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Full Length Research Paper

The effect of mechanical rock properties and brittleness on drillability

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This paper examines the relationships between drilling rate index (DRI) and some mechanical properties of rocks in order to evaluate the effect of properties of strength, indexes, and brittleness of rock on rock drillability. For this purpose, some index properties (Shore scleroscope hardness (SSH), and point load strength (PLS) and geomechanical (uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS)) values of 32 sedimentary, igneous and metamorphic rock samples were determined. Then, the brittleness concepts which use the uniaxial compressive strength and tensile strength of rocks were determined for calculations. Four different brittleness concepts were used in the statistical analysis. In this study, a new brittleness concept (B4) which was found as a result of laboratory studies has proposed by authors for percussive drilling and rotary drilling. The relationships among of DRI and both mechanical rock properties and brittleness concepts were evaluated using regression analysis and statistical methods. As a result, decreasing linear relationships were found among of DRI and uniaxial compressive strength, shore scleroscope hardness, diametral and axial point load strength. In additional to meaningful relations were obtained between drillability of rocks and brittleness of B3 and B4.

Key words: Drilling rate index, uniaxial compressive strength, Brazilian tensile strength, shore scleroscope hardness, point load strength, brittleness.

INTRODUCTION

Tunnel excavation using methods of mechanical excavation like as tunnel boring machines (TBM's) and roadheaders has become increasingly common in recent years. Selection of machinery and equipment without physical, mechanical and petrographic properties of rock may cause dramatic problems during working. Therefore, it is important to find rock properties before starting tunnelling operations.

Drillability is a term used in construction to describe the influence of a number of parameters on the drilling rate (drilling velocity) and the tool wear of the drilling tool (Thuro and Spaun, 1996). In this evaluation, the drillability term was defined as a penetration rate. The ability to predict the performance of rock drills is important in drilling operations. No single parameter defines the drillability of a rock (Altindag, 2004).

Usually, the main subject in preliminary site investigations prior to tunnelling projects is the prediction of tunnel stability. During the last years in conventional drill and blast tunnelling, problems have occurred also connected to the accurate prediction of drillability in hard rock. The drillability is not only decisive for the wear of tools and equipment but is along with the drilling velocity, a standard factor for the progress of excavation works. The estimation of drillability in predicted rock conditions might bear an extensive risk of costs. Therefore an improved prediction of drilling velocity and bit wear would be desirable. The drillability of a rock mass is determined by various geological and mechanical parameters. Drillability of rock is one of the important parameter to decide the progress and economics of excavation. It is

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Table 1. The influence factors on drillability.

Rock mass factor (Lislerud, 1988)	Machine factor	Operating process (Thuro and Spaun, 1996)
Rock type Rock mass jointing Type and continuity Frequency Orientation Hydrothermal decomposition Stress distribution in rock	Drilling machine type Thrust force Bit type Rotation The quality and intensity of flushing Power transfer	Drilling methods Operation and maintenance of machine rig Experience of operator Logistic support

Geological parameter (Chen and Vogler, 1992; Thuro and Spaun, 1996)
Strength properties, such as uniaxial compressive strength, tensile strength, point load strength.
Hardness, such as Schmidt rebound hardness, total hardness, Mohr hardness, Shore scleroscope hardness, NCB cone indenter
Energy properties, such as fracture toughness, toughness index, critical energy release rate and acoustic emission properties.
Rock internal texture, such as grain size, grain shape, mineral composition, porosity, cementation and cementation degree
Empirical parameters, such as drillability index, Goodrich drillability, Morris' drillability, specific energy test by instrumented cutting, NTH drillability test, direct cutting testing, etc
Mechanical rock properties, such as Young's modulus, destruction work, brittleness of rock, elastic/plastic properties

influenced by many variables. These factors are listed in Table 1.

Knowledge of drillability of rocks in engineering projects is very important to determine drilling costs. In drilling operations, so many parameters such as the properties of rock and the drilling equipment affect the drilling performance.

Although the parameters of drilling equipment can be controlled, change to the rock parameters cannot be. Rock drillability cannot be measured by a single index or a single test. It is influenced by many parameters. Various rock parameters have been used to predict the performance of drilling rigs.

For many researchers, uniaxial compressive strength (UCS) of rock is the most widely used parameter for rock drillability (Paone and Madson, 1966; Paone et al., 1969a,b; Fowell and McFeat-Smith, 1976; Poole and Farmer, 1978; Aleman, 1981; Karpuz et al., 1990; Akcin et al., 1994; Bilgin et al., 1996; Huang and Wang, 1997; Kahraman, 1999; Kahraman et al., 2003a,b; Tanaino, 2005; Akun and Karpuz, 2005). Many different rock parameters, such as tensile strength, quartz content, apparent porosity, p-wave velocity and porosity can be used to predict the drillability (Howarth, 1987; Akcin et al., 1994; Kahraman, 1999). A wide range of empirical tests has been used to predict the drilling performance. These tests are given as Schmidt rebound hardness, point load strength, Shore scleroscope hardness, Taber abrasion, cone indenter number, drilling rate index (DRI), coefficient of rock strength (CRS), rock brittleness, impact strength index (ISI), Cerchar abrasivity index (CAI), specific energy (SE), texture coefficient (TC), etc. (McFeat- Smith and Fowell, 1977; Howarth et al., 1986; Kovscek et al., 1988; Nilsen and Ozdemir, 1993; Kahraman et al., 2003a, b). Singh et al. (2006) emphasized that in actual drilling, some relatively low-strength rocks are more difficult to drill than the rocks with higher strength and brittle rocks although very hard rocks can be easily drilled when compared to less hard but tougher rocks.

