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Estimation of Rock Cuttability from Shore Hardness and Compressive Strength Properties

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Summary

Shore hardness has been used to estimate some mechanical and physical properties of rocks for many years. This study differs from previous studies in a way that it is directly oriented to rock cuttability. Two Shore hardness values (SH_1 and SH_2) and a coefficient of deformation value (K) have been measured for 30 different rock samples. In the first stage of the study, optimum specific energy values for 16 different rock samples obtained from full-scale cutting tests were correlated with the Shore hardness values of the same rock samples changing SH_1 values from 9 to 66 and SH_2 values from 25 to 83, with deformation coefficient values changing from 26 to 195. In the second stage, the performance of a roadheader used in the Küçüksu (Istanbul) tunnel was recorded in detail and the instantaneous cutting rate of the machine was determined. Then, the relationship between Shore hardness values, deformation coefficient and the instantaneous cutting rate of the machine was determined for different formations encountered. It is concluded that there is a relationship between Shore hardness values, optimum specific energy and compressive strength, which may be used to estimate the rock cuttability and the instantaneous cutting rates of roadheaders within certain limits of reliability.

Keywords: Shore hardness, rock cuttability, specific energy, full-scale cutting test, roadheader.

1. Introduction

One of the most important factors affecting the production rates in mining or civil engineering projects is the performance of the mechanical excavators such as roadheaders, continuous miners, shearers etc. The prediction of the machine performance plays a major role in decision making for the practicing engineer and the cuttability of rock is the key factor in performance prediction (Rostami et al., 1994). This has been enlightened by data collected in machine driven tunnels where the variation in rock cuttability has resulted in very high cutter costs of tunnelling machines at their limit of application.

Rock cuttability is usually determined with the aid of laboratory cutting rigs which need highly sophisticated instrumentation (Bilgin et al., 1997a, b) and research engineers are always interested in finding a method to predict rock cuttability from one of the simple rock properties. With rock excavation technology progress the need of understanding and quantifying the physical and mechanical rock properties relevant with the machine performance becomes a necessity for developing performance prediction models.

Shore scleroscope hardness is one of the simplest methods given the surface hardness of the tested material and it is determined from the rebound height of a diamond or tungsten-carbide tipped hammer dropped onto a horizontal smooth surface. Although it is previously demonstrated that Shore hardness is related to some extent to rock cuttability (McFeat-Smith, 1977; McFeat-Smith and Fowell, 1977), the number of the research works in this respect is very limited. In the light of this fact, this study is aimed to investigate the relationship between Shore hardness and rock cuttability using the sophisticated laboratory equipment and in situ observations in Küçüksu tunnel.

2. Previous Studies

2.1 Shore Scleroscope Hardness

In Shore scleroscope test, a diamond tip is dropped from a fixed height and makes a minute indentation into the rock specimen. The hammer then rebounds, but not to its original height because some of the energy in the falling tip is dissipated in producing an indentation. The instrument used is supplied in two models designated Model C and Model D. Model C-2 consists of a vertically disposed barrel containing a glass tube which is graded from 0 to 140. A diamond tip is dropped from a specified height and rebounds within the glass tube. According to the suggested methods published by the International Society for Rock Mechanics (IRSM), a test specimen having a minimum surface area of $10\,cm^2$ and a minimum thickness of 1 cm is necessary. Measurement points should have at least 5 mm distance from each other and only one test must be carried out at the same spot. The minimum number of tests for each rock is recommended to be 20 for statistical reliability (ISRM, 1978).

Rabia and Brook (1978) suggested that the minimum specimen volume should be $40\,cm^3$ to obtain consistent values and the mean of at least 50 readings for 5 specimens should be taken as the 'Shore hardness' of a rock. However, Altındağ (2002) emphasized that a minimum volume of $80\,cm^3$ is necessary for reliable results. Altındağ and Güney (2005) developed an empirical method to estimate Shore hardness values for the specimens less than $80\,cm^3$ in volume.

