Journal of African Earth Sciences 141 (2018) 1–8

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

# A sampling study on rock properties affecting drilling rate index (DRI)

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ARTICLE INFO

*Article history:*
Available online 1 February 2018

*Keywords:*
Drilling rate index
Rock properties
Simple regression
Multiple regression
Statistical analysis

ABSTRACT

Drilling rate index (DRI) developed in Norway is a very useful index in determining the drillability of rocks and even in performance prediction of hard rock TBMs and it requires special laboratory test equipment. Drillability is one of the most important subjects in rock excavation. However, determining drillability index from physical and mechanical properties of rocks is very important for practicing engineers such as underground excavation, drilling operations in open pit mining, underground mining and natural stone production. That is why many researchers have studied concerned with drillability to find the correlations between drilling rate index (DRI) and penetration rate, influence of geological properties on drillability prediction in tunneling, correlations between rock properties and drillability. In this study, the relationships between drilling rate index (DRI) and some physico-mechanical properties (Density, Shore hardness, uniaxial compressive strength (UCS, $\sigma_c$), Indirect tensile strength (ITS, $\sigma_t$)) of three different rock groups including magmatic, sedimentary and metamorphic were evaluated using both simple and multiple regression analysis. This study reveals the effects of rock properties on DRI according to different types of rocks. In simple regression, quite high correlations were found between DRI and uniaxial compressive strength (UCS) and also between DRI and indirect tensile strength (ITS) values. Multiple regression analyses revealed even higher correlations when compared to simple regression. Especially, UCS, ITS, Shore hardness (SH) and the interactions between them were found to be very effective on DRI values.

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## 1. Introduction

Selecting machinery and equipment without examining the physical, mechanical and chemical properties of the rock may cause dramatic problems during working. Therefore, in drilling and blasting excavation, it is very important to find the rock properties before starting operation. Drillability can be defined as drilling a rock in a certain time by a drilling bit. In other words, it is the ease of drilling a rock mass. Drilling speed is measured as the length of advance of excavation equipment within the rock mass in a time unit. Drilling rate index and drilling speed can be assumed to originate from the same concept. Drilling rate index is defined as low or high and drilling speed is defined as fast or slow.

Drillability of rock affected by many different factors such as drilling machine parameters and geotechnical characteristics of rock mass. The machine parameters depend on the drilling method and technical properties of the drilling bit used. Geotechnical parameters influence the drilling performance and the wear of the bit. Condition and structure of rock mass, mechanical behavior and mineral composition of rock material are the main characteristics that affecting the drillability. Therefore, for evaluating each rock from the point of view its penetrability, the effects of the most important parameters should be considered. It is very important to know the qualitative and quantitative effect of each parameter on drilling (Hoseinie et al., 2008). Recognition of rock properties would be of great help in choosing the appropriate type of drilling system and prediction of drilling rate. As unconfined compressive strength (UCS), elasticity modulus and tensile strength are the most used rock properties, the ratio of unconfined compressive strength to tensile strength defined as brittleness of a rock material and rock modulus defined as the ratio of elastic modulus to unconfined compressive strength are also used to predict penetration rate (Selmer-Olsen and Blindheim, 1970; Thuro, 1996; Kahraman, 1999, 2003; Altındağ, 2002; Dahl, 2003; Plinninger, 2008; Karaman, 2008; Yaralı and Soyer, 2011, 2013; Dahl et al., 2012; Ceryan, 2014; Yaralı, 2016; Rostami and Chang, 2017; Capik et al., 2017). Many empirical tests have also been proposed to predict the drilling performance such as Point Load Strength, Schmidt Rebound

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https://doi.org/10.1016/j.jafrearsci.2018.01.015
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Hardness, Shore Scleroscope Hardness, Cone Indenter Number, Drilling Rate Index (DRI), Coefficient of Rock Strength (CRS), Impact Strength Index (ISI), Cerchar Abrasiveness Index (CAI), Specific Energy (SE).

## 2. Aim of the study

As can be seen in the literature survey, many of the researchers worked about drilling process, drilling classification, drillability prediction, drilling rate, penetration rate, correlating between the rock and machine properties and drillability. Also, they predicted bit life according to the drillability and rock properties. The aim of this study is to reveal the change in drilling rate index (DRI) according to rock types and rock mechanical and physical properties. The factors affecting drilling rate index are given on Fig. 1. Since the number of factors affecting DRI is too many, more interest is given to rock mechanical and physical properties in this study. Influential factors are examined using linear and multiple regression. $R^2$ values are found to be more than 80% in many of the analysis (Minitab, 2000). Therefore, these equations will provide important sights to field engineers and researchers.

## 3. Experimental studies

### 3.1. Physico-mechanical properties

Rock samples collected from different locations were classified according to geological origins and laboratory tests were carried out on total 26 different rock type consist of nine magmatic, 11 metamorphic and 6 sedimentary. Tests are carried out according to the ISRM 1981. The names and regions of rock samples collected from various regions are listed in Table 1.

Physical and mechanical properties of rock samples were determined according to methods suggested by ISRM 1981. In order to determine the Drilling Rate Index (DRI) of the samples, Brittleness test ($S_{20}$) and Miniature drilling test (Sievers' J) were also carried out on each rock samples according to methods suggested by SINTEF (Bruland, 1998).

