low |
| 14 | Granite 2 | 3.43 ± 0.21 | 24 ± 1 | 18 | Extremely Low |
| 15 | Andesite | 2.40 ± 0.25 | 30 ± 2 | 22 | Extremely Low |

Table 4: Test results of physical and mechanical properties

| No. | Rock Type | Density (g/cm$^3$) | | | Porosity (n) (%) | $V_p$ (Km/s) | SRH | BTS (MPa) | UCS (MPa) |
|---|---|---|---|---|---|---|---|---|---|
| | | $\rho_b$ | $\rho_d$ | $\rho_{sat}$ | | | | | |
| 1 | Sandstone 1 | 2.52 ± 0.01 | 2.51 ± 0.02 | 2.57 ± 0.02 | 6.22 ± 0.28 | 5.29 ± 0.65 | 38 ± 1 | 6.73 ± 1.51 | 138 ± 22 |
| 2 | Sandtone 2 | 2.53 ± 0.07 | 2.48 ± 0.06 | 2.55 ± 0.05 | 7.18 ± 1.02 | 4.26 ± 0.32 | 45 ± 2 | 6.14 ± 0.94 | 84 ± 49 |
| 3 | Sandstone 3 | 2.24 ± 0.01 | 2.19 ± 0.01 | 2.30 ± 0.01 | 11.62 ± 0.36 | 2.30 ± 0.05 | 30 ± 3 | 0.49 ± 0.28 | 50 ± 5 |
| 4 | Sandstone 4 | 2.62 ± 0.01 | 2.62 ± 0.01 | 2.63 ± 0.01 | 1.21 ± 0.40 | 5.88 ± 0.13 | 36 ± 2 | 6.90 ± 3.24 | 133 ± 12 |
| 5 | Siltstone | 2.71 ± 0.01 | 2.70 ± 0.02 | 2.73 ± 0.02 | 1.05 ± 0.19 | 5.33 ± 0.21 | 50 ± 3 | 7.59 ± 3.87 | 60 ± 5 |
| 6 | Sandy Dolomite | 2.78 ± 0.01 | 2.76 ± 0.05 | 2.78 ± 0.05 | 1.27 ± 0.24 | 5.97 ± 0.11 | 43 ± 1 | 11.81 ± 3.24 | 131 ± 24 |
| 7 | Dolomite (Pinkish) | 2.82 ± 0.01 | 2.82 ± 0.01 | 2.82 ± 0.01 | 0.37 ± 0.10 | 4.63 ± 0.43 | 33 ± 5 | 12.65 ± 5.28 | 111 ± 52 |
| 8 | Slate | 2.46 ± 0.02 | 2.65 ± 0.01 | 2.66 ± 0.02 | 1.21 ± 0.63 | 3.70 ± 0.38 | 50 ± 2 | 22.68 ± 2.94 | 126 ± 49 |
| 9 | Quartzite | 2.46 ± 0.01 | 2.82 ± 0.02 | 2.82 ± 0.01 | 0.37 ± 0.71 | 3.15 ± 0.31 | 45 ± 3 | 4.86 ± 2.53 | 56 ± 9 |
| 10 | Phyllite | 2.55 ± 0.01 | 2.54 ± 0.13 | 2.61 ± 0.12 | 7.59 ± 1.20 | 2.02 ± 0.69 | 29 ± 3 | 4.77 ± 2.02 | 54 ± 30 |
| 11 | Granitic Gneiss | 2.58 ± 0.01 | 2.58 ± 0.01 | 2.60 ± 0.01 | 1.07 ± 0.08 | 1.76 ± 0.02 | 33 ± 3 | 2.76 ± 1.16 | 60 ± 9 |
| 12 | Dolerite | 3.06 ± 0.02 | 3.06 ± 0.04 | 3.06 ± 0.04 | 0.13 ± 0.05 | 7.26 ± 0.49 | 55 ± 2 | 12.81 ± 3.03 | 224 ± 78 |
| 13 | Granite 1 | 2.55 ± 0.01 | 2.54 ± 0.01 | 2.55 ± 0.01 | 1.46 ± 0.17 | 3.81 ± 0.61 | 36 ± 3 | 3.57 ± 1.25 | 75 ± 43 |
| 14 | Granite 2 | 3.07 ± 0.01 | 3.06 ± 0.03 | 3.07 ± 0.03 | 0.52 ± 0.03 | 6.32 ± 0.11 | 35 ± 1 | 17.99 ± 3.53 | 232 ± 32 |
| 15 | Andesite | 2.83 ± 0.07 | 2.83 ± 0.15 | 2.83 ± 0.15 | 0.38 ± 0.04 | 6.16 ± 0.53 | 49 ± 1 | 14.40 ± 0.97 | 241 ± 25 |

$\rho_b$: Bulk density, $\rho_d$: Dry density, $\rho_{sat}$: Wet density, n : Porosity, $V_p$: Velocity of primary waves, $R_n$: Schmidt rebound hardness, $\sigma_t$: Brazilian tensile strength, $\sigma_c$: uniaxial compressive strength.

less denser and more porous rocks. A similar relationship can be observed between DRI and $V_p$ (Figure 8). The increase in the primary wave velocities are very much dependent upon the increase in the density and decrease in the porosity and have been shown in the past several investigations.

