

Cuttability Assessment of Selected Rocks Through Different Brittleness Values

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Abstract Prediction of cuttability is a critical issue for successful execution of tunnel or mining excavation projects. Rock cuttability is also used to determine specific energy, which is defined as the work done by the cutting force to excavate a unit volume of yield. Specific energy is a meaningful inverse measure of cutting efficiency, since it simply states how much energy must be expended to excavate a unit volume of rock. Brittleness is a fundamental rock property and applied in drilling and rock excavation. Brittleness is one of the most crucial rock features for rock excavation. For this reason, determination of relations between cuttability and brittleness will help rock engineers. This study aims to estimate the specific energy from different brittleness values of rocks by means of simple and multiple regression analyses. In this study, rock cutting, rock property, and brittleness index tests were carried out on 24 different rock samples with different strength values, including marble, travertine, and tuff, collected from sites around Konya Province, Turkey. Four previously used brittleness concepts were evaluated in this study, denoted as B_1 (ratio of compressive to tensile strength), B_2 (ratio of the difference between compressive and tensile strength to the sum of compressive and tensile strength), B_3 (area under the stress–strain line in relation to compressive and tensile strength), and $B_9 = S_{20}$, the percentage of fines (<11.2 mm) formed in an impact test for the Norwegian University of Science and Technology

(NTNU) model as well as B_{9p} (B_9 as predicted from uniaxial compressive, Brazilian tensile, and point load strengths of rocks using multiple regression analysis). The results suggest that the proposed simple regression-based prediction models including B_3 , B_9 , and B_{9p} outperform the other models including B_1 and B_2 and can be used for more accurate and reliable estimation of specific energy.

Keywords Brittleness · Rock cuttability · Specific energy · Small-scale rock cutting tests · SPSS · Regression analysis

1 Introduction

There is growing demand for mechanized rock excavation capacity in civil engineering, tunneling, and the hard rock mining industry. For this reason, mechanical excavators have been widely used throughout the world in tunneling and mining for very low- to medium-strength rocks. Roadheaders, continuous miners, and shearers are mechanical excavators used to cut different types of rock in various mining and tunneling operations by means of picks mounted on their cutting heads or drums. One of the most important factors affecting production rates in mining or civil engineering projects is the performance of such mechanical excavators. Prediction of machine performance plays a major role in decision-making for practicing engineers, and rock cuttability is a key factor in such performance prediction (Rostami et al. 1994).

Rock cuttability refers to the resistance against cutting by mechanical tools such as pick cutters and roller cutters. Cuttability is an important parameter for mechanical rock excavation, and can be determined through full- or small-scale linear cutting tests, indentation tests, and various rock

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property tests, such as uniaxial compressive strength (UCS) tests, Brazilian tensile strength (BTS) tests, point load strength (PLS) tests, etc. (Fowell and McFeat-Smith 1976; McFeat-Smith and Fowell 1977). The specific energy, optimum cutting geometry, and forces acting on cutters can be measured and/or predicted based on these tests. Determination of these parameters helps to select and design mechanical miners and to predict their performance for feasibility and planning purposes (Fowell and McFeat-Smith 1976; McFeat-Smith and Fowell 1977; Roxborough 1973; Bilgin 1989).

The cuttability of a rock by picks can be expressed by the forces acting on the pick and the specific energy consumed during cutting tests. Rock cutting tests carried out in the laboratory also represent a successful, reliable, and efficient method to observe tool–rock interactions and estimate tool forces and specific energy. As well as being expensive and time-consuming, such rock cutting tests require complex laboratory facilities and high-quality samples. For this reason, theoretical, semiempirical, and empirical models are used for estimation of pick forces and specific energy in the absence of a rock cutting rig (Copur et al. 2001; Goktan and Yilmaz 2005a; Tiryaki et al. 2010). Since the standardized specific energy is known to be closely related to intact rock properties and cutting conditions such as depth of cut, pick type, pick geometry, line spacing, etc., many studies have been conducted in order to build predictive models for the specific energy, employing simple rock mechanics tests that can be carried out without use of a rock cutting rig. Intact rock properties that are known to influence cutting forces and specific energy are rock type, rock texture and mineralogy, porosity, density, uniaxial compressive, tensile, and shear strengths, elasticity modulus, Poisson's ratio, rock brittleness, fracture toughness, Shore and Schmidt hardness, etc.

Rock brittleness is a combination of rock properties rather than a single parameter, therefore being crucial for underground projects such as tunneling. Different researchers have described and measured rock brittleness using various rock testing methods; however, there is no agreement on the measurement of brittleness in the rock mechanics community, except for indirect measurement as a function of rock strength measurements, such as UCS and BTS (Altindag 2002a; Bieniawski 1967; Cook et al. 1984; Eberhardt et al. 1988; George 1995; Gong and Zhao 2007; Hucka and Das 1974; Kahraman 2002; Pang and Goldsmith 1990; Protodyakonov 1963; Schwartz 1964; Yagiz 2004; Yagiz and Ozdemir 2001). In fact, a general law to define brittleness is that a more brittle rock breaks at very low deformation (Gong and Zhao 2007).

In this study, specific energy values of rock samples investigated by rock cutting tests were calculated by two different methods, namely the mechanical specific energy

(SE_{Mec}) calculated from cutting forces, and the electrical specific energy (SE_{Elec}) calculated from electrical current and voltage values. In mechanical rock excavation processes, engineers need to estimate the specific energy using easily applicable, more economic, and easy sample preparation methods. Since the SE_{Elec} method can be applied in both the laboratory and the field and is easy to apply, it will be frequently used by engineers working on mining, civil, geotechnical, and underground projects. For this reason, the SE_{Elec} method was used for the determination of specific energy.