### 3.2. Determination of drilling rate index (DRI)

Drilling rate index (DRI) is a measure of hardness or ease of rock drillability. DRI is determined according to suggested method developed at the Engineering Geology Laboratory of the Norwegian Institute of Technology (NTNU) of the University of Trondheim. The DRI is based on the results of two different laboratory tests; the Brittleness test ($S_{20}$) and the Sievers' J-miniature drill test (Yarali and Kahraman, 2011). The principles and pictures of these tests are shown in Fig. 2. In Fig. 2, "a" refers to brittleness test, "b" refers to miniature drilling test and finally "c" refers to the drilling rate index chart (Dahl, 2003).

The DRI value is a combination of two parameters mentioned above: brittleness value ($S_{20}$), and the Sievers'J value (SJ Value). The SJ miniature drill test developed by H. Sievers in the 1950s is an indirect measure of surface hardness of the rock (Dahl, 2003). This test was carried out according to the method suggested by SINTEF (NTNU, 1998). The SJ value was obtained from a miniature drill test (Fig. 2b) as the hole in the rock sample measured after 200 revolutions in 1/10 mm. The test was repeated four to eight times for each rock samples. SJ value was calculated as the mean value of the test holes.

The brittleness value, $S_{20}$, is an indirect measure of rock resistance to crack growth and crushing by repeated impacts. This test was developed by N. von Matern and A. Hjelmer in 1943 (Dahl, 2003).

This test was performed on three equal extractions from the 11.2–16.0 mm fraction. The aggregate volume of the rock sample

**Table 1**
Rock samples used in tests.

| Sample Name | Sample Code | Origin of Sample | Region |
|---|---|---|---|
| Basalt 1 | GB | Magmatic | Gumushane/Turkey |
| Basalt 2 | FB | Magmatic | Izmir/Turkey |
| Granite 1 | KG I | Magmatic | Izmir/Turkey |
| Granite 2 | KG II | Magmatic | Izmir/Turkey |
| Granite 3 | GG | Magmatic | Giresun/Turkey |
| Granite 4 | BG | Magmatic | Italy |
| Granite 5 | SG | Magmatic | Aksaray/Turkey |
| Granite 6 | BPG | Magmatic | Norway |
| Granite 7 | RPG | Magmatic | Spain |
| Marble 1 | BB | Metamorphic | Izmir//Turkey |
| Marble 2 | AW | Metamorphic | Afyon/Turkey |
| Marble 3 | KW | Metamorphic | Aydın/Turkey |
| Marble 4 | YW | Metamorphic | Mugla/Turkey |
| Marble 5 | ES | Metamorphic | Mugla/Turkey |
| Marble 6 | FBE | Metamorphic | Mugla/Turkey |
| Marble 7 | FBR | Metamorphic | Mugla/Turkey |
| Marble 8 | FR | Metamorphic | Mugla/Turkey |
| Marble 9 | G | Metamorphic | Afyon/Turkey |
| Marble 10 | B | Metamorphic | Burdur/Turkey |
| Marble 11 | K | Metamorphic | Mugla/Turkey |
| Limestone 1 | L1 | Sedimentary | Izmir/Turkey |
| Limestone 2 | L2 | Sedimentary | Manisa/Turkey |
| Limestone 3 | L3 | Sedimentary | Antalya/Turkey |
| Limestone 4 | L4 | Sedimentary | Denizli/Turkey |
| Limestone 5 | L5 | Sedimentary | Denizli/Turkey |
| Limestone 6 | L6 | Sedimentary | Denizli/Turkey |

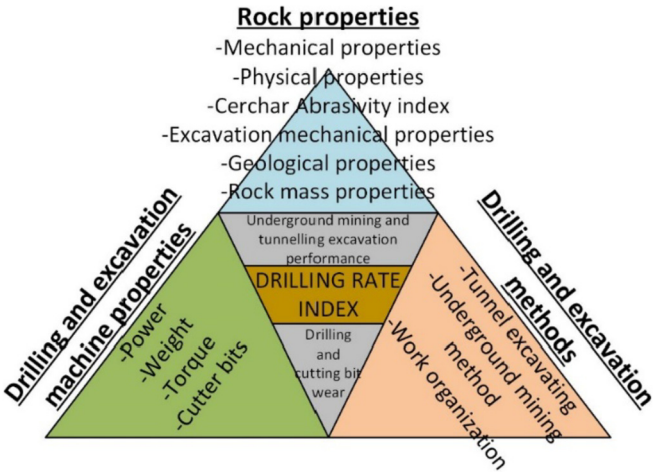



**Fig. 1.** Main factors affecting drilling rate index.

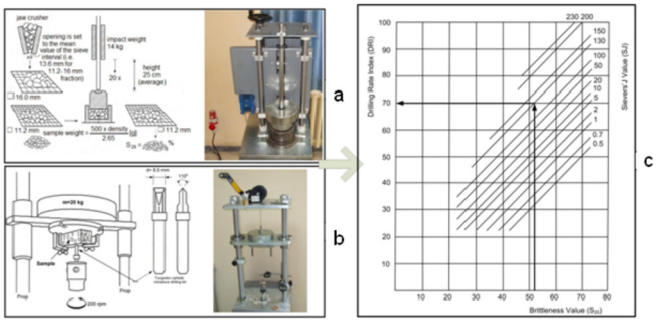



**Fig. 2.** Determination stages of DRI (Dahl, 2003).

corresponds to that of a 500 g aggregate with a density of 2.65 g/cm$^3$ in the fraction 11.2–16.0 mm. The brittleness value is equal to percentage of undersized material that passes through a 11.2 mm mesh after 20 drops of 14 kg hammer. The brittleness value was presented as a mean value of 3 or 4 parallel test (Bruland, 1998). All test results for different rock groups are given in Tables 2–4.