In this study, the raw data set obtained from the experimental works was used to investigate the relationships between drilling rate index (DRI) and some strength properties (uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS)), some index properties (Shore scleroscope hardness (SSH), and point load strength (PLS)). In addition, the correlations between the different brittleness concepts and the DRI were also analyzed using the regression analysis.

BRITTLENESS

Brittleness is one of the most important mechanical properties of rocks. Some researchers have investigated the relation between brittleness and drilling rates. However, there are no available studies on the relation between the brittleness and the DRI (Yarali, 2007; Altindag, 2010).

Brittleness is defined by a few researchers for different purposes. Hetenyi (1966) define brittleness as the lack of ductility. Ramsey (1967) defined brittleness as follows: "When the internal cohesion of rocks is broken, the rocks are said to be brittle". Obert and Duvall (1967) defined brittleness as follows: "materials such as cast iron and many rocks usually terminate by fracture at or only slightly beyond the yield stress''. Brittleness is defined as a property of materials that rupture or fracture with little or no plastic flow.

Some brittleness index definitions obtained from stress - strain curves were introduced and used in the literature (Baron, 1962; Coates and Parsons, 1966; Aubertin and Gill, 1988; Aubertin et al., 1994; Ribacchi, 2000; Hajiabdolmajid and Kaiser, 2003). A simple index of brittleness ($B1 = \sigma_c/\sigma_t$) is the ratio of compressive strength to tensile strength (Equation 1). This definition has been used in many studies. But, this has not yet exactly explained the brittleness concept of rock. This subject is criticized and discussed by Altindag (2000, 2002, 2003).

Evans and Pomeroy (1966) theoretically showed that the impact energy of a cutter pick is inversely proportional to brittleness. Singh (1986) indicated that cuttability, penetrability, and the Protodyakonov strength index of coal strongly depend on the brittleness of coal. Singh (1987) showed that a directly proportional relationship existed between *in-situ* specific energy and brittleness (B2) of three Utah coals (Equation 2). Goktan (1991) stated that the brittleness concept (B2) adopted in his study might not be a representative measure of rock cutting specific energy consumption. Kahraman (2002) statistically investigated the relationships between three different brittleness definitions for both drillability and borability using the raw data obtained from the experimental works of different researchers. Altindag (2000, 2002, 2003) found significant correlations between his proposed new brittleness concept (B3), (Equation 3) and the penetration rate of percussive drills, the drillability index in rotary drilling, and the specific energy in rock cutting. Kahraman and Altindag (2004) correlated fracture toughness values with different brittleness values using the raw data obtained from the experimental works of two researchers. They indicated that the Altindag's (2003) brittleness concept can be used as a predictive rock property for the estimation of the fracture toughness value. Kahraman et al. (2003a, b) found a strong correlation between Los Angeles abrasion loss and the Altindag's brittleness (B3) for 26 different rocks. Gunaydin et al. (2004) found a very strong correlation between hourly production and brittleness B3 and they emphasized that the brittleness B3 is the most reliable index among the brittleness indexes adopted in their study. Yarali (2007) found a power relation with correlation coefficient of 0.86 between drilling rate index (DRI) and brittleness B3 for 14 different rocks. Yilmaz et al. (2008) stated that the grain size seems to predominantly influence their relative brittleness index values in granitic rocks. In this study, the used brittleness concepts from the compressive strength and tensile strength are given as follows:

$$B1 = \frac{\sigma_c}{\sigma_t} \quad \text{(Hunca and Das, 1974)} \tag{1}$$

$$B2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \quad \text{(Hunca and Das, 1974)} \tag{2}$$

$$B3 = \frac{\sigma_c * \sigma_t}{2} \quad \text{(Altındag, 2002)} \tag{3}$$

In this study, a new brittleness concept, B4 is proposed given such as:

$$B4 = (\sigma_c * \sigma_t)^{0.72} \tag{4}$$

where B1, B2, B3, and B4 denote brittleness, σ_c is the uniaxial compressive strength and σ_t is Brazilian tensile strength.

LABORATORY STUDIES

Rock blocks were collected from natural outcrops, tunnel constructions and mining sites in Turkey and Norway for the laboratory testing. Block samples were inspected for macroscopic defects to provide test specimens free from fractures, partings or alteration zones. A total of 32 different rock types were sampled. Table 2 shows the locations and names of the rocks sampled.

Uniaxial compressive strength (UCS)

Uniaxial compressive strength tests were performed on trimmed core samples having a length-to-diameter ratio of 2.0 to 2.5. The stress rate was applied within the limits of 1.0 MPa/s. The tests were repeated five times for each rock type and the results were averaged. The tests were carried out according to ISRM (1979) suggested method.

Brazilian tensile strength (BTS)

Brazilian tensile strength tests were conducted on core samples having a thickness-to- diameter ratio of 0.5. A loading rate of 200 N/s was applied. The test was repeated ten times for each rock type and the results were averaged. The tests were performed in accordance with ISRM (1978) suggested method.

Shore scleroscope hardness (SSH)

The Shore scleroscope hardness test is used in empirical equations concerning drillability and wearing of drill tools, which is also influenced by rock mineralogy, elasticity and cementation (Rabia and Brook, 1978; Altindag, 2006).

The Shore scleroscope hardness measures the surface hardness in terms of elasticity of the material. A diamond-tipped hammer is allowed to fall from a known height on the surface of the specimen to be tested and the hardness number depending on the height to which the hammer rebounds is determined.