This paper is concerned with establishing prediction models for rock cuttability through different brittleness values of rocks. The relation between specific energy and brittleness was investigated. For this purpose, rock cutting, brittleness index, and rock mechanics tests were performed on 24 samples representing marble, travertine, and tuff, obtained from sites around Konya Province. Four previously used brittleness concepts were evaluated in this study, denoted as B_1 (ratio of compressive to tensile strength), B_2 (ratio of the difference between compressive and tensile strength to the sum of compressive and tensile strength), B_3 (area under the stress–strain line in relation to compressive and tensile strength), and $S_{20} = B_9$ [percentage of fines (<11.2 mm) formed in an impact test for the NTNU model] as well as B_{9p} (B_9 predicted from uniaxial compressive, Brazilian tensile, and point load strengths of rocks using multiple regression analysis). Although rock brittleness is generally accepted as a property that contributes to rock cuttability, the relation between brittleness and rock cutting efficiency has not been fully established. Relatively little published material is available on the relation between rock brittleness and rock cutting efficiency. B_9 has been used as a method for tunnel boring machine (TBM) performance prediction testing and drillability testing. However, in this study, $S_{20} = B_9$ is used for prediction of specific energy obtained from small-scale rock cutting tests. This is one of the research activities differentiating this research from similar previous work. For this reason, to develop the proposed models, a database composed of brittleness values including B_1 , B_2 , B_3 , B_9 , and B_{9p} as well as specific energy values including relieved and unrelieved cutting modes was established using the dataset obtained from experimental studies. In this study, correlations between specific energy and brittleness values of rocks were analyzed using simple regression analysis, and some prediction equations are derived for assessment of specific energy.

2 Previous Studies on Rock Cuttability

Specific energy is defined as the energy required to cut a unit volume of rock, being an important indicator of rock cuttability (Fowell and McFeat-Smith 1976; McFeat-Smith

and Fowell 1977; Copur et al. 2001; Balci et al. 2004). Various prediction models have been developed for specific energy by correlating rock properties with specific energy values. McFeat-Smith and Fowell (1977) carried out the best-known study, correlating some rock properties with specific energy, in which samples of coal and Coal Measure strata were subjected to linear cutting in the laboratory. They made an effort to correlate specific energy and pick wear rate, respectively, with petrographic and a wide range of engineering properties of rocks. They analyzed the obtained test data using a stepwise curvilinear multiple regression technique and developed an equation for prediction of laboratory specific energy. They also suggested a predictive model for the pick wear rate. Their studies indicated the importance of rock properties such as quartz content and cementation coefficient together with uniaxial compressive strength, cone indenter and Shore hardness indices of rocks in rock cutting. McFeat-Smith and Fowell (1977, 1979) suggested a model for prediction of specific energy using cone indenter hardness and plasticity index obtained by Shore scleroscope hardness tests for Coal Measure rocks. Fowell and Pycroft (1980) found good correlations between specific energy and uniaxial compressive strength and cone indenter hardness for different Coal Measure rocks. Demou et al. (1983) investigated relations between laboratory cutting performance (normal force, cutting force, and specific energy) and compressive strength of three different rock samples. Fowell et al. (1991) determined a relation between specific energy and fracture toughness of different rock samples. Bilgin et al. suggested a performance prediction model based on rock compressive strength and rock quality designation (Bilgin et al. 1996, 1997a, b). Bilgin et al. (2002) designed a research program to investigate the possibility of using Schmidt rebound values to predict the breaking performance of hydraulic impact hammers. At the end of this study, a prediction model concerning instantaneous breaking rates of hydraulic impact hammers from Schmidt hammer rebound values was explained. Copur et al. (2001) stated that specific energy obtained from full-scale linear cutting tests in optimum cutting conditions was highly correlated to uniaxial compressive strength and Brazilian tensile strength. Altindag (2003) investigated the correlations between specific energy and brittleness concepts and showed that specific energy was strongly correlated with the B_3 brittleness (area under the stress–strain line in relation to compressive and tensile strength). Balci et al. (2004) tested 23 different rock types and studied the predictability of specific energy from physical and mechanical properties. They found good and strong correlations between specific energy and some rock properties such as uniaxial compressive strength, Brazilian tensile strength, static and dynamic elastic modulus, and Schmidt hammer

value. Yilmaz et al. (2007) found a relation between cutting force and rock properties (shear strength and uniaxial compressive strength) in addition to some cutting conditions such as depth of cut and line spacing. Balci and Bilgin (2007) correlated the specific energy and uniaxial compressive strength and Brazilian tensile strength of different rock samples, as well as specific energy values obtained from small- and full-scale linear cutting tests. Tiryaki and Dikmen (2006) carried out small-scale linear cutting tests to analyze relations between specific energy and texture coefficient using six different sandstone samples. The tests and subsequent analyses revealed that the texture coefficient and feldspar content of sandstones affected rock cuttability. The felsic and mafic mineral contents of sandstones did not exhibit any statistically significant correlation with specific energy. Cementation coefficient, effective porosity, and pore volume had good correlations with specific energy as well as, but the Poisson's ratio exhibited the highest correlation with specific energy and seemed to be the most reliable specific energy prediction tool in sandstones. Dursun et al. (2011) investigated the correlations between specific energy, brittleness index (S_{20} , NTNU model), and some rock properties. They found good correlation between specific energy and S_{20} brittleness. They mentioned that S_{20} and some mechanical properties of rocks can be used for assessment of rock cutting and predicting of specific energy. Copur (2010) and Copur et al. (2011) suggested a model based on the specific energy obtained from linear cutting tests in unrelieved cutting mode. In these studies, they used a small-scale linear cutting rig for full-scale simulation of the cutting action of chain saw machines by using chain saw tools of chisel type. Copur et al. (2001, 2011) and Copur (2010) found close relations between specific energy, normal forces, cutting forces, coarseness index, optimum ratio of line spacing to cutting depth, and different rock properties such as UCS, BTS, and static and dynamic elasticity modulus. Tiryaki (2008) determined a relation between specific energy and cone indenter hardness and UCS for different rock types. Su and Akcin (2011) made an attempt at a model to numerically predict tool forces from rock cutting tests using three-dimensional particle flow code. In this paper, three-dimensional numerical modeling of the rock cutting test was conducted in unrelieved mode, and tool forces acting on the point attack pick were recorded. Abu Bakar and Gertsch (2013) performed full-scale linear cutting tests on a brittle sandstone using a chisel-type tool. An inverse relation in the power function was determined between coarseness index and specific energy. Comakli et al. (2014) tested eight different metallic ores and carried out small-scale linear cutting tests to analyze relations between specific energy and ore properties. They used simple and multiple regression models for estimation of