## 4. Regression analysis

In regression analysis of many engineering problems, a correlation is sought between variables. Understanding the correlation can help the problem owner handle it more effectively, as explained by Hines and Montgomery (1990). Regression analysis is a statistical technique for modelling the relationship between independent (regressor) variables of the problem and the dependent (response) variable(s). Linear regression methods are appropriate when the relationship between the response variables and regressor variables can be built linearly. Polynomial regression is one of the methods applied when the relationship between the response and regressor variable is curvi-linear. Simple and multiple linear regression methods were used to analyze the data set. Second degree polynomial regression models with one variable and two variables are given in Equations (1) and (2), respectively.

$$y = \beta_0 + \beta_1 x + \beta_{11} x^2 + \ldots + \varepsilon \quad (1)$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1 + \beta_{22} x_2 + \beta_{12} x_1 x_2 + \ldots + \varepsilon \quad (2)$$

The fitted model "ŷ" is determined by computing estimates of all the parameters using the least squares method. Once the model has been determined, the accuracy with which the model describes the relationship between the regressor and response variables is given by the coefficient of determination, $R^2$. This is a measure which indicates the amount of variability in the data explained by the regression model. It is the ratio of regression sums of squares to the total sums of squares, hence, $0 \leq R^2 \leq 1$.

### 4.1. Evaluation of magmatic rocks test results

#### 4.1.1. Simple regression analysis for magmatic rocks

DRI was selected to be the response variable. Simple regression analyses were made between DRI and density, unit volume weight, porosity and shore hardness properties, respectively. The best relation between DRI and density was revealed with an $R^2$ value 0.42 (Equation (3)). It is seen that as density of the rock increases (Fig. 3), DRI value decreases and the rock becomes harder to drill.

$$DRI = -140.19\rho + 429.87 \quad R^2 = 0.42 \quad (3)$$

Then, the correlation between DRI and unit volume weight ($\gamma$) values were examined, but in this study, the correlation between DRI and density values were found as "weak".

Later on, the relation between DRI and the mechanical properties of the rocks were examined by simple regression. A strong polynomial relation was found between DRI and $\sigma_c$ values as seen in Fig. 4 and Equation (4). It is harder to drill rocks with high $\sigma_c$ values and hence more energy and diamond bits are required. In addition, the results are demonstrated with a 95% confidence interval as given in Fig. 4. It should be noted that only one of the samples is outside the interval in this plot.

$$DRI = 98.12 - 0.29\sigma_c \quad R^2 = 0.57 \quad (4)$$

$$DRI = -89.96 + 2.33\sigma_c - 0.009\sigma_c \quad R^2 = 0.93 \quad (5)$$

Similar to DRI and UCS ($\sigma_c$), a polynomial relation was also found between DRI and $\sigma_t$ values, as seen in Equation (5). The $R^2$ value between DRI and UCS values was found as 0.93. UCS often varies very large ranges for rocks. Therefore, polynomial relation is more compatible with UCS and DRI. Similarly, exponential relation is more compatible than linear regression between ITS ($\sigma_t$) and DRI for magmatic rocks (Equation (6)). A linear regression cannot be found between ITS and DRI.

$$DRI = -2.31\sigma_t + 46.14\sigma_t - 162.78 \quad R^2 = 0.72 \quad (6)$$

#### 4.1.2. Multiple regression analysis for magmatic rocks

The multiple regression analysis were also made on the physical and mechanical properties of magmatic rocks. As stated before, the response variable is DRI. Firstly, two dependent variables were selected and then three and four dependent variables were selected in multiple regression. The first analysis was carried out between DRI versus $\sigma_c$ and $\rho$. The relation found between DRI versus *UCS* and density ($\rho$) can be seen in Fig. 5. As *UCS* and $\rho$ values increase, DRI values decrease.

$$DRI = 340 - 0.23\sigma_c - 94\rho \quad R^2 = 0.74 \quad (7)$$

As seen in Equation (7), the $R^2$ value turned out to be 0.74. It should be noted that the relation between DRI versus UCS ($\sigma_c$) and density ($\rho$) is stronger than the simple regression relation between DRI and density and weaker than the relation between DRI and $\sigma_c$. This situation shows us that the interaction between UCS ($\sigma_c$) and density ($\rho$) is also effective on DRI. In the next step, shore hardness was also added into the analysis. In this case, the $R^2$ value turned out to be 0.61. The relation is stronger compared to simple regression between DRI and SH alone. However it decreased a little bit compared to Equation (7). The next regression analysis was carried out between DRI versus ITS ($\sigma_t$) and density ($\rho$). However, it can be stated that the relation between these variables is poor.