The detailed research studies carried out by different investigators indicated that there is a close relationship between Shore hardness and compressive strength of rock (Judd and Huber, 1962; Szlavin, 1974; Kocagül and Santi, 1999). It is evident that the hardness test uses a small surface area and as a consequence the presence of a large number of hard crystals, such as a free large size quartz crystal, contributes to very high individual readings so that to the average rebound values may become unrelated to the cohesive strength of the test specimen. In such cases, the relationship between Shore hardness and compressive strength values is found to be unreliable.

Deliormanlı and Onargan (2000) showed that the impact resistance of marble might be predicted from Shore hardness on micritic rock samples. Su et al. (2004) demonstrated that Shore hardness might be a guide to predict the volatile content of coal and Hardgrove index. McFeat-Smith stated that (1977) if rebound tests are made constantly at one location on the surface of the rock, a "work hardening" surface is created. Within this test zone the intergranular structure of rock is altered to a fine homogenous powder. A ratio of the change in rebound values during the test to the final hardness provides a convenient relative measure of the energy required for this process.

McFeat-Smith (1977) defined a "coefficient of plasticity or deformation coefficient" given by Eq. (1).

$$K = \frac{SH_2 - SH_1}{SH_1} \times 100\% \tag{1}$$

where K is the deformation coefficient expressed as a percentage. SH_2 is the final Shore hardness value after approximately 15–20 tests at the same point and SH_1 is the first reading.

2.2 Previous Studies on Rock Cuttability

Specific energy is defined as the energy to a rock unit volume and it is an important indicator of rock cuttability (Çopur et al., 2001; Balci et al., 2004). Specific energy is correctly obtained by carrying out full scale cutting experiments in laboratory and the cutting rate of mechanical excavators, which are roadheaders, continuous miners, TBM's etc., may be predicted from the following equation (Rostami et al., 1994; Çopur et al., 2001):

$$\mathrm{ICR} = k\frac{P}{SE_{opt}}, \tag{2}$$

where ICR is the instantaneous cutting rate of the excavating machine in m^3/h, P the cutting power of the machine in kW, k the energy transfer ratio from the cutting head to the tunnel face and SE_{opt} the optimum specific energy in kWh/m^3 which is obtained from full scale laboratory cutting tests using real life cutters. Rostami and Ozdemir (1994) pointed out that k changes between 0.45 and 0.55 for roadheaders and between 0.85 and 0.90 for TBM's.

Widely accepted rock cuttability assessment for the performance estimation of roadheader is the specific energy measured from core cutting tests (McFeat-Smith and Fowell, 1977, 1979). A chisel pick having rake angle of -5°, a tool width of 12.7 mm, and a cutting depth of 5 mm was used to cut a core of 76 mm in diameter. Detailed laboratory and in-situ investigations carried out by Fowell and McFeat-Smith showed that there is a close relationship between specific energy values and the performance of medium and heavy weight "roadheaders" (McFeat-Smith and Fowell, 1977; Fowel and Johson, 1982, 1991; Johson and Fowell, 1984).

Rock cuttability classification based on core cutting test was usually criticized as the effect of rock discontinuities were not well reflected in performance prediction.

Bilgin and co-workers developed a performance prediction equation based on rock compressive strength and rock quality designation as given in Eqs. (3) and (4) (Bilgin et al., 1996, 1997a, b):

$$\mathrm{ICR} = 0.28 \cdot P \cdot (0.974)^{\mathrm{RMCI}}, \tag{3}$$

$$\mathrm{RMCI} = \sigma_{\mathrm{c}} \cdot \left(\frac{\mathrm{RQD}}{100}\right)^{\frac{2}{3}}, \tag{4}$$

where ICR is the instantaneous cutting rate of roadheaders in m^3/h, P the power of cutting head in HP, RMCI the rock mass cuttability index, σ_c the uniaxial compressive strength in MPa and RQD the rock quality designation in %.