specific energy from ore properties. They found that a significant practical model including the Schmidt hammer value and density of ores was produced from the multiple regression analysis. Tumac (2014) used Shore hardness values to estimate the field performance of chain saw machines. For this purpose, Shore hardness values were correlated with the physical and mechanical properties of natural stone samples, cutting parameters (normal force, cutting force, and specific energy) obtained from linear cutting tests in unrelieved cutting mode, and areal net cutting rate of chain saw machines. He found strong relations between Shore hardness, cutting forces, and specific energy. Dogruoz and Bolukbasi (2014) investigated the effect of cutting tool wear and bluntness on the specific energy of cutting for different rock types using full-scale cutting tests. The relationships between wear flats and cutting forces, specific energy, and various rock properties such as uniaxial compressive strength, tensile strength, indentation index, Shore hardness, Schmidt hammer hardness, and density were examined and are discussed in this paper. They offered a formula in this study that can also be used to estimate the specific energy of cutting in rocks of low or medium strength, which can be used to estimate the production rate for a given machine, assuming a reasonable value for the wear. Additionally, they used specific energy to calculate the instantaneous cutting rates of a selected roadheader for eight metallic ores. Inyang (2002) investigated drag bit cutting parameters of rock such as bit geometry, forces, and specific energy and found that the specific energy was the most comprehensive criterion for efficiency of mechanical excavators. Singh (1986) carried out experimental studies to determine the relation between in-seam coal cutting performance and a brittleness index related to compressive and tensile strength. Deketh et al. (1998) carried out experimental studies to correlate rock cutting performance with the failure envelope obtained from triaxial compression tests.

3 Previous Studies on Rock Brittleness

A group of researchers developed a brittleness test to be used as one of the predictive parameters for TBM performance (NTH 1994). Another group of researchers investigated brittle and ductile failure modes by triaxial testing and connected this information with rock cutting (Deketh et al. 1998; Verhoef et al. 1996). Another group of researchers found a relation between specific energy and different brittleness values of rocks using data from previous rock cutting studies (Altindag 2003; Tiryaki 2006; Goktan and Yilmaz 2005b). Kahraman et al. (2000) and Kahraman (2002) indicated that the performance of

TBMs and rotary drills was related to the ratio of rock UCS and BTS. Altindag (2002a, 2003) suggested the product of UCS and BTS as a brittleness index, indicating a correlation between the index and percussive and rotary blast hole drilling performance. Altindag (2002b) also stated a correlation between the coarseness index of rock cutting and percussive drilling performance. Yarali and Kahraman (2011) developed drillability using different rock brittleness values. Goktan (1991) stated that brittle rock should have lower specific energy than less brittle rock.

Even though brittleness is often calculated by means of UCS and BTS values of rock in engineering practice, several special tests are used for some specific purposes such as tunneling performance estimation. Blindheim and Bruland (1998) suggested as a brittleness value the percentage of material passing a 11.2-mm mesh after the aggregate has been crushed in a mortar as one of the main rock parameters for estimation of TBM performance in the NTNU prognosis model. Similarly, the punch penetration test, originally intended to provide a direct method for estimating the normal load on disc cutters, was developed in the late 1960s to provide a direct laboratory method to investigate rock behavior under the indenter (Hamilton and Handewith 1971). Since its initial development, a number of major modifications and improvements have been made in terms of the test procedure and data evaluation. Szwedzicki (1998) used this test to measure rock hardness and stated that it could be used for predicting rock cuttability. Furthermore, the punch penetration test can also provide qualitative data for investigating rock toughness and brittleness under the indenter for TBM penetration rate estimation (Dollinger et al. 1998; Yagiz 2002, 2003, 2006, 2008). Yagiz (2002) used the punch penetration test to investigate rock brittleness and toughness, being one of the input rock properties for the Modified Colorado School of Mines Model (CSM) to estimate the penetration rate of tunneling machines. Consequently, the rock brittleness classification was introduced through the brittleness index generated as a result of the punch penetration test (Yagiz 2009). Copur et al. (2003) defined a brittleness index based on the ratio of the force increment to decrement period of punch penetration (indentation) test results. Accordingly, there is no reliable way to measure rock brittleness directly; rather, in the literature, numerous rock strength ratios have been used in different approaches to measure it indirectly.

Performance prediction and cost evaluation models for drill and blast tunneling, TBM tunneling, and rock quarrying have been developed by correlating laboratory tests and in situ geological data with production data from tunneling projects. The models are continuously updated

and revised as new tunneling data become available (Dahl et al. 2010). In recent years, the Building and Infrastructure Research Institute Trondheim, Norway (SINTEF) method has been extensively used in connection with cost/time estimates and planning of major international underground projects, and it is gaining acceptance as a recognized and widely used method for TBM performance prediction testing (Dahl et al. 2012). This brittleness value ($S_{20} = B_9$) has been extensively used at NTNU/SINTEF in connection with drillability testing of rock samples since the 1960s.

4 Rock Brittleness Indices

Various empirical equations are given in the literature to estimate and calculate rock brittleness using different approaches. So far, five common approaches have been used to determine brittleness values.

(A) *Strength-ratio-based approach* Three formulae are available:

$$B_1 = \sigma_c / \sigma_t \text{ (Hucka and Das 1974; Altindag 2002a; Kahraman 2002),}$$

$$B_2 = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)} \text{ (Hucka and Das 1974; Kahraman 2002),}$$

$$B_3 = (\sigma_c - \sigma_t) / 2 \text{ (Altindag 2002a),}$$

where σ_c is the uniaxial compressive strength and σ_t is the Brazilian tensile strength.

(B) *Strain-based approach* The brittleness is defined as an absolute index based on the absolute irreversible longitudinal (parallel to σ_1) strain ε_{li} at failure, i.e., $B_4 = \varepsilon_{li} \times 100$, % (George 1995). From the viewpoint of rock failure, rocks are classified as follows: $\varepsilon_{li} < 3$ % brittle; $3\% < \varepsilon_{li} < 5$ % brittle–ductile; $\varepsilon_{li} > 5$ % ductile.

Another strain-based approach is to define the brittleness as $B_5 = \frac{\text{reversible strain}}{\text{total strain}} = \frac{DE}{OE}$, as shown in Fig. 1 (Hucka and Das 1974).