**Table 2**
Physical and mechanical properties of Magmatic rocks tested.

| Sample Codes | Density$\rho$ (g/cm$^3$) | Unit Weight $\gamma$ (kN/m$^3$) | Porosity n (%) | Shore hardness (SH) | UCS $\sigma_c$ (MPa) | Indirect Tensile Strength $\sigma_t$ (MPa) | Brittleness Value $S_{20}$ | Sievers' J Value SJ (1/10 mm) | DRI |
|---|---|---|---|---|---|---|---|---|---|
| GB | 2.71 | 24.92 | 5.56 | 58 ± 2.81 | 99.19 | 7.42 | 43.86 | 85.7 | 54 |
| KG I | 2.65 | 25.70 | 0.92 | 87 ± 3.72 | 177.80 | 7.66 | 50.32 | 7.20 | 48 |
| FB | 2.74 | 26.39 | 0.18 | 98 ± 2.64 | 206.40 | 13.82 | 30.02 | 3.80 | 25 |
| KG II | 2.70 | 26.19 | 1.10 | 90 ± 2.69 | 112.00 | 10.50 | 55.87 | 10.8 | 57 |
| GG | 2.68 | 25.90 | 0.71 | 97 ± 2.72 | 131.50 | 11.20 | 64.93 | 10.7 | 67 |
| BG | 2.60 | 25.70 | 0.68 | 99 ± 2.66 | 156.00 | 9.50 | 61.97 | 9.00 | 62 |
| SG | 2.64 | 25.51 | 1.43 | 75 ± 3.52 | 121.00 | 11.00 | 70.13 | 14.20 | 73 |
| BPG | 2.76 | 26.59 | 0.12 | 100 ± 3.27 | 182.00 | 13.50 | 52.16 | 3.60 | 47 |
| RPG | 2.55 | 25.70 | 0.60 | 97 ± 3.02 | 118.00 | 8.00 | 69.23 | 5.60 | 68 |

**Table 3**
Physical and mechanical properties of Metamorphic rocks tested.

| Sample Codes | Density ρ (g/cm$^3$) | Unit Weight γ (kN/m$^3$) | Porosity n (%) | Shore hardness (SH) | UCS $\sigma_c$ (MPa) | Indirect Tensile Strength $\sigma_t$ (MPa) | Brittleness Value $S_{20}$ | Sievers' J Value SJ (1/10 mm) | DRI |
|---|---|---|---|---|---|---|---|---|---|
| BB | 2.78 | 26.59 | 0.118 | 52 ± 2.14 | 52.74 | 8.69 | 44.91 | 82.6 | 55 |
| AW | 2.75 | 26.59 | 0.123 | 46 ± 3.10 | 57.66 | 6.57 | 54.38 | 85.2 | 65 |
| KW | 2.69 | 26.29 | 0.264 | 37 ± 3.14 | 23.43 | 3.61 | 82.83 | 52.3 | 89 |
| YW | 2.75 | 26.59 | 0.098 | 42 ± 2.61 | 45.67 | 5.40 | 58.44 | 52.5 | 67 |
| ES | 2.78 | 26.68 | 0.23 | 56 ± 2.48 | 110.39 | 10.06 | 46.85 | 41.0 | 54 |
| FBE | 2.72 | 26.39 | 0.37 | 59 ± 2.19 | 134.72 | 5.87 | 50.43 | 50.2 | 59 |
| FBR | 2.69 | 26.19 | 0.42 | 65 ± 1.82 | 149.87 | 6.22 | 53.64 | 55.4 | 62 |
| FR | 2.71 | 26.39 | 0.17 | 65 ± 0.86 | 169.89 | 6.75 | 51.52 | 48.1 | 60 |
| G | 2.66 | 26.49 | 0.26 | 62 ± 2.47 | 82.00 | 9.10 | 37.20 | 41.0 | 45 |
| B | 2.70 | 26.49 | 0.14 | 60 ± 3.57 | 83.20 | 11.80 | 37.86 | 41.0 | 45 |
| K | 2.66 | 26.49 | 0.25 | 61 ± 1.73 | 75.50 | 9.30 | 35.36 | 30.8 | 42 |

**Table 4**
Physical and mechanical properties of Sedimentary rocks tested.

| Sample Codes | Density ρ (g/cm$^3$) | Unit Weight γ (kN/m$^3$) | Porosity n (%) | Shore hardness (SH) | UCS $\sigma_c$ (MPa) | Indirect Tensile Strength $\sigma_t$ (MPa) | Brittleness Value $S_{20}$ | Sievers' J Value SJ (1/10 mm) | DRI |
|---|---|---|---|---|---|---|---|---|---|
| L1 | 2.72 | 26.29 | 0.69 | 61 ± 0.95 | 64.61 | 5.43 | 50.76 | 59.80 | 59 |
| L2 | 2.68 | 26.09 | 1.19 | 54 ± 0.82 | 59.25 | 4.26 | 60.05 | 80.10 | 71 |
| L3 | 2.64 | 23.35 | 8.67 | 28 ± 1.91 | 61.60 | 7.20 | 50.86 | 52.10 | 58 |
| L4 | 2.74 | 26.49 | 0.58 | 65 ± 1.48 | 69.20 | 6.95 | 41.25 | 40.50 | 47 |
| L5 | 2.76 | 26.39 | 0.60 | 69 ± 0.97 | 77.80 | 8.60 | 37.52 | 35.10 | 43 |
| L6 | 2.71 | 26.09 | 0.54 | 70 ± 1.80 | 73.40 | 7.70 | 40.11 | 42.50 | 47 |