Dunn et al. (1997) made a comparison between the models described by Bilgin (1996, 1997b) and McFeat-Smith and Fowel (1977, 1979) using the data obtained from Kambalda Mine where Voest Alpine AM75 roadheader was used. There were two distinct groups of data at this project. The first group of data, which fits Bilgin's model, was strongly influenced by the jointing and weakness zones in rock mass. The other group of data was on the line produced by McFeat-Smith and Fowell and corresponded to areas where less jointing and weakness zones were present.

Hughes (1972) and Mellor (1979) demonstrated that specific energy might be given by:

$$SE = \frac{\sigma_c^2}{2E}, \tag{5}$$

where SE is the specific energy, E the secant modulus from zero to failure load and σ_c the compressive strength.

Farmer and Garritty (1987) and Poole (1987) showed that excavation rate in m^3/h might be predicted correctly for a given power of roadheader, using specific energy values as given by Eq. (5). Krupa et al. (1993a, b, 1994) and Sekula et al. (1991) stated that the advance rate of a tunnel-boring machine for a given power is directly related to specific energy values according to Eq. (5). Kahraman et al. (2003) also showed that the specific energy values calculated with Eq. (5) might be used in estimating penetration rates of percussive drills.

Thuro and Plinninger (1998, 1999) defined the area of stress-strain curve as destruction work, which has the unit of specific energy, and they reported that there is a good statistical relationship between destruction work and cutting rate of excavating machines and drilling rate of drill rigs. However, some practicing engineers and research workers strongly emphasized that the rock cuttability is directly related to some basic rock properties for massive rock formations such as rock compressive strength and that instantaneous cutting rate of mechanical excavators may be predicted from compressive strength (Uehigashi et al., 1987; Schneider, 1998; Gehring, 1989, 1997).

The measurement of specific energy and destruction work needs a sophisticated testing equipment. The methods are time consuming and relatively expensive, whereas the research engineers are interested in finding a method to predict specific energy from simple rock properties (Çopur et al., 2001; Balcı et al., 2004).

3. Physical and Mechanical Properties of Rocks Tested

Some of the rock properties obtained are given in Table 1 and the methods used to obtain these rock properties are given below.

3.1 Uniaxial Compressive Strength

Uniaxial compression tests are performed on trimmed core samples, which have a diameter of 54 mm and a length to diameter ratio of 2. The stress rate is applied within the limits of 0.5–1.0 MPa/s.

3.2 Brazilian Tensile Strength

Brazilian tensile strength tests are conducted on core samples having diameter of 54 mm and a length to diameter ratio of 1. The tensile load on the specimens is applied continuously at a constant stress rate such that failure would occur within 5 mm of displacement.

3.3 Static Elasticity Modulus

Tangent Young's Modulus is measured at a stress level equal to 50% of the ultimate uniaxial compressive strength.

3.4 Density

Trimmed core samples are used in the determination of natural density. The specimen volume is calculated from an average of several caliper readings and the weight of specimen is determined using a sensitive balance. The natural density values are obtained from the ratio of the specimen weight to specimen volume.

3.5 Shore Scleroscope Hardness

Shore hardness values SH_1, SH_2 and deformation coefficient values K as defined by McFeat-Smith are measured using Shore Scleroscope Model C2 (McFeat-Smith, 1997)

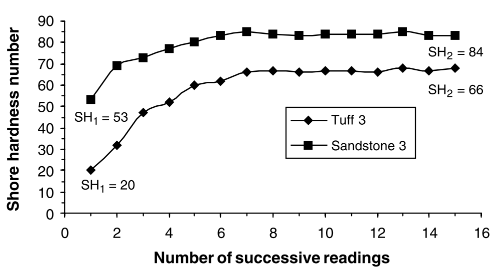

Fig. 1. Example for Shore hardness values SH_1 and SH_2 obtained during one of the 15 tests for each rock