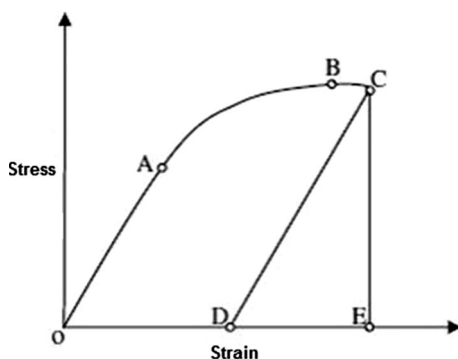


Fig. 1 Determination of brittleness from a stress–strain diagram (Hucka and Das 1974)

(C) *Reversible-energy-based approach* In this approach, the brittleness is defined as $B_6 = \frac{\text{reversible energy}}{\text{total energy}} = \frac{\text{Area DCE}}{\text{Area OABCE}}$, as shown in Fig. 1 (Hucka and Das 1974; Vihtuk 1998).

(D) *Mohr-envelope-based approach* The brittleness can be determined from Mohr's envelope at $\sigma_n = 0$ as $B_7 = \sin \varphi = [\delta\tau / \delta\sigma_n] / [1 + (\delta\tau / \delta\sigma_n)^2]^{1/2}$ (Hucka and Das 1974), where φ is the angle of internal friction for the rock.

(E) *Special-test-based approach* Brittleness values can also be determined from special tests:

$B_8 = q\sigma_c$ (Protodyakonov 1963), where q is the percentage of fines formed in the Protodyakonov impact test.

$B_9 = S_{20}$ (Blindheim and Bruland 1998), where S_{20} is the percentage of fines (<11.2 mm) formed in an impact test for TBM performance prediction in the NTNU (1998) model.

Yagiz (2009) suggested a new brittleness index obtained from the punch penetration test. His new brittleness index is $B_{10} = F_{\max} / P$ (Yagiz 2002, 2009), where F_{\max} is the maximum force applied on the rock sample (kN) and P is the corresponding penetration at maximum force (mm).

Copur et al. (2003) used the punch penetration test, defining the brittleness as $B_{11} = P_{\text{inc}} / P_{\text{dec}}$, where P_{inc} and P_{dec} refer to the force increment and decrement, respectively, in the test.

5 Experimental Studies

The testing program in this study included rock cutting, rock mechanics, and brittleness index tests. Additionally, mineralogical and petrographic analyses were performed on rock samples. A total of 24 different rock samples having different strength values, representing marble, travertine, and tuff, collected from sites around Konya Province, Turkey, were used for the small-scale linear rock cutting, rock mechanics, and brittleness index tests. The sampling locations of the rocks are shown on the geological map of the Konya region in Fig. 2. Rock block samples were transported to the Rock Mechanics Laboratory in the Mining Engineering Department of Selçuk University. Cylindrical core specimens were prepared from block samples for UCS, BTS, and PLS tests, and block samples were prepared for rock cutting tests (Fig. 3). Standard testing procedures as suggested by the International Society for Rock Mechanics (ISRM) were used for testing the cuttability and mechanical properties of the rocks. According to the mineralogical and petrographic analyses,