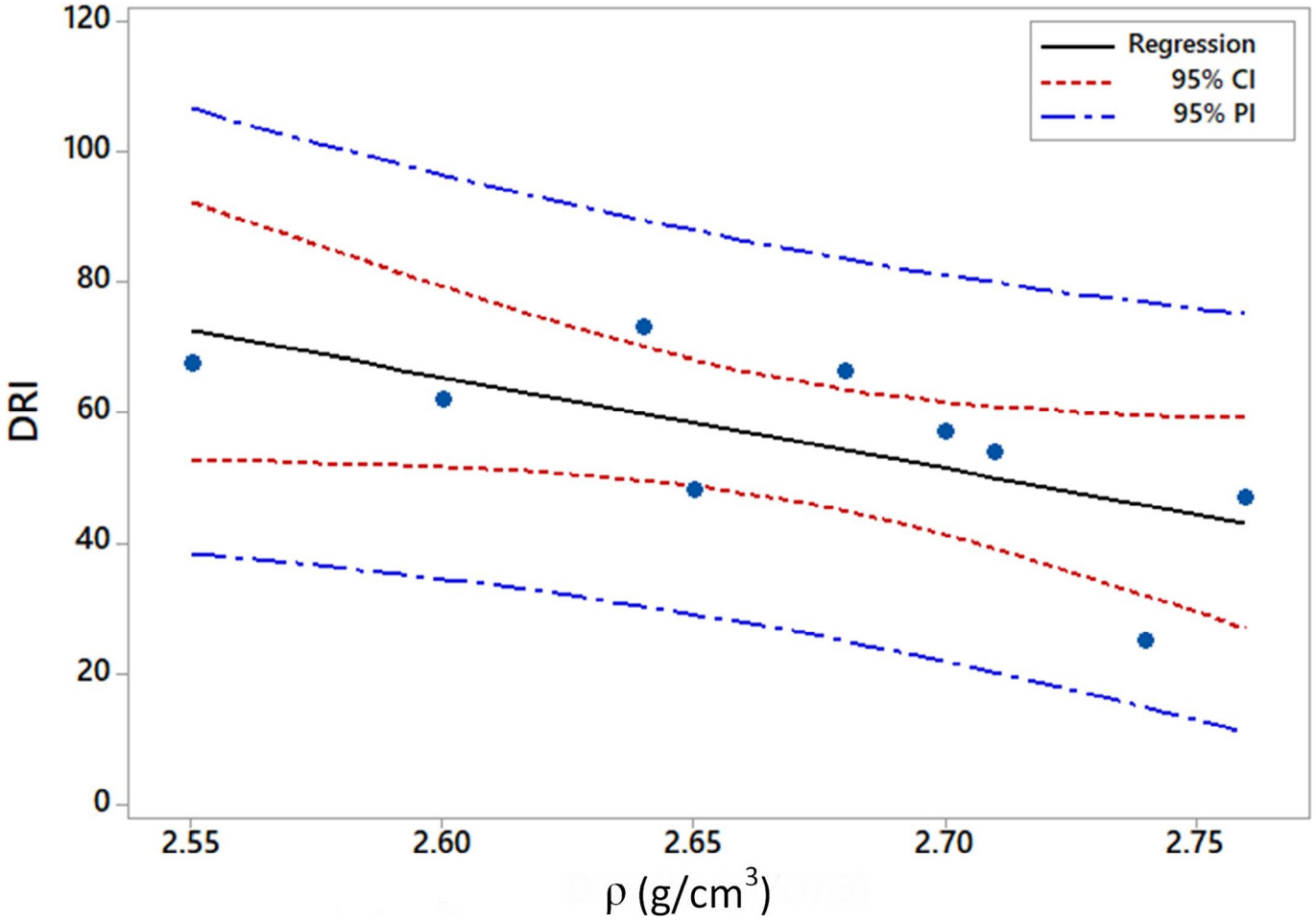



**Fig. 3.** Relationship between density and DRI for Magmatic rocks.

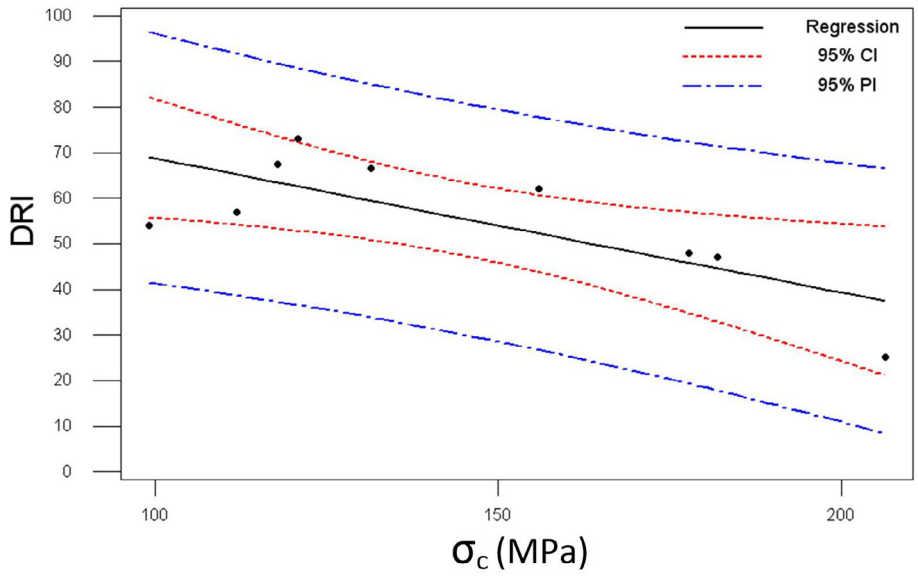



**Fig. 4.** Relationship between UCS ($\sigma_c$) and DRI for Magmatic rocks.

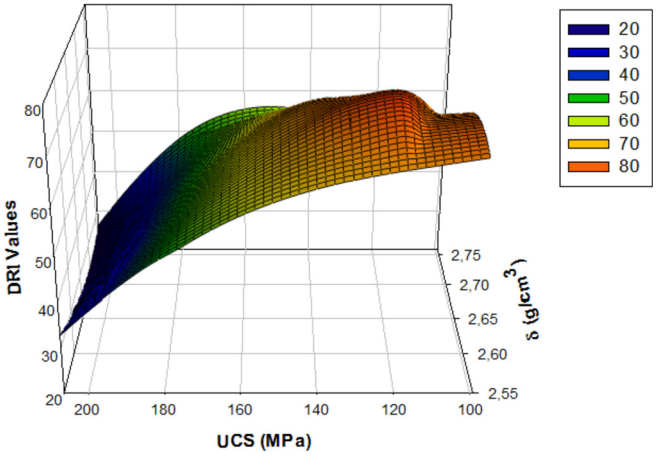



**Fig. 5.** DRI versus $\sigma_c$ and ρ values.

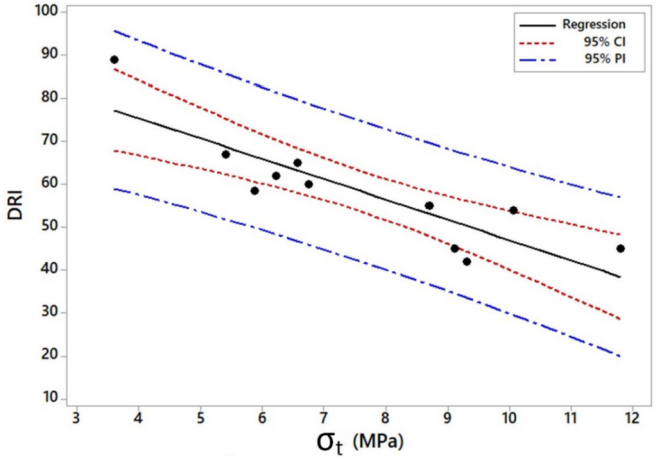



**Fig. 6.** Relationship between $\sigma_t$ (MPa) and DRI in Metamorphic rocks.

### 4.2. Evaluation of metamorphic rocks test results

#### 4.2.1. Simple regression analyses for metamorphic rocks

The response variable is again determined to be DRI. Firstly, the relation between DRI and UCS ($\sigma_c$) was examined by simple regression. The $R^2$ value was found 0.66 and all values are within the 95% confidence interval. After this, regression analysis was carried out between DRI and density (ρ) and then between DRI and unit volume weight (γ) values. However, no significant relation was revealed in these analyses.

The regression equation between DRI and ITS ($\sigma_t$) can be seen in Equation (8). In addition, in Fig. 6, it can be seen that most of the values are within 95% confidence interval.