In order to perform the tests, samples having a diameter of 54 cm and a thickness of 3 cm were prepared. Then, upper and lower surfaces were polished with emery. "D" model scleroscope was used to perform the tests. Shore scleroscope hardness values were recorded for 20 times in 5 mm spacing on the surface and the average value was accepted as Shore scleroscope hardness value. The tests were carried out according to ISRM suggested method

Table 2. The types and locations of the rocks tested.

Rock code	Rock type	Location
1	Quartzite	Trondheim, Norway
2	Limestone	Trondheim, Norway
3	Diabase (Light gray)	Dorukan Tunnel, Turkey
4	Diabase (Dark gray)	Dorukan Tunnel, Turkey
5	Granodiorite	Dorukan Tunnel, Turkey
6	Lithic arenite sandstone	TTK Kozlu Enterprice dumping site, Turkey
7	Siltstone	TTK Kozlu Enterprice dumping site, Turkey
8	Limestone (Micritic)	ZKU New entrance construction site, Turkey
9	Syenite (Porfiric)	Devrek-Yenice, Turkey
10	Dolomite	Devrek, Turkey
11	Porfiric basaltic andesite	Zonguldak–Kdz. Eregli, km 34, Turkey
12	Porfiric basaltic andesite	Zonguldak–Kdz. Eregli, km 35, Turkey
13	Basaltic andesite	Zonguldak–Kdz. Eregli km 42, Turkey
14	Dolerite	Devrek-Yenice, Turkey
15	Alkali granite	Devrek-Yenice, Turkey
16	Basalt	Hasan Dagi Mountain, Turkey
17	Andesitic basalt	Zonguldak -Kdz. Eregli, km 26, Turkey
18	Porfiric andesite	Zonguldak -Kdz. Eregli, km 37, Turkey
19	Traki-andesite	Kdz. Eregli-Alaplı Quarry , Turkey
20	Basaltic andesite	Kdz. Eregli–Devrek, km 11,Yazicilar Village, Turkey
21	Dolomitic limestone	Kdz. Eregli–Devrek, km 25,Yazicilar Village, Turkey
22	Basaltic andesite	Amasra, Turkey
23	Limestone	Hema Mining-New shaft construction, Turkey
24	Siltstone (Fine grained)	Turkali-Gobu, Turkey
25	Siltstone (Coarse grained)	Zonguldak-Devrek, km 18, Turkey
26	Porfiric basaltic andesite	Zonguldak-Devrek, km 18, Turkey
27	Granite	Yenice- Kayabasi, Turkey
28	Dolomitic limestone	Between Zonguldak and Filyos, Turkey
29	Dolomite	Between Zonguldak Filyos, Turkey
30	Basaltic andesite	Between Zonguldak– and Yenice, km 50, Turkey
31	Marl	Zonguldak–Devrek Karaman, Turkey
32	Sandstone (Fine grained)	TTK Armutcuk Enterprise dumping site, Turkey

(Altindag and Guney, 2006).

Point load strength (PLS)

The PLS tests were performed on NX size core samples of rock. The tests were carried out diametrally and axially with core specimens having length-to-diameter ratio greater than 1.0. The tests were carried out according to ISRM (1985) suggested methods. The PLS test was repeated at least ten times for each rock type and the average value was used as the point load strength.

Drillability of rocks

In this study, drillability of rocks was evaluated on the basis of the drilling rate index (DRI). This index test was developed at the Engineering Geology Laboratory of the Norwegian Institute of Technology (NTH) in 1960's for evaluating the drillability of rocks by percussive drilling (Lien, 1961; Nilsen, 2003).

Today, the NTH/NTNU (in 1996, as result of a merger, NTH changed name to NTNU – the Norwegian University of Science and Technology and the Norwegian method now is referred to as the NTNU method) drillability laboratory is operated by SINTEF Rock and Soil Mechanics in close co-operation with NTNU, Department of Geology and Mineral Resources Engineering and Civil Transport Engineering (Nilsen, 2003).

The DRI is derived from as chart between the brittleness (S_{20}) and the Sievers' J-Value (SJ). The lower the DRI value, the more difficult it is to bore the rock (De Graaf and Bell, 1997). Both the preparation of samples and the DRI tests were carried out according to Dahl (2003) suggestions.

The Sievers' J miniature drill test

The direct test method for estimating cutter life is based on the principles of the Sievers' J miniature drill test (Sievers, 1950). The Sievers' J miniature drill test has so far been used to measure the

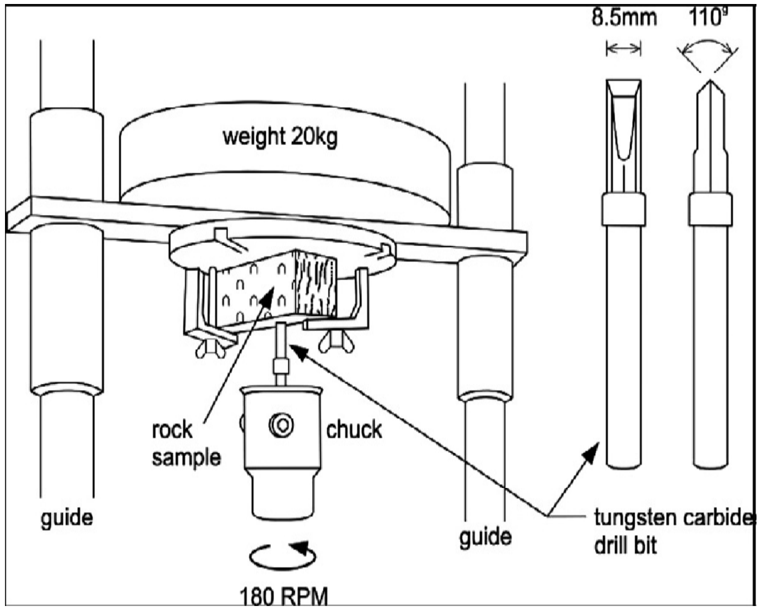

Figure 1. Outline of the Sievers'J miniature drill test (Dahl, 2003).