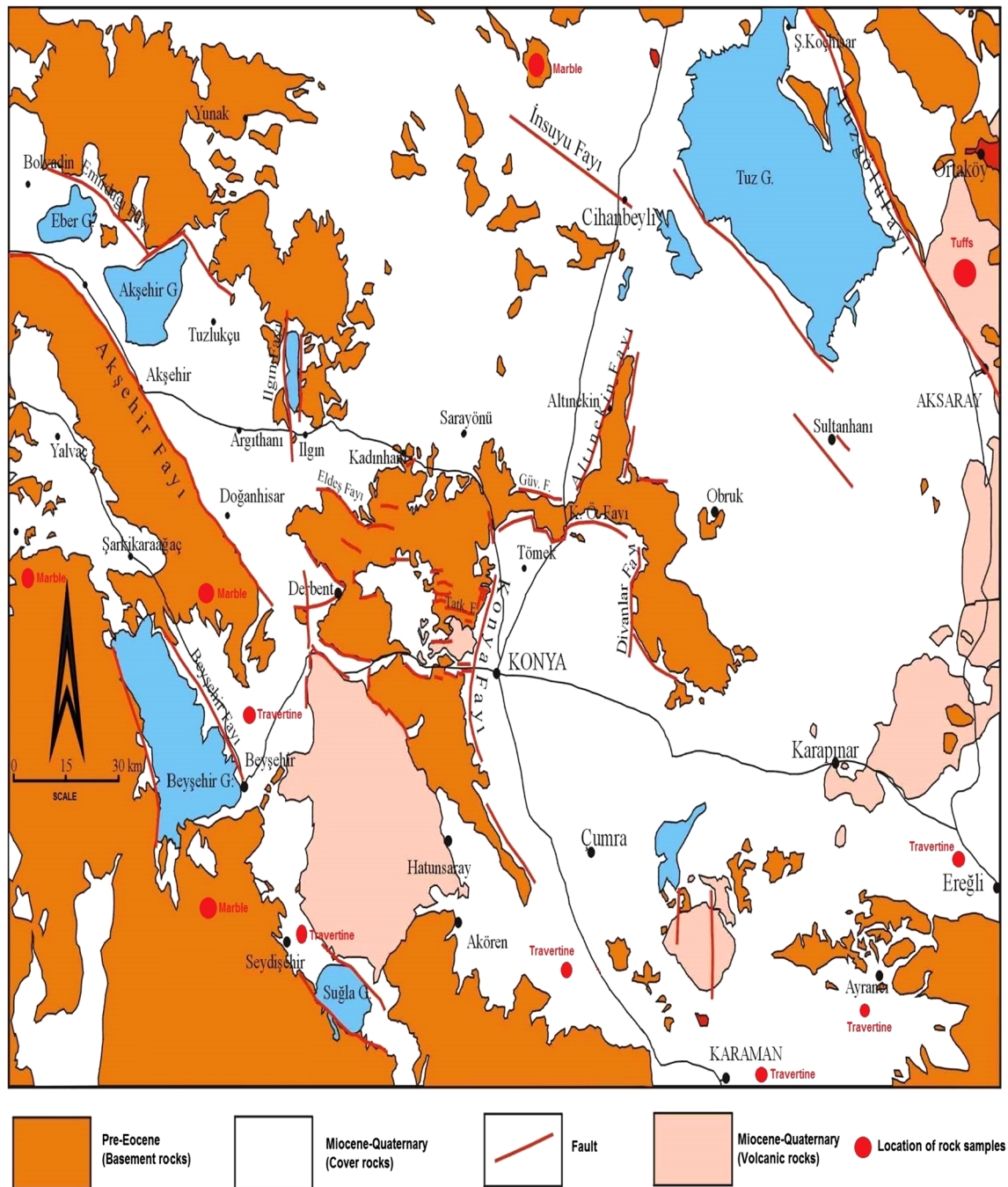


Fig. 2 Geological map of Konya region showing basement and cover rocks and main faults (prepared from geological map of Turkey at 1/500,000 scale; Koçyigit 1984; Görür et al. 1984; Eren 1993, 1996)

the marble samples were composed of a high percentage of fossil and calcite crystals. Granoblastic texture had been created by recrystallization of calcite minerals. The travertine samples were composed of high fossil and calcite crystals. The matrix of the rocks was made up of carbonates. The tuff samples were composed of quartz, biotite, and feldspar minerals, different rock fragments, and pumice grains. The groundmass of the rocks was composed of volcanic glass.

5.1 Rock Mechanics Tests

All tests were carried out in the laboratory for determination of UCS, BTS, and PLS. NX cylindrical core specimens (54 mm diameter) were prepared from block samples by drilling in such a way that the drilling direction was perpendicular to the plane of the thin section. The standard testing procedures suggested by the ISRM for testing mechanical properties of rock were

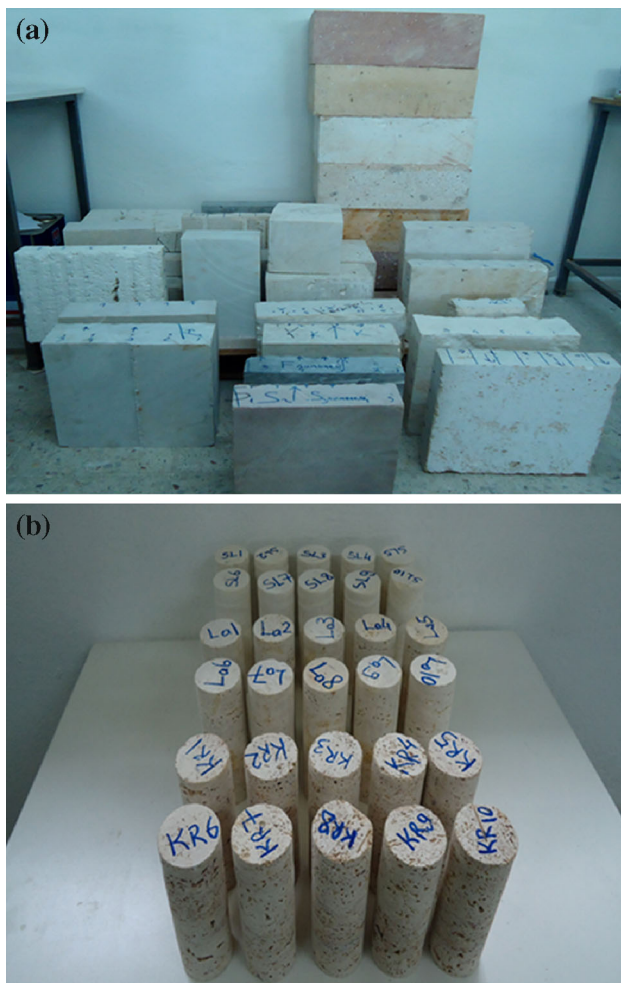


Fig. 3 Block (a) and cylindrical core (b) specimens used for rock cutting and mechanics tests

followed throughout the tests (ISRM 2007). The results of the tests related to the determination of the engineering properties of the samples are summarized in Table 1, and the testing procedures are briefly given below. The tests were repeated at least ten times for each rock type, and the average value is recorded.

The UCS values were determined on a hydraulic testing machine with capacity of 3000 kN. The loading rate was applied within the limits of 2 kN/s. Cylindrical specimens of NX diameter with length-to-diameter ratio of 2.5:1 were used.

The BTS tests were performed on disc specimens of NX diameter and length-to-diameter ratio of 0.5–1, loaded using a hydraulic testing machine with capacity of 3000 kN. The loading rate was applied within the limits of 0.2 kN/s. The tensile load on the specimens was applied continuously at constant stress rate, such that failure would occur within 5 mm of displacement.

The PLS test was intended as an index test for the strength classification of rock materials. Specimens used for PLS were NX size drill core samples with 1:2 ratio, tested across their diameter.

5.2 Rock Cutting Tests

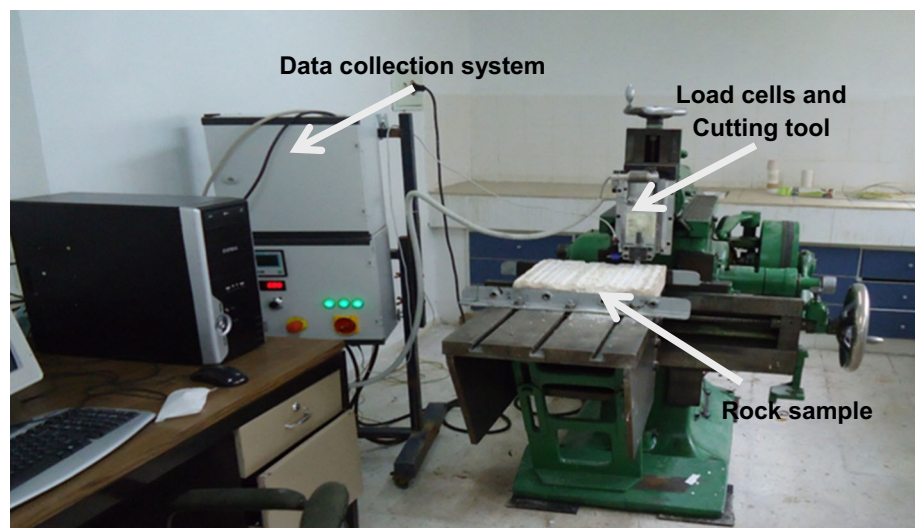
A small-scale rock cutting test rig has been developed for determination of cuttability of rocks. This test rig, which is a modified Kloop shaping machine having a stroke of 450 mm and a power of 4 kW, was used (Fig. 4). The rig, which is similar to the one originally developed by Fowell and McFeat-Smith (1976) and McFeat-Smith and Fowell (1977, 1979) is located in the laboratories of the Mining Engineering Department at Selçuk University. It is suggested as a standard laboratory rock cutting test to measure the cuttability of rocks by the International Society for Rock Mechanics Commission (Balci and Bilgin 2007). It is called the “core cutting rig,” as it was originally designed to cut core samples with diameter of 76 mm using a standard chisel tool for predicting the performance of roadheaders. Rock cutting tests were carried out using standard cutting picks on blocks of rock samples under the conditions presented in Table 2 and illustrated in Fig. 5.