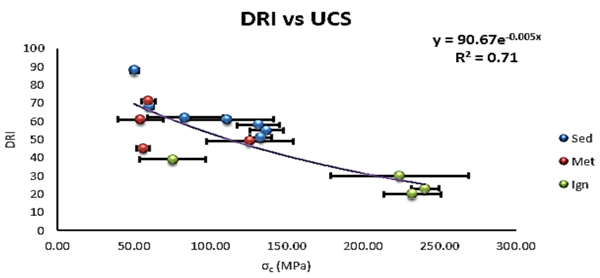


Fig. 1: DRI of tested rock types correlated with $\sigma_c$

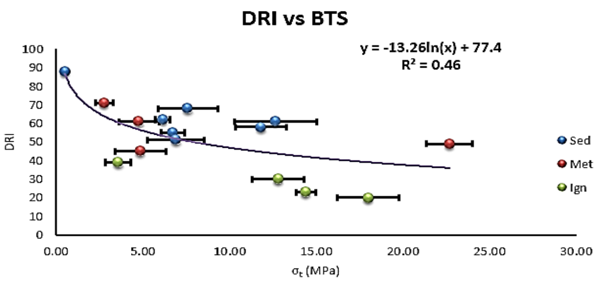


Fig. 2: DRI of different rock types correlated with $\sigma_t$

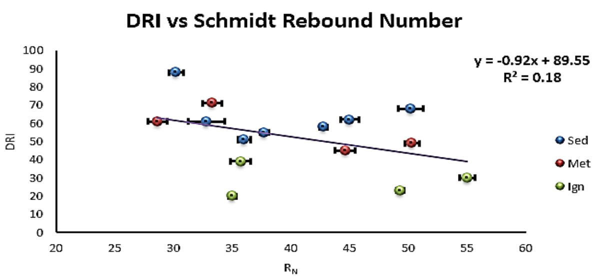


Fig. 3: DRI of tested rock types correlated with $R_n$

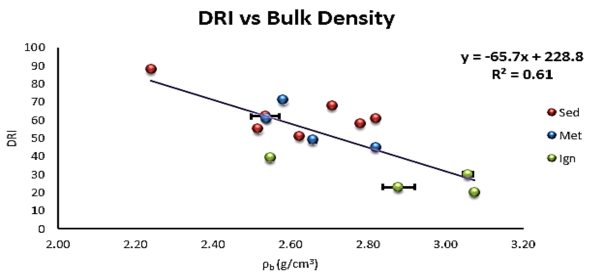


Fig. 4: DRI of tested rock types correlated with bulk density ($\rho_b$)

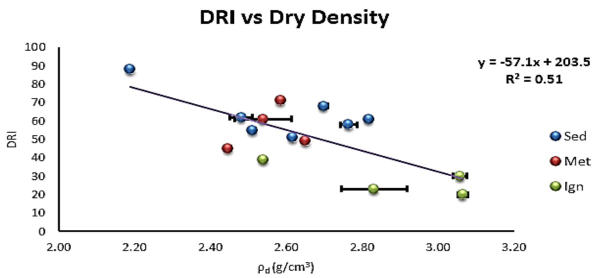


Fig. 5: DRI of tested rock types correlated with $\rho_d$

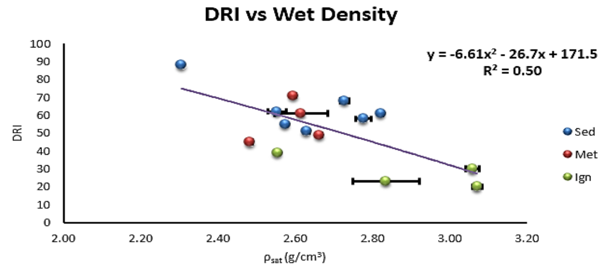


Fig. 6: DRI of tested rock types correlated with $\rho_{sat}$

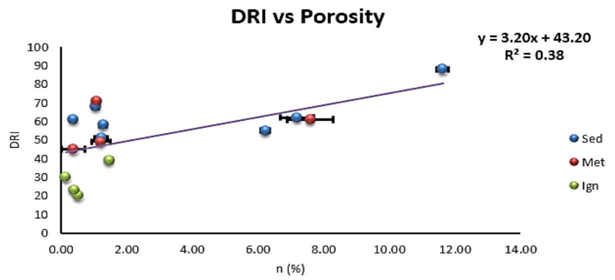


Fig. 7: DRI of tested rock types correlated with n

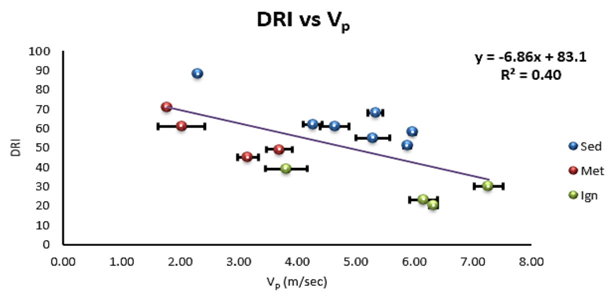


Fig. 8: DRI of tested rock types correlated with $V_p$

Further study is required to validate the derived equation for other rock types as well.In addition, the effect of porosity and $\sigma_c$on drilling rate index needs to be investigated, which is a part of upcoming research of the authors.

## 4. Conclusions

The relations between the drilling rate index (DRI) and various properties of selected Pakistani rocks were evaluated by using simple regression technique on Microsoft EXCEL. DRI values were correlated with the tested physical and strength properties of rocks and equations of best fit line and corresponding values of coefficient of correlation ($R^2$) were determined for each relationship. Reasonably moderate correlations were found between the $\sigma_c$ and densities ($\rho_b$, $\rho_d$, $\rho_{sat}$) and of rocks, whereas $\sigma_t$, $V_p$ and $R_n$ showed poor correlations with the DRI values. The trends obtained in this study are in line with the several previous investigations conducted in this regard. It is important to mention here that the statistical relationships could be improved further if more rock types are added to the database, which is currently in progress.

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