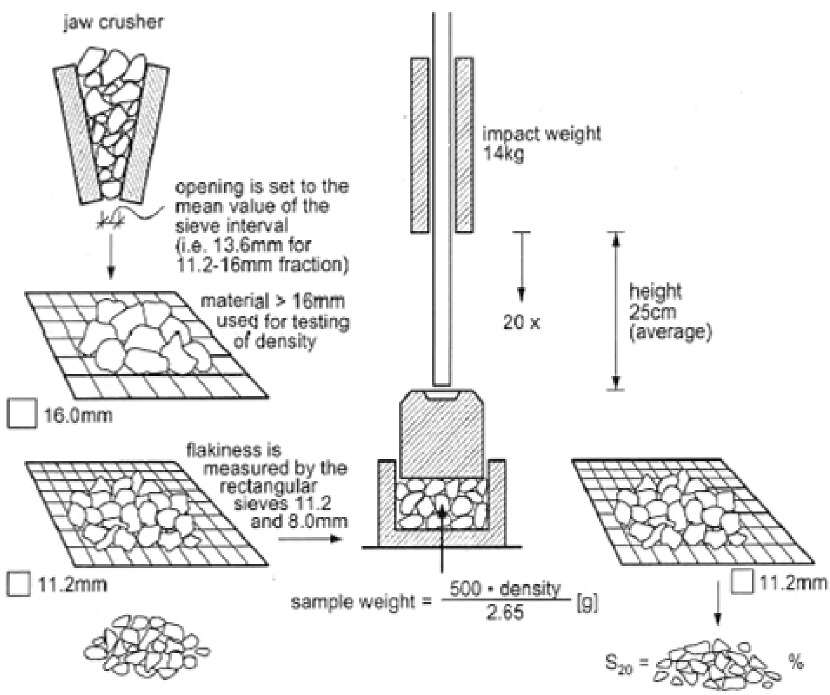

Figure 2. Outline of the brittleness test (Dahl, 2003).

surface hardness of rock samples (or resistance to indention). The Sievers' J-value is defined as the mean value of the measured drill hole depth in 1/10 mm of 4 to 8 drill holes after 200 revolutions of the 8.5 mm miniature drill bit. The standard procedure is to use the pre-cut surface of the sample which is perpendicular to the foliation of the rock. The SJ-value is hence measured parallel to the foliation. The drill hole depth has until recently been measured by use of a slide calliper subsequent to the test (Dahl, 2003). An outline of the Sievers'J test is shown in Figure 1.

The brittleness test

The brittleness test gives a good measure for the ability of the rock to resist crushing by repeated impacts. The test method was developed in Sweden by N. von Matern and A. Hjelmer in 1943. Several modified versions of the test have been developed for various purposes. An outline of the test is shown in Figure 2. The sample volume corresponds to 500 g of density 2.65 g/cm^3 from the fraction 16 to 11.2 mm. The brittleness value S_{20} equals the

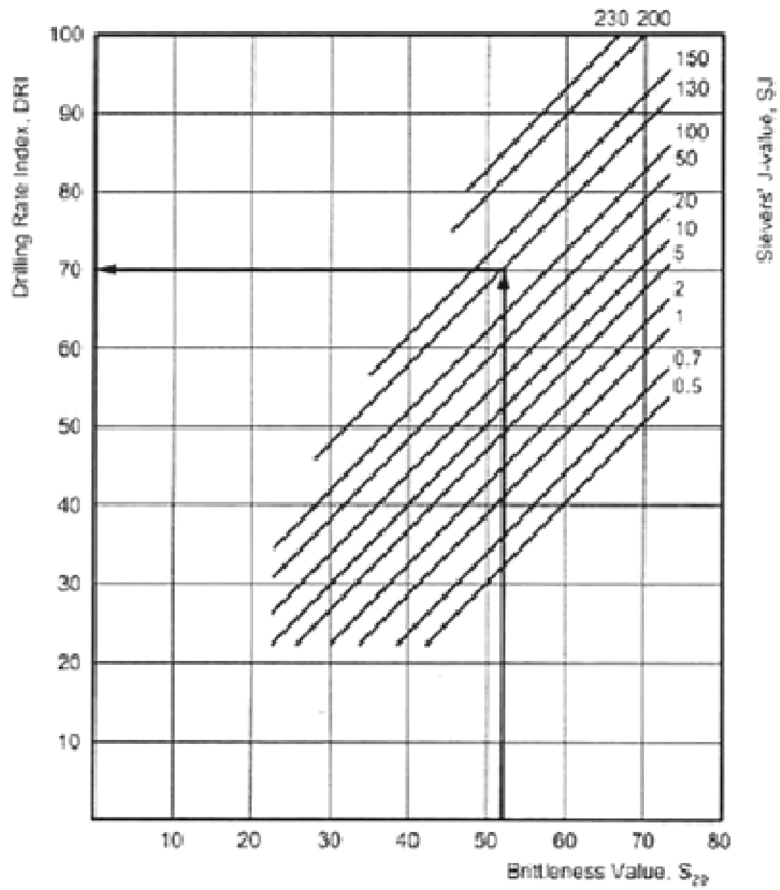

Figure 3. Diagram for assessment of DRI (Dahl, 2003).