$$DRI = 94.43 - 4.75\sigma_t \quad R^2 = 0.76 \tag{8}$$

The relation between DRI and SH is given by an adjusted $R^2$ value 0.55. The regression equation is given by Equation (9) and it can be seen in Fig. 7 that most of the values are again within the 95% confidence interval.

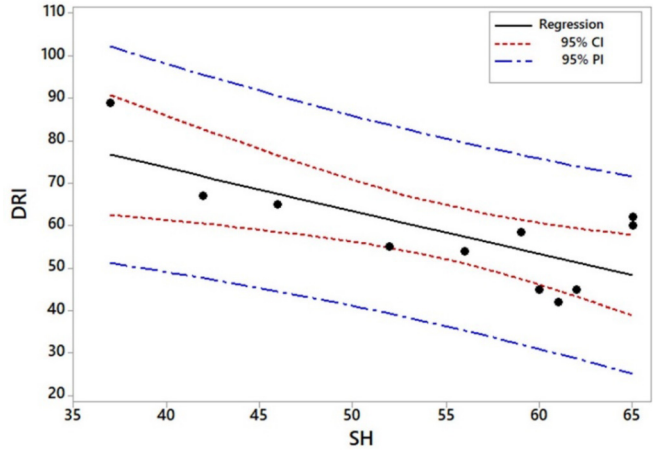



**Fig. 7.** Relationship between SH and DRI in Metamorphic rocks.

$$DRI = 114.19 - 1.01SH \quad R^2 = 0.55 \tag{9}$$

*4.2.2. Multiple regression analyses for metamorphic rocks*

After simple regression analyses on metamorphic rocks, multiple regressions were made between DRI and mechanical and physical properties of rocks. The correlations figured out on DRI can be seen in Equations (10) through (14). One of the striking results is that significant relation was revealed in the regression analysis between DRI versus UCS and density values. However, when SH is added into the analysis, the $R^2$ value turned out to be 0.89 (Equation (10)). Then in Equation (11), the relation between DRI versus $\sigma_c$ and SH can be seen which is weaker than Equation (10). Therefore it can be said that the interaction between SH and density are also effective on DRI.