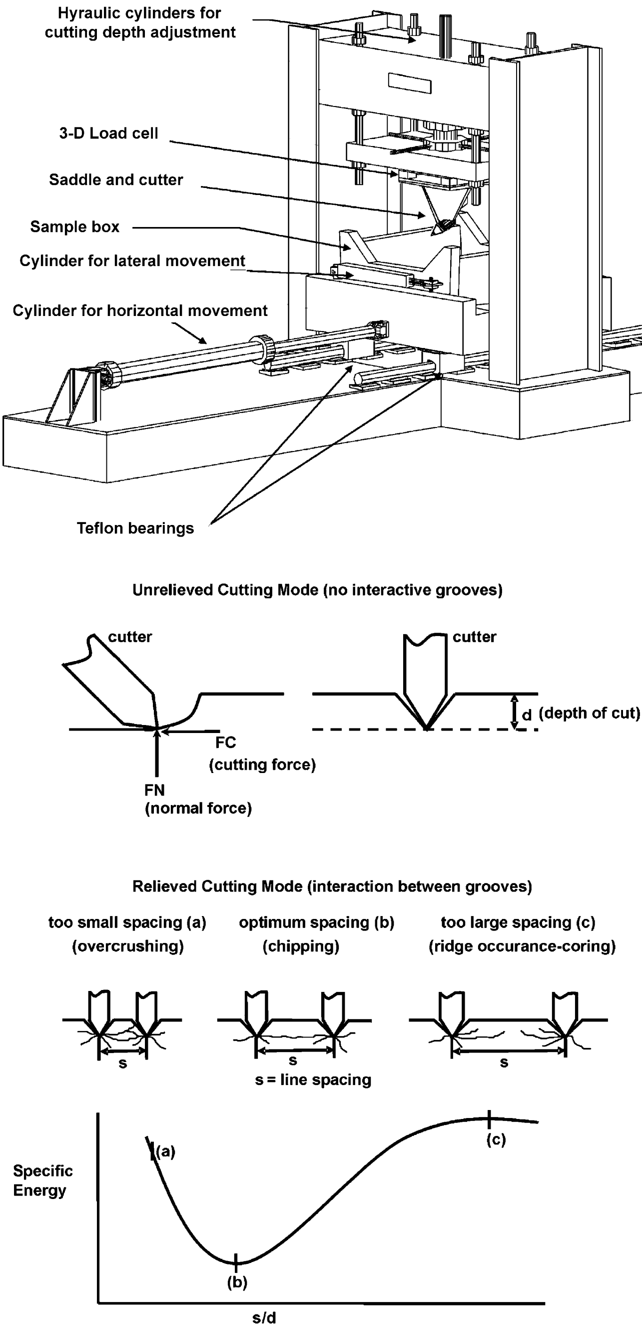

Fig. 2. Schematic view of Linear Cutting Machine, definition of unrelieved and relieved cutting modes and optimum specific energy

Prismatic rock samples having a size of $20 \times 15 \times 15$ cm are used through the experiments. Measurement points are at a distance of at least 5 mm from each other and only one test at the same spot is carried out to obtain SH_1 values and the minimum number of tests for each rock is taken as 50. SH_1 is calculated as the average of 50 points. To obtain SH_2, 15 rebound tests are made constantly at one location of the rock surface. After the first rebound, the *SH* values steadily increase and stay constant after a certain rebound. SH_2 is the constant value of *SH*. Deformation coefficient *K* is taken as the difference in percentage between the values of SH_2 and SH_1 as given by Eq. (1). Typical examples for sandstone and tuff samples are illustrated in Fig. 1.

4. Rock Cutting Tests

The linear cutting machine used was built as an outcome of NATO supported project (Eskikaya et al., 2000). The schematic view of the cutting rig is given in Fig. 2. It includes a stiff reaction frame on which the cutter and the force dynamometer of 50 t capacity are mounted. A data acquisition system is used to record the cutter forces in three perpendicular directions. Data recording rate is adjustable up to 50,000 Hz. The hydraulic cylinders can move the sample box in which the rock sample is cast with concrete to eliminate pre-failure of the specimen. Rock blocks having a size of $100 \times 60 \times 70$ cm are used through the experiments. The entire test is carried out with an S-35/80H conical cutter manufactured by Sandwick. It has a gauge of 80 mm, flange diameter of 35 mm, tip diameter of 22 mm and primary tip angle of 80°. The constant conditions throughout the testing programme are attack angle of 55°, cutting speed of 12.7 mm/s and skew angles of 0°.