Table 3. Classification categories of DRI (Dahl, 2003).

Category	DRI
Extremely low	≤ 25
Very low	26 -32
Low	33 - 42
Medium	43 - 57
High	58 - 69
Very high	70 - 82
Extremely high	≥ 93

percentage of material that passes the 11.2 mm mesh after the aggregate has been crushed by 20 impacts in the mortar. The brittleness value is the mean of 3 to 5 parallel tests (Dahl, 2003).

Assessment of drilling rate index (DRI)

Figure 3 is used to asses the drilling rate index (DRI) from thebrittleness value, S_{20} and the Sievers'J-value. The classification of DRI is presented in Table 3. The classification of DRI of each rock is given in Table 4.

RESULTS AND DISCUSSION

Evaluation of results

In this study, 32 different rock types (sedimentary, igneous, and metamorphic) were tested in the laboratory. Two of rock samples were brought from SINTEF, Norway, others were collected from Zonguldak Region, Turkey. The average test results are given as uniaxial compressive strength range from 31 to 165 MPa, Brazilian tensile strength from 2.57 to 17.07 MPa, Shore scleroscope hardness from 23.10 to 77.65, diametral point load strength from 1.94 to 7.98 MPa, axial point load strength from 1.82 to 7.25 MPa (Soyer, 2009).

Table 3 presents the classification of DRI. S_{20}, SJ, DRI values and the classification of DRI of each rock are given in Table 4. It was found that sedimentary rocks, both non clastic (limestone, dolomite etc.) and clastic (siltstone, marl, sandstone, etc.), of DRI values from high to very high. It was also found that igneous rocks, both plutonic (granite, diorite, etc.) and volcanic (andesites), of DRI from medium to high, except samples no 14, 15 of DRI.

UCS, Brazilian tensile strength, and the brittleness

Table 4. The drilling rate index values and its classification.

Rock code	Rock type	SJ	S_{20}	DRI	Class
1	Quartzite	2.42 ± 0.16	52.45±0.49	45	Medium
2	*Limestone*	60.80 ± 4.75	47.37±0.23	58	High
3	*Diabase (Light gray)*	50.43 ± 6.85	37.35±2.06	48	Medium
4	*Diabase (Dark gray)*	87.72 ± 1.61	49.94±0.24	61	High
5	*Granodiorite*	13.20 ± 1.50	65.63±2.74	66	High
6	*Lithic arenite sandstone*	96.90 ± 1.29	54.71±3.48	69	High
7	*Siltstone*	133.39 ± 7.27	46.57±1.52	65	High
8	Limestone (Micritic)	67.84 ± 1.05	57.70±1.56	68	High
9	Syenite (Porfiric)	56.91 ± 1.39	42.27±2.29	51	Medium
10	Dolomite	89.73 ± 1.30	69.47±2.91	76	Very high
11	Porfiric basaltic andesite	102.57 ± 0.57	40.79±2.43	55	Medium
12	Porfiric basaltic andesite	103.68 ± 0.42	50.87±3.54	65	High
13	Basaltic andesite	80.46 ± 0.36	42.53±1.88	52	Medium
14	Dolerite	55.72 ± 2.12	26.58±2.44	35	Low
15	Alkali granite	3.10 ± 0.26	44.20±1.38	39	Low
16	Basalt	36.98 ± 4.70	41.33±2.06	46	Medium
17	Andesitic basalt	119.71 ± 1.88	48.00±2.45	64	High
18	Porfiric andesite	91.53 ± 1.47	55.26±1.33	69	High
19	Traki-andesite	39.07 ± 2.94	60.49±1.74	60	High
20	Basaltic andesite	91.73 ± 3.31	53.39±2.69	63	High
21	Dolomitic limestone	32.18 ± 0.46	57.24±0.70	63	High
22	Basaltic andesite	103.68 ± 0.25	74.43±1.00	86	Extremely high
23	Limestone	75.03 ± 0.86	57.11±1.44	68	High
24	Siltstone (Fine grained)	76.51 ± 0.29	63.65±0.32	74	Very high
25	Siltstone (Coarse grained)	94.30 ± 0.45	63.90±2.17	74	Very high
26	Porfiric basaltic andesite	28.84 ± 1.51	66.52±1.26	71	Very high
27	Granite	4.63 ± 0.27	55.51±1.48	56	Medium
28	Dolomitic limestone	91.68 ± 0.77	62.12±1.85	73	Very high
29	Dolomite	84.10 ± 1.48	63.59±1.89	75	Very high
30	Basaltic andesite	41.96 ± 2.71	43.61±2.33	50	Medium
31	Marl	85.28 ± 1.46	63.83±1.49	72	Very high
32	Sandstone (Fine grained)	122.93 ± 0.88	63.50±0.89	80	Very high

SJ : Sievers' J miniature drill test, S_{20}: The brittleness test, DRI: Drilling rate index.

values (B1, B2, B3, and B4) are given in Table 5. The result were analysed using the method of least squares regression. The values of brittleness B1 range from 6.78 to 21.83, B2 range from 0.74 to 0.91 except 0.62. The lack of the correlation between DRI and the brittleness B2 may be because of this narrow range. Sample no 22, the values of brittleness B3 and B4 were found lower than others, because of having high porosity. Sample no 1 which is from Norway, the values of brittleness B3 and B4 were found higher than others, because of having high strength.