The data collection system included two load cells (cutting and normal), a current and a voltage transducer, a power analyzer, an alternating current (AC) power speed control system, a laser sensor, a data acquisition card, and a computer. The data collection phase of this study included two parts: the electrical data obtained through the current and voltage transducers, and the mechanical data (tool forces) obtained using a platform-type load cell with capacity of 750 kgf. Three tests were carried out on each rock sample, in which cutting forces and electrical current and voltage were recorded. After each cutting test, the length of cut was measured and the rock cuttings for the cut were collected and weighed for specific energy determination.

The electrical parameters in the cutting process, such as current and voltage values, were recorded by the current and voltage transducers located on the power line that transfers electricity to the shaping machine. Additionally, during the time when the chisel tool was cutting the rock sample, the electrical data were recorded through the laser sensor, which was located at the current transducer in the power line. When the chisel tool completes the cutting operation, the laser sensor finishes collecting the electrical data. When analysing linear rock cutting data, it is necessary to remove the entry chip in the cut and the exit end chip from the data. The specific energy values were calculated by using Eqs. (1) and (2).

Table 1 Summary of results of rock mechanics tests

Rock code number	Rock type	UCS (MPa)	BTS (MPa)	PLS (MPa)
1	Travertine	18.56 ± 2.57	1.75 ± 0.23	2.14 ± 0.34
2	Travertine	27.55 ± 4.06	2.94 ± 0.90	3.68 ± 0.37
3	Travertine	30.69 ± 5.19	2.96 ± 0.57	4.30 ± 0.01
4	Travertine	32.23 ± 4.83	3.74 ± 0.98	3.94 ± 0.56
5	Travertine	25.95 ± 8.60	2.86 ± 0.71	3.61 ± 0.98
6	Travertine	28.11 ± 10.46	3.01 ± 0.63	4.51 ± 0.43
7	Travertine	14.82 ± 3.84	2.96 ± 0.31	3.35 ± 0.75
8	Travertine	19.22 ± 6.58	2.79 ± 0.59	3.66 ± 0.76
9	Travertine	22.45 ± 6.02	3.44 ± 0.86	3.35 ± 0.75
10	Travertine	28.19 ± 5.47	4.24 ± 0.65	4.79 ± 0.37
11	Travertine	43.95 ± 8.45	4.83 ± 1.25	4.57 ± 0.39
12	Marble	71.98 ± 11.41	6.51 ± 1.29	5.69 ± 0.71
13	Marble	80.73 ± 25.88	4.43 ± 0.55	5.73 ± 0.70
14	Marble	56.16 ± 12.77	6.04 ± 0.63	4.95 ± 0.70
15	Marble	54.63 ± 8.61	4.22 ± 0.89	3.84 ± 0.64
16	Marble	58.87 ± 12.98	4.76 ± 1.61	4.59 ± 0.94
17	Marble	71.18 ± 9.79	6.88 ± 1.21	6.95 ± 1.64
18	Tuff	19.67 ± 4.94	1.96 ± 0.61	3.04 ± 0.33
19	Tuff	4.44 ± 1.18	1.05 ± 0.09	0.76 ± 0.36
20	Tuff	7.86 ± 1.27	1.39 ± 0.12	1.17 ± 0.08
21	Tuff	11.86 ± 0.79	1.52 ± 0.14	1.69 ± 0.12
22	Tuff	11.23 ± 2.10	1.59 ± 0.35	1.58 ± 0.50
23	Tuff	8.23 ± 1.72	1.19 ± 0.46	1.37 ± 0.13
24	Tuff	9.35 ± 1.17	1.78 ± 0.36	1.29 ± 0.16

Fig. 4 Small-scale rock cutting test rig

$$SE_{\text{Mec}} = [(FC \cdot L)/Q]10^{-1}, \quad (1)$$

$$SE_{\text{Elec}} = [(P \cdot h)/Q]3.6, \quad (2)$$

where SE_{Mec} is the mechanical specific energy in MJ/m^3 , SE_{Elec} is the electrical specific energy in MJ/m^3 , FC is the average cutting force acting on the tool in kN, L is the

cutting length in cm, P is the average net power in kW, ($P = \sqrt{3}IV\cos\phi$), I is the average current during the cutting in amps, V is the average voltage in V, $\cos\phi$ is assumed to be 0.8, h is the cutting time in seconds, and Q is the volume cut in cm^3 ($Q = Y/D$, where Y is the yield in grams and D is the density in g/cm^3).

Table 2 Rock cutting test parameters

Cutting depth	2 mm
Cutting speed	36 cm/s
Rake angle	-5°
Clearance angle	5°
Pick tip material	Tungsten carbide (10 % cobalt)
Pick width	12.7 mm
Data sampling rate	1000 Hz

The rock cutting tests were performed in both the relieved (interaction between grooves) and unrelieved (no interaction between grooves) cutting mode. The effect of line spacing and depth of cut on specific energy and cutting efficiency is explained in Fig. 6. If the line spacing is too close (case a), the specific energy is very high and the cutting is not efficient, since the rock is overcrushed; tool wear is also high in this region due to high friction between the tool and rock. If the line spacing is too wide (case c),

the specific energy is very high again and the cutting is not efficient, since the cuts cannot generate relieved cuts (tensile fractures from adjacent cuts cannot reach each other to form a chip), creating a ridge or a groove-deepening (coring) situation, which might result in shock loads causing gross failures in cutting tools or stalling of the machine in some cases. The minimum specific energy is obtained for an optimum ratio of line spacing to depth of cut (case b), which indicates the most efficient cutting condition and the largest chips, as well as the minimum tool wear.