The cutting tests were performed in unrelieved and relieved cutting modes. The initial cutting tests were carried out in unrelieved mode to determine the variation of

Table 1. Some mechanical properties, Shore hardness and specific energy values of the rocks tested

Rock type	σ_c (MPa ± sd)	σ_t (MPa ± sd)	E_t (GPa)	δ (g/cm^3)	SH_1 ± sd	SH_2 ± sd	*K* (%)	SE (kWh/m^3)
Tuff 2	10.8 ± 0.4	1.2 ± 0.01	1.4	1.70	30 ± 4.28	71 ± 4.17	136	2.7 ± 0.03
Tuff 3	26.6 ± 0.6	2.6 ± 0.02	2.4	1.80	19 ± 3.55	56 ± 7.75	195	2.2 ± 0.01
Tuff 4	14.4 ± 0.5	1.5 ± 0.1	1.6	1.71	24 ± 3.86	54 ± 5.89	125	2.4 ± 0.02
Tuff 5	18.7 ± 0.6	2.3 ± 0.02	1.6	1.71	28 ± 4.55	67 ± 6.15	139	2.1 ± 0.02
Tuff 6	5.7 ± 0.2	0.2 ± 0.01	0.4	1.49	9 ± 1.76	25 ± 4.90	178	1.3 ± 0.01
Trona	29.7 ± 0.7	2.2 ± 0.4	3.4	2.13	29 ± 3.70	40 ± 1.97	38	2.7 ± 0.6
Serpentinite	38.1 ± 10	5.7 ± 0.5	2.3	2.49	42 ± 5.59	64 ± 4.88	52	6.2 ± 1.3
Cromite 1	32.2 ± 4.4	3.7 ± 0.6	3.5	4.03	20 ± 2.29	37 ± 2.62	85	3.9 ± 0.8
Cromite 2	46.9 ± 10	4.5 ± 0.6	2.3	3.39	26 ± 4.65	43 ± 10.08	65	6.4 ± 1.3
Copper ore, yellow	33 ± 2.5	3.4 ± 0.02	–	4.13	19 ± 3.28	46 ± 9.42	142	3.7 ± 0.6
Copper ore, black	41 ± 3.6	5.7 ± 0.03	–	4.07	43 ± 5.70	71 ± 6.11	65	9.2 ± 0.9
Siltstone	57.9 ± 3	5.3 ± 0.2	30.0	2.65	42 ± 5.38	62 ± 7.10	48	9.6 ± 0.7
Limestone	121 ± 7	7.8 ± 0.3	57.0	2.72	54 ±	72 ±	33	12.0 ± 1.4
Sandstone 1	113.6 ± 7	6.6 ± 0.3	17.0	2.65	60 ± 7.39	81 ± 3.82	35	12.6 ± 1.2
Sandstone 2	173.6 ± 10	11.6 ± 0.4	28.0	2.67	66 ± 10.3	83 ± 5.60	26	15.4 ± 1.1
Sandstone 3	87.4 ± 4	8.3 ± 0.3	33.3	2.67	52 ± 3.95	75 ± 3.39	44	5.4 ± 0.5

σ_c Compressive strength, σ_t tensile strength, *SH* Shore hardness, δ specific gravity, *K* deformation coefficient, *SE* specific energy obtained from full scale cutting test.

specific energy with depth of cut. This helps to find the optimum depth of cut value at which the relieved cutting tests will be carried out to determine the optimum specific energy and cutter spacing. Optimum specific energy will serve to predict the cutting rate of the machine intended to be used in the rock formation tested. Unrelieved cutting modes and the effect of cutter spacing and depth of cut are shown in Fig. 2. While there is no interaction between the cutting grooves in the case of unrelieved cutting mode, there has to be an interaction between grooves in the relieved cutting mode as seen in Fig. 2.