There are no significant correlation between DRI value and the brittleness B1, B2. However, there are a strong correlation between DRI value and the brittleness B3, B4 (Figure 4 to 5). The relation follows an exponential function. DRI value decreases with increasing brittleness B3 and B4, R^2 = 0.73 and 0.75, respectively. The statistical relations are showed as followed (Equations 5 to 6).

$$DRI = 77.163 * e^{-0.005 B3} \qquad R^2 = 0.73 \qquad (5)$$

$$DRI = 85.532 * e^{-0.0027 B4} \qquad R^2 = 0.75 \qquad (6$$

where, DRI is the drilling rate index, B3 and B4 are the brittleness.

As seen in Figures 6 and 7, decreasing linear relationships between DRI and uniaxial compressive strength (UCS), Brazilian tensile strength (BTS) were found (R^2 = 0.71 and 0.55, respectively). Similar relationships were determined between DRI and shore scleroscope hardness (SSH) (Figure 8) (R^2 = 0.64). Figure 9 and 10 also revealed declining linear the relationships between DRI and diametral ($Is_{(50)\perp}$) and axial ($Is_{(50)//}$) point load strengths with good coefficients of determination, 0.71

Table 5. UCS, Brazilian tensile strength, and brittleness values.

Rock code	UCS (MPa)	BTS (MPa)	B1	B2	B3	B4
1	164.77 ± 12.29	17.07 ± 2.35	9.65	0.81	1406.31	304.341
2	78.24 ± 10.52	10.34 ± 2.46	7.57	0.77	404.50	124.086
3	117.89 ± 8.55	8.15 ± 2.26	14.47	0.87	480.40	140.442
4	98.39 ± 7.92	7.89 ± 2.82	12.47	0.85	388.15	120.454
5	64.55 ± 10.43	6.14 ± 1.99	10.51	0.83	198.17	74.235
6	75.63 ± 22.53	6.69 ± 1.18	11.30	0.84	252.98	88.505
7	67.64 ± 9.15	6.19 ± 2.84	10.93	0.83	209.35	77.226
8	82.51 ± 13.84	6.78 ± 1.63	12.17	0.85	279.71	95.142
9	182.10 ± 8.47	8.34 ± 1.17	21.83	0.91	759.36	195.282
10	91.38 ± 6.49	7.70 ± 2.85	11.87	0.84	351.81	112.224
11	110.86 ± 4.32	8.30 ± 2.16	13.36	0.86	460.07	136.136
12	76.45 ± 4.15	7.62 ± 1.66	10.03	0.82	291.27	97.958
13	132.48 ± 6.54	8.76 ± 2.65	15.12	0.88	580.26	160.898
14	175.5 ± 10.85	16.50 ± 3.56	10.64	0.83	1447.88	310.791
15	141.56 ± 8.48	11.75 ± 2.85	12.05	0.85	831.67	208.499
16	120.73 ± 3.45	10.78 ± 3.45	11.20	0.84	650.73	174.740
17	77.80 ± 18.05	9.42 ± 3.49	8.26	0.78	366.44	115.564
18	82.93 ± 10.73	5.17 ± 0.85	16.04	0.88	214.37	78.557
19	104.53 ± 23.54	5.75 ±0.86	18.18	0.90	300.52	100.188
20	92.53 ± 12.82	11.20 ± 2.11	8.26	0.78	518.17	148.307
21	51.37 ± 11.40	5.66 ± 0.87	9.08	0.80	145.38	59.393
22	28.61 ± 5.76	2.57 ± 0.61	11.13	0.84	36.76	22.072
23	78.99 ± 17.91	9.08 ± 1.94	8.70	0.79	358.61	113.782
24	75.75 ± 22.53	11.18 ± 0.99	6.78	0.74	423.44	128.243
25	81.03 ± 16.19	7.54 ± 1.48	10.75	0.83	305.48	101.375
26	65.72 ± 11.53	5.85 ± 1.87	11.23	0.84	192.23	72.626
27	101.16 ± 16.99	8.32 ± 1.90	12.16	0.85	420.83	127.672
28	31.57 ± 10.21	4.36 ± 0.99	7.24	0.76	68.82	34.666
29	31.70 ± 4.38	7.45 ± 1.13	4.26	0.62	118.08	51.135
30	143.14 ± 16.32	12.38 ± 2.58	11.56	0.84	886.04	218.226
31	89.60 ± 14.46	7.03 ± 1.68	12.75	0.85	314.94	103.626
32	69.02 ± 12.39	4.08 ± 0.82	16.92	0.89	140.80	58.041

UCS: Uniaxial compressive strength; BTS: Brazilian tensile strength B1, B2, B3, B4: Brittleness concepts.

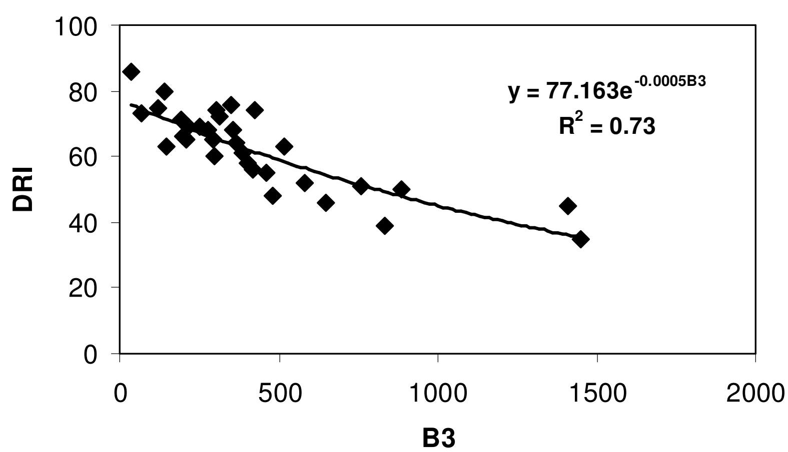

Figure 4. Relationship between brittleness (B3) and drilling rate index (DRI).