In this study, the small-scale rock cutting tests were carried out on 24 different types of rock samples at different cutter spacings. The ratio of cutter spacing to depth of cut (s/d) was maintained as 1, 2, 3, 4 or 5 through the testing program for the relieved cutting tests. Depth of cut (d) values were 2 mm for both relieved and unrelieved cuts. Cutter spacing values were varied as 2, 4, 6, 8 or 10 mm at 2 mm depth of cut depending on the sample, observations on the breakage pattern, and the fact that the

Fig. 5 Rock cutting parameters (Balci and Bilgin 2007)

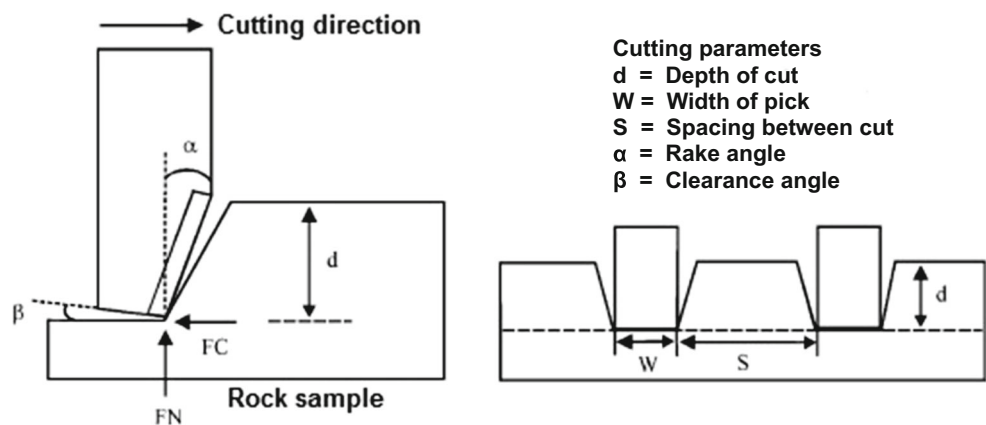


Fig. 6 Effect of line spacing and depth of cut on specific energy and cutting efficiency (Copur 2010)

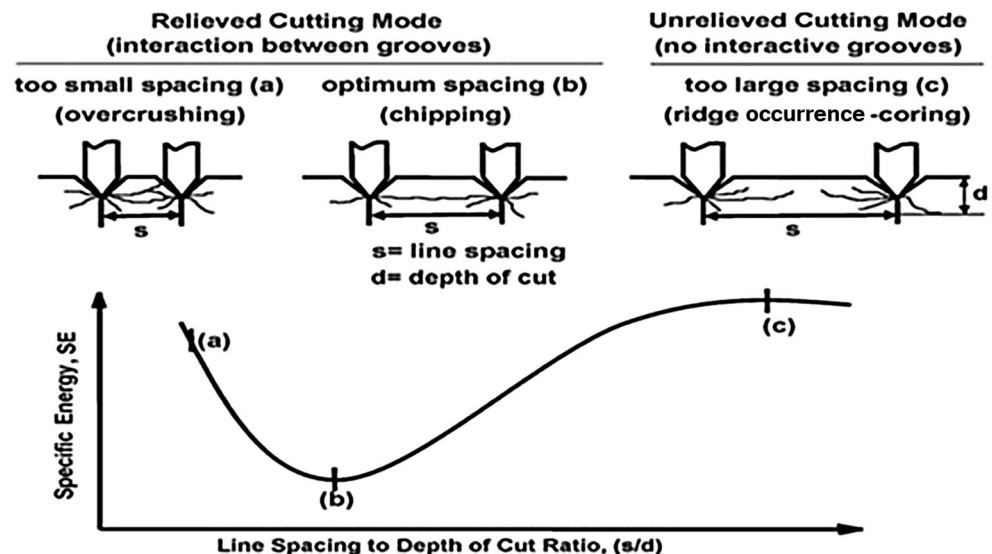


Table 3 Small-scale rock cutting test results

Rock code number	Rock type	Unrelieved cutting		Relieved cutting	
		SE1 _{Mec} (MJ/m ³)	SE1 _{Elec} (MJ/m ³)	SE2 _{Mec} (MJ/m ³)	SE2 _{Elec} (MJ/m ³)
1	Travertine	29.75	30.06	21.29	22.60
2	Travertine	28.48	26.15	23.45	21.14
3	Travertine	36.17	32.52	32.40	26.50
4	Travertine	43.89	39.70	40.08	35.59
5	Travertine	28.68	30.13	26.24	25.33
6	Travertine	38.95	38.70	38.36	32.53
7	Travertine	32.45	26.44	31.02	24.32
8	Travertine	31.24	25.98	27.18	23.71
9	Travertine	34.81	34.85	30.97	26.17
10	Travertine	38.65	33.10	35.99	32.20
11	Travertine	32.40	34.54	29.36	32.07
12	Marble	63.45	59.02	57.96	54.50
13	Marble	62.19	55.07	42.10	46.91
14	Marble	62.68	60.13	61.37	56.27
15	Marble	42.15	40.91	39.02	35.12
16	Marble	47.75	41.66	39.24	39.74
17	Marble	60.08	58.43	52.37	47.82
18	Tuff	17.42	17.70	12.92	13.84
19	Tuff	5.68	11.08	5.41	9.29
20	Tuff	6.15	11.65	5.28	8.08
21	Tuff	11.07	11.20	10.82	7.77
22	Tuff	9.84	11.83	8.19	10.75
23	Tuff	10.24	12.34	8.73	11.41
24	Tuff	7.27	8.22	7.01	7.49

optimum ratio of line spacing to depth of cut (s/d) for chisel tools usually varies between 1 and 5. In the small-scale rock cutting tests, four different specific energy values were obtained: SE1_{Mec}, SE1_{Elec}, SE2_{Mec}, and SE2_{Elec}. The specific energies SE1_{Mec} and SE1_{Elec} were obtained from unrelieved cutting with a depth of cut of 2 mm. The specific energies SE2_{Mec} and SE2_{Elec} are the optimum specific energies obtained in the relieved cutting mode with a depth of cut of 2 mm. The results of the small-scale rock cutting test are summarized in Table 3.