In Equation (12), the relation between DRI versus UCS, SH and porosity was examined which reveals a strong relationship with an $R^2$ value 0.87. However, no significant relation was found between DRI versus UCS, density and porosity.

$$DRI = 438 + 0.30\sigma_c - 102\rho - 2.37SH \quad R^2 = 0.89 \tag{10}$$

$$DRI = 146 + 0.25\ \sigma_c - 2.01\ SH \quad R^2 = 0.81 \tag{11}$$

$$DRI = 143 + 0.21\sigma_c - 2.02SH + 34.9n \quad R^2 = 0.87 \tag{12}$$

The analyses between DRI and different combinations of indirect tensile strength, SH, UCS, porosity and density all revealed quite strong relationships which are given in Equations (13) and (14).

$$DRI = 115 - 3.33\sigma_t - 0.62SH + 10.7n \quad R^2 = 0.86 \tag{13}$$

$$DRI = 310 - 1.50\sigma_t + 0.21\sigma_c - 60.30\rho - 1.73SH \quad R^2 = 0.91 \tag{14}$$

*4.3. Evaluation of sedimentary rock test results*

Sedimentary rock samples compiled from the Aegean region of Turkey were examined. Limestone 3 is lymra stone which is defined as clayey limestone and is used for trading. All other samples of limestones are used for cement and aggregate production.

*4.3.1. Simple regression analysis for sedimentary rocks*

The first regression analysis was made between DRI and $\sigma_c$ values. The regression equation can be seen in Equation (15). The $R^2$ value is 0.83 and it can be seen from the figure that all points are within the 95% confidence interval. On the other hand, the $R^2$ value is 0.85 in linear regression between DRI and UCS ($\sigma_c$) (Equation (16)) (Fig. 8). It can be explained $\sigma_c$ values are very variable in sedimentary rocks.

$$DRI = -19.4 + 3.02\sigma_c - 0.029\ \sigma_c \quad R^2 = 0.83 \tag{15}$$

$$DRI = 145.70 - 1.35\sigma_c \quad R^2 = 0.85 \tag{16}$$

The $R^2$ value between DRI and ρ was found to be 0.61. After this analysis, regression between DRI and unit volume weight (γ) was considered but no significant relation was found between DRI and γ values.

The relation between DRI and SH was found to be linear as seen in Fig. 9 and Equation (17). The $R^2$ value between DRI and SH was found to be 0.88. The hardness of L3 sample is very different from the other samples due to geological content or incorrect sampling. Therefore, L3 is excluded from analysis. Thus, polynomial regression analysis revealed a value of 0.94 and all the points are within 95% confidence interval (Equation (18)).

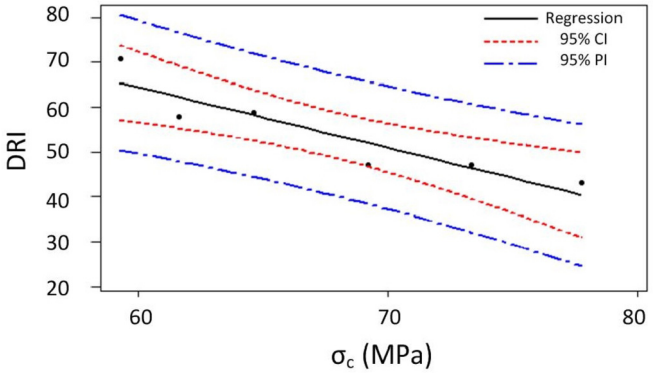



**Fig. 8.** Relationship between DRI and $\sigma_c$ in Sedimentary rocks.

$$DRI = 161.6 - 1.7\ SH \quad R^2 = 0.88 \tag{17}$$

$$DRI = 379.9 + 8.79\ SH + 0.06SH^2 \quad R^2 = 0.94 \tag{18}$$

The regression analysis between DRI and $\sigma_t$ values was made. The $R^2$ value is 0.65 for linear line and it can be noticed that as $\sigma_t$ increases, DRI decreases. In addition, the regression analysis between DRI and porosity ($n$) reveals quite a weak relationship.

*4.3.2. Multiple regression analyses for sedimentary rocks*

In Equations (19) through (20), regression analysis between DRI and different combinations of rock properties can be found. When these equations are examined, it can be seen that UCS and ITS is very effective on DRI. In addition, including other independent variables into these analysis, such as unit volume weight (γ), SH or porosity ($n$), increases the $R^2$ value even more.

$$DRI = 315 - 3.00\sigma_t - 89.60\rho \quad R^2 = 0.94 \tag{19}$$

$$DRI = 370 + 0.24\sigma_c - 4.88\sigma_t - 111\rho \quad R^2 = 0.94 \tag{20}$$

## 5. Discussion and results

In literature, relations between DRI and rock properties are studied by Thuro (1996), Altındag (2002), Yaralı and Soyer (2011), Yaralı (2016), Capik et al. (2017), Yetkin et al. (2016). In this study, detailed linear and multiple regression analysis is carried out on

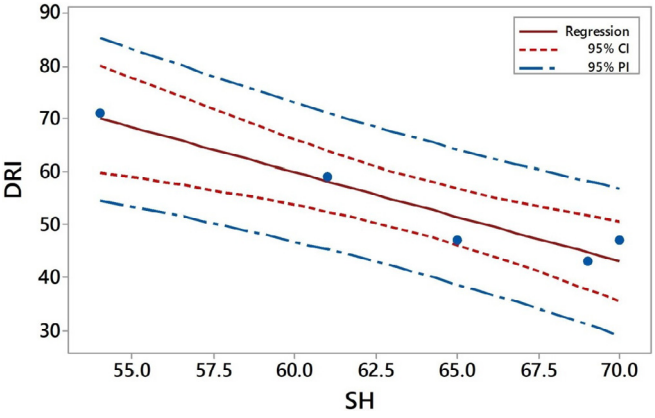



**Fig. 9.** Relationship between DRI and SH in sedimentary rocks.

rock formation origins and properties. In most of regression analysis, $R^2$ values turned out to be greater than 0.8. By this way, factors affecting DRI of sample rocks from different regions of Turkey, Norway, Spain and Italy are included to literature.