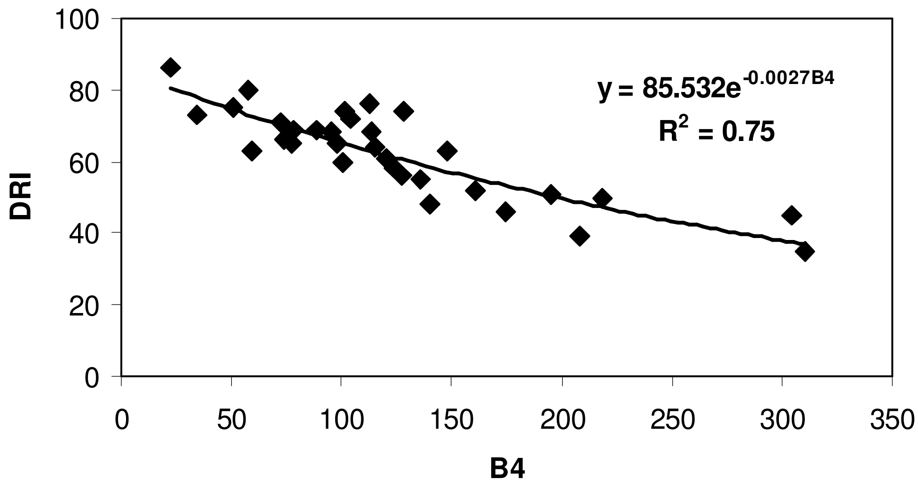

Figure 5. Relationship between brittleness (B4) and drilling rate index (DRI).

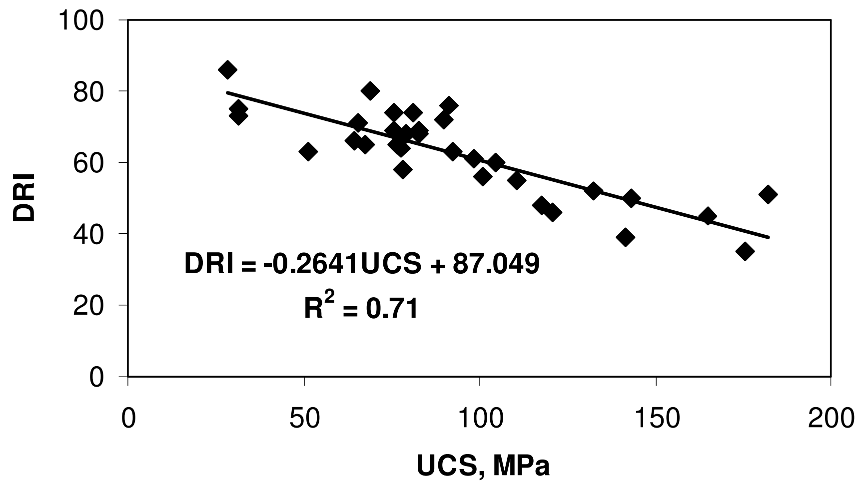

Figure 6. DRI of different rock type correlated with UCS.

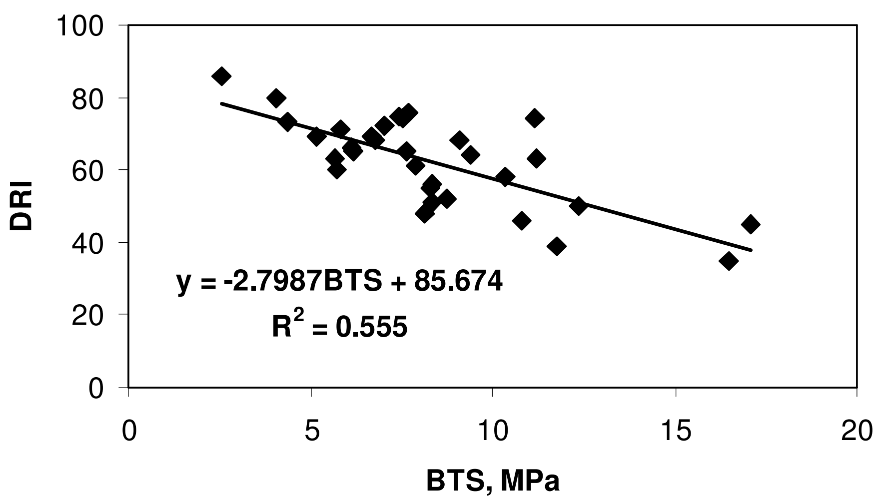

Figure 7. DRI of different rock type correlated with BTS.