The specific energy values given in Table 1 include the results of several research projects sponsored by Turkish State Planning Organization (DPT), Istanbul Technical University and Karaelmas University Research Founds, and General Directorate of Mineral Research and Exploration (MTA) (Bilgin et al., 2006).

5. Results and Discussions

5.1 Estimation of Optimum Specific Energy from Shore Hardness

The relationship between optimum specific energy obtained from laboratory full scale cutting tests, Shore hardness and deformation coefficient are shown in Figs. 3 and 4, respectively. As illustrated in these figures, the optimum specific energy or instan-

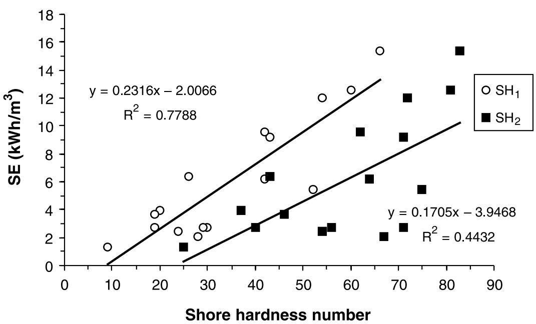

Fig. 3. Relationship between optimum specific energy (SE) and Shore hardness

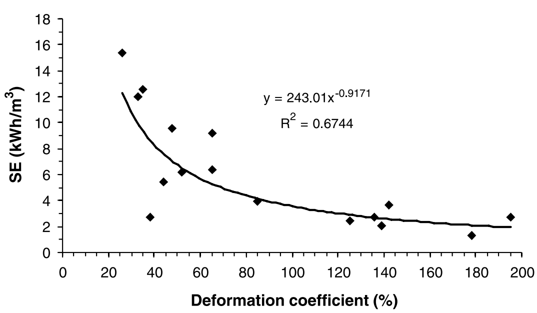

Fig. 4. Relationship between optimum specific energy (SE) and deformation coefficient

taneous cutting rate of a roadheader, as calculated using Eq. (2), for a given cutting power, may be estimated using SH_1 and deformation coefficient values. However, SH_2 is found to give a less reliable correlation than SH_1 and deformation coefficient.

5.2 Measurement of Performance of the Roadheader at Küçüksu Tunnel

Küçüksu tunnel is a part of sewage project, which is situated between Küçüksu and Hekimbaşı in the Anatolian part of Istanbul (Bilgin et al., 2005). The project consists of a sewage plant having a capacity of 7 m^3/s, three shafts and two tunnels with 2.2 m final diameter and length 95.8 and 1037.2 m, respectively. The tunnels were excavated using SM1 model shielded Herrenknecht roadheader having a cutting power of 90 kW and total power of 224 kW. The cutting head is axial type having 36 conical cutters of 75° tip radius.

The excavation of the tunnel started on 27th August 2002 and ended on 9th August 2003. Rock samples were collected systematically and geological observations were made and the performance of roadheader was recorded continuously during tunnel excavation. The technique described by Poole and Farmer (1978) was used in defining zones for detailed site investigations. The criteria used to separate these zones were according to the obtained geological data and totally independent of any statistical tests used in order to assess correlations between zones. For each zone data about tunnel geology, rock mass structure, intact rock properties, machine performance were carefully collected. The typical cross section view of the tunnel alignment is given in Fig. 5.

The relevant rock properties and net cutting rate of the roadheader are given in Table 2.