In this study, three different types of rocks were investigated: Magmatic, metamorphic and sedimentary. A number of samples were taken from each of these groups. The mechanical, physical and drilling properties of all these samples were first determined through a number of laboratory experiments. Then, by using these values, a number of regression analyses were made in order to identify the relations between the DRI and other properties of rocks.

- When Magmatic rocks are considered, the measure of linear relationship between $\sigma_c$ and DRI found to be 0.57 and the measure of exponential relationship found to be 0.93.
- In addition, multiple regression was made between $\sigma_c$, $\rho$ and DRI values. The strength of relationship turned out to be 0.74. In case these listed factors are considered alone, the relationship seems to get weaker. However, when they are considered together, it gets stronger.
- When Metamorphic rocks are considered, the linear relationship between $\sigma_t$, SH and DRI is 0.76 and 0.55, respectively. Also, as seen in Equations (10)–(14), the multiple regression values are over 0.80.
- When Sedimentary rocks are considered, the measure of linear relationship between $\sigma_c$ and DRI found to be 0.85 and the measure of exponential relationship found to be 0.83. In addition, the measure of linear relationship between SH and DRI found to be 0.88 and the measure of exponential relationship found to be 0.94. Equations (19) and (20), the multiple regression values are 0.94.

Shortly, although strength values of rocks are very variable depending on geologic structure and formation, both simple and multiple regression analyses showed that the most significant rock characteristics affecting DRI are UCS and ITS. On the other hand, density and hardness are also important criteria among physical properties.

Magmatic rocks contain high quartz since they are deeply located. The hardness values of these rocks are found to be high as usual. However, brittleness values of these rocks are found to be high. On the other hand, metamorphic and sedimentary rocks are limestone origined and their hardness values are lower compared to magmatic rocks. The DRI results are given in Fig. 10. Normally, it should be expected that magmatic rocks would have lower DRI values. However, except for a few samples, all magmatic rocks turned out to have higher DRI values than metamorphic and sedimentary rocks. This is an important point for field studies.

## 6. Conclusions

In this study, the correlations between DRI and different mechanical, physical and drillability properties of rocks were analyzed. The analyses were carried out according to three different rock types which are magmatic, metamorphic and sedimentary rocks. A number of samples were taken from each group of rocks. First, the properties of all samples were determined by laboratory experiments. Then, the correlation between these values was analyzed by simple and multiple regressions.

In simple regression, quite high correlations were found between DRI and UCS and also between DRI and ITS values. Multiple regression analyses revealed even higher correlations when compared to simple regression. Especially, UCS, ITS, SH and the interactions between them were found to be very effective on DRI values which is greater than 0.8. As a result of this study, experimental rock properties should be studied in underground mining, open pit mining, and tunneling projects.

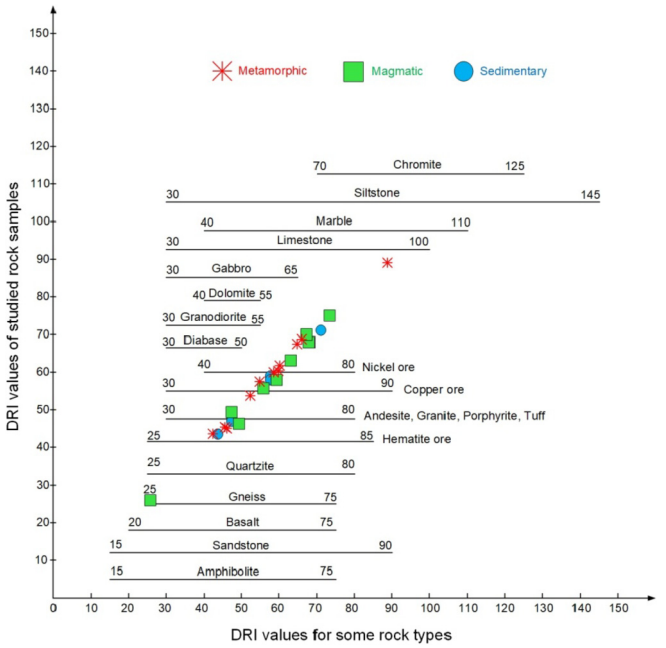



**Fig. 10.** DRI values for studied with some rock types from literature (modified from NTNU, 1998).

## Acknowledgements

This study was supported by Scientific Research Coordinator of Dokuz Eylul University under the project number of 2007KBFEN53. The authors gratefully acknowledge reviewers and also special thanks to Prof. Dr. Bjorn Nilsen (NTNU, Norway), Filip Dahl (SINTEF, Norway), Prof. Dr. Amund Bruland (NTNU, Norway), and Prof. Dr. Olgay Yaralı (Bülent Ecevit University, Turkey) for developing drilling rate index test procedures.

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