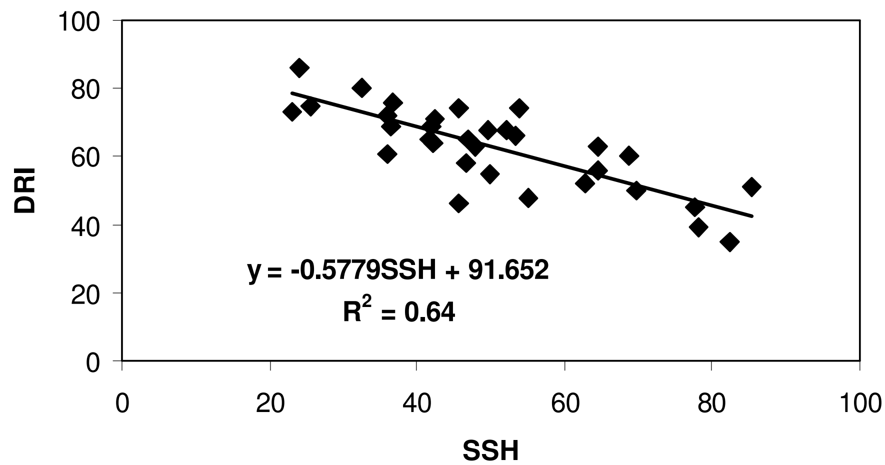

Figure 8. DRI of different rock type correlated with shore scleroscope hardness (SSH).

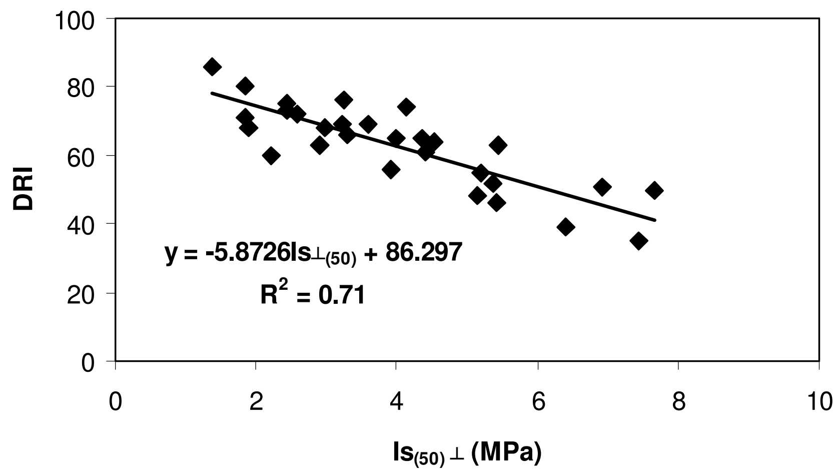

Figure 9. DRI of different rock type correlated with diametral point load strength index ($Is_{\perp(50)}$).

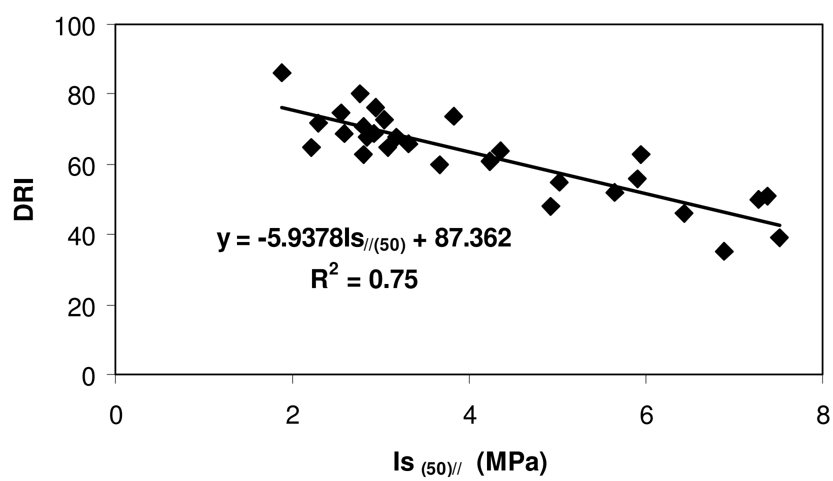

Figure 10. DRI of different rock type correlated with axial point load strength index ($Is_{//(50)}$).

and 0.75, respectively.

The results of this study were compared with the results previously obtained by different researchers (Movinkel and Johannessen, 1986; Tamrock, 1988; NTNU, 1988; Palstrom, 1995; Bruland et al., 1995; Thuro, 1996; Yarali and Soyer, 2007; Yenice et al., 2009; Altındag, 2010; Yarali, 2010). It was seen that there was an agreement between this study and previous studies. Further study is required to see how varying the rock type affects correla-tions. Futher studies are needed to check how variety of geological phenomena together rock properties affects drillability of rock.

Conclusions

The relationships between the large amount of data obtained from rock mechanic tests, and drillability tests, were evaluated by using regression and correlation analysis methods including EXCEL program. DRI values were correlated with the corresponding brittleness values. The equation of the best-fit line, and the correlation coefficient were determined for each regression.

Thirty two different rock types (sedimentary, igneous, and metamorphic) were tested in the laboratory for the investigation of the relations between the DRI and strength, index properties, and brittleness of rocks. DRI values were correlated with strengths (UCS and BTS) and indexes properties (Shore scleroscope hardness, axial and diametral point load strength). It was seen that there are good correlation between DRI and them. However, it was found a weak relationship between DRI and BTS.

A new brittleness concept (B4) which was found by laboratory studies was suggested by authors for per-cussive drilling and rotary drilling. The brittleness values of B1, B2, B3 and B4 were correlated with DRI values. It was seen that there is no correlation between DRI and the brittleness of B1 and B2. However, there is a strong exponential relation between DRI and the brittleness of B3 and B4.

In the end of this study, it is clear that strength of rock effect on drillability of rock and the indirect test methods can be used to predict the drillability of rocks, especially researcher who has not got drillability set. Also, these tests require less or almost no sample preparation. Thus, this information may be available at an early stage in the project and research. Concluding remark is that both B3 and B4 can be used for the assessment of rock drillability.

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