Along the tunnel alignment, where the detailed roadheader performance analysis was carried out, limestone is the main rock (72%) encountered with compressive strength values ranging from 98.2 to 145.2 MPa and RQD values from 75 to 90%. In the tunnel route, 16% of the rock formations are composed of andesite and diabase

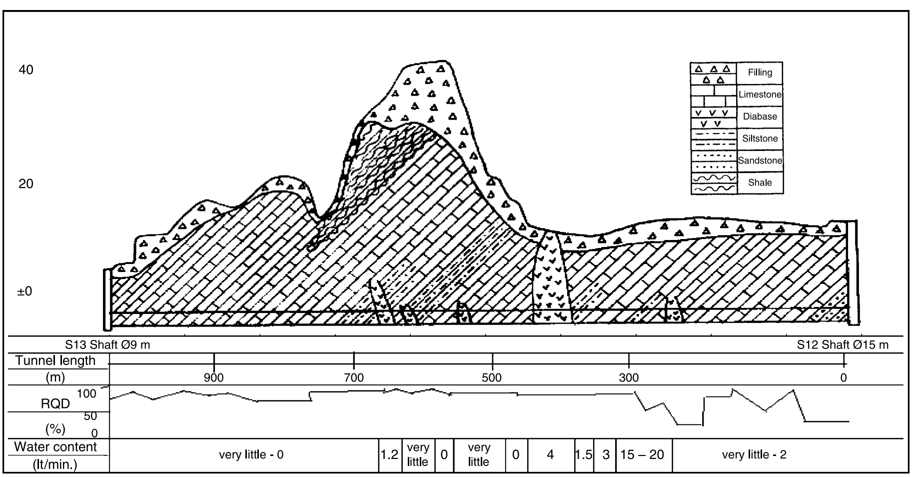

Fig. 5. A geological cross section of Küçüksu tunnel

Table 2. Net cutting rate of roadheader

Ring no.	Rock	σ_c MPa ± sd	RQD (%)	SH_1 ± sd	SH_2 ± sd	DC (%)	NCR (m^3/h)
400	Sandstone	55.7 ± 6	90	25 ± 1.99	44 ± 5.68	76	6.85
491	Limestone	98.2 ± 19	90	53 ± 2.92	76 ± 4.71	43	4.36
492	Siltstone	92.4 ± 22	90	51 ± 6.34	79 ± 1.81	55	3.60
608	Limestone	122.7 ± 19	90	52 ± 3.74	74 ± 4.67	33	3.00
613	Limestone	95.7 ± 15	90	46 ± 5.28	72 ± 2.29	57	3.52
641	Limestone	120.4 ± 10	90	54 ± 3.52	74 ± 3.10	37	2.68
667	Limestone	127.8 ± 6	90	54 ± 3.21	76 ± 3.70	41	3.30
722	Andezite	163.8 ± 8	90	56 ± 4.81	83 ± 6.93	48	3.45
739	Limestone	145.2 ± 1.4	90	54 ± 3.03	76 ± 4.96	41	3.33
768	Limestone	120.5 ± 9	75	67 ± 5.66	89 ± 2.73	33	3.55
810	Siltstone	82.6 ± 9	90	47 ± 4.8	70 ± 7.48	49	4.10
852	Limestone	116.4 ± 9	90	50 ± 3.42	75 ± 2.68	50	3.33
872	Diabase	77.0 ± 8	80	50 ± 2.9	72 ± 1.46	44	4.94
905	Siltstone	75 ± 7	80	51 ± 3.37	72 ± 4.37	41	5.10
*	Sandstone	75 ± 6	80	35	51	65	5.00

* The performance of the same roadheader in other tunnel in Istanbul (Haliç).

dykes with compressive strength ranging from 77 to 163.8 MPa and RQD 80–90%. Siltstone and sandstone are met in 12% of the tunnel with compressive strength from 55.7 to 92.4 MPa and RQD 80–90%.

5.3 Estimation of Roadheader Cutting Rate from Shore Hardness

The relationship between net (instantaneous) cutting rate values and Shore hardness SH_1, SH_2 and K values are given in Figs. 6 and 7. It is important to note that the correlation coefficient values are not as good as observed for optimum specific energy. This may be due to the fact that the number of Shore hardness values obtained in the field ($SH_1 = 25$–67; $SH_2 = 44$–89) is not as large as measured in the laboratory ($SH_1 = 6$–66; $SH_2 = 26$–66). Therefore, more in situ observations should be made to estimate the performance of roadheaders from Shore hardness. However, Fig. 9 emphasizes that net cutting rate of roadheader in Küçüksu Tunnel may be predicted from rock compressive strength with higher reliability than Shore hardness values. Compressive strength values of 30 samples are plotted against SH_1 and SH_2 values in

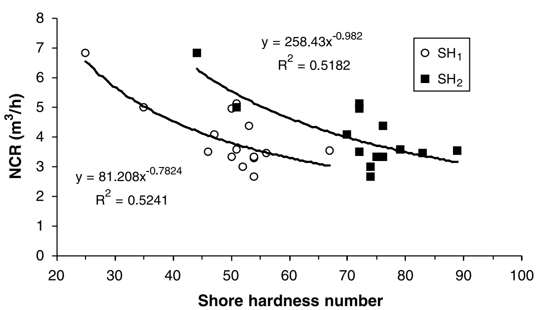

Fig. 6. Relationship between net cutting rate (NCR) and Shore hardness

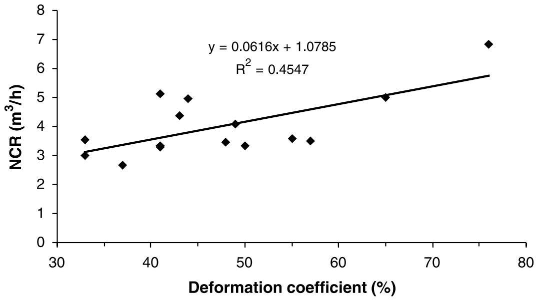

Fig. 7. Relationship between net cutting rate (NCR) of roadheader and deformation coefficient

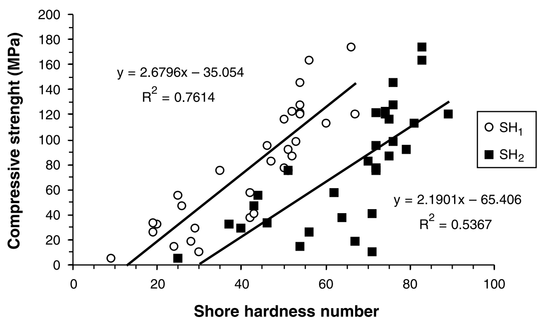

Fig. 8. Relationship between compressive strength and Shore hardness

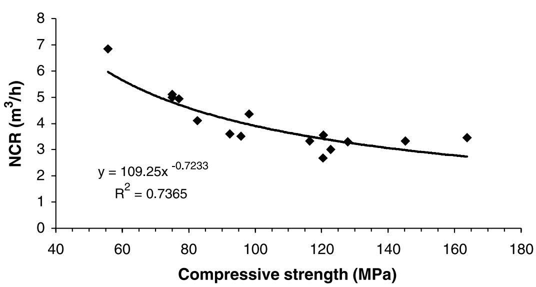

Fig. 9. Relationship between net cutting rate (NCR) and compressive strength

Fig. 8. This figure shows that compressive strength may be estimated using SH_1 values with a higher acceptable reliability limits than SH_2 values.

6. Conclusion

Two Shore hardness values, SH_1 and SH_2, and the coefficient of deformation value, K, are defined for 30 different rock samples. It is proved that optimum specific energy values obtained from full-scale cutting tests may be predicted from SH_1 values within acceptable standard reliability limits. However, the relationship between net cutting rates of a roadheader in Küçüksu tunnel and Shore hardness values are not as good as the results observed for specific energy values, suggesting that further in-situ studies are needed to estimate the performance of roadheaders from Shore hardness values. It is found that there is a good relation between SH_1 and compressive strength values than that obtained for SH_2 values.

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