5.3 Brittleness Testing

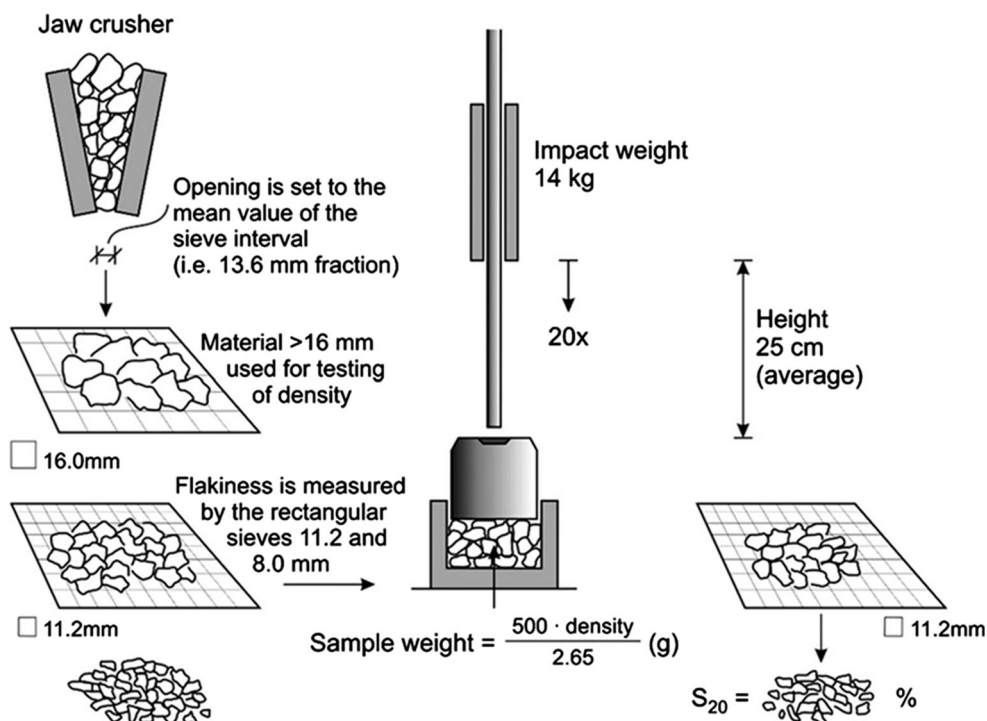
The brittleness test method, utilised by NTNU, was originally developed in Sweden by Matern and Hjelmer (1943). The original test was initially intended for determination of strength properties of aggregates, but several modified versions of the test were later developed for various purposes. The version of the S_{20} test developed for determination of rock drillability has been used since the end of the 1950s, and this brittleness value was used here, being one

of the main rock parameters for estimation of TBM performance in the NTNU prognosis model.

The direct standard testing method [S_{20} ; the percentage of fines (<11.2 mm) formed in an impact test for the NTNU model] was used for measuring rock brittleness. An outline of the test is presented in Fig. 7 (NTNU 1998). The brittleness value S_{20} was measured by the brittleness test, giving a value for the rock resistance against crushing due to repeated (20) weight-drop impacts. The tested rock sample of 500 g aggregate in the fraction 11.2–16.0 mm was inserted into the mortar. The brittleness value S_{20} is the percentage of undersized material which passes through the 11.2-mm sieve after crushing in the mortar by the weight drops. The mean value for a minimum of three replications was chosen as the rock sample's S_{20} value. In the brittleness test, the number of weight drops is dependent on the strength of the materials tested, with more weight drops being required for harder rocks (Dahl 2003).

The four previously used brittleness concepts and a predicted brittleness index were used for prediction of

Fig. 7 Outline of principle of the brittleness test (Dahl 2003)



cuttability. The results for the brittleness values are summarized in Table 4.

6 Model Development Studies

This paper is concerned with modeling the cuttability using different brittleness values of rocks. The results of the tests in the laboratory and the measured and calculated brittleness values were utilized as input variables to generate the prediction models. In the present study, statistical analyses including simple and multivariable regression analyses were carried out.

6.1 Multiple Regression Analysis

At the first stage of the modeling analysis, the data obtained for the B_9 brittleness and from the rock mechanics tests (UCS, BTS, and PLS) were evaluated by multiple regression analysis. Most problems in mining and geology involve complex and interacting forces, which are impossible to isolate and study separately (Davis 1973). Therefore, the multiple regression technique should be used to construct such complex prediction models. In this study, multiple linear regression analysis was applied for prediction of the brittleness index B_9 .

Correlation coefficients between the dependent variable and independent variables were determined using the SPSS statistical package (version 15.0) with the bivariate correlation technique. In this analysis, the correlation

coefficients between B_9 (the dependent variable) and the other selected rock properties (UCS, BTS, and PLS, the independent variables) were investigated. A correlation matrix was obtained as a result of applying the bivariate correlation technique to the test data. The correlation matrix was constructed between B_9 and the other, independent variables; Pearson's correlation coefficient (r) values are given in Table 5. The value of B_9 was well correlated with the rock properties UCS, BTS, and PLS with r values of -0.764 , -0.806 , and -0.866 , respectively. The correlation coefficients were also statistically significant at $p = 0.01$ level, and were only considered to provide rough estimates of B_9 . All types of relations between B_9 and UCS, BTS, and PLS were negative.

Multiple linear regression analysis was applied to the data for prediction of B_9 from the UCS, BTS, and PLS values of the rocks. As mentioned above, in this study, B_9 was analyzed using regression analysis techniques on the UCS, BTS, and PLS values of the rock samples. The results indicated good correlation between B_9 as the response parameter and UCS, BTS, and PLS as predictors, in a linear combination with 95 % confidence level. The resulting model developed for estimation of the brittleness index is given in Eq. (3).

$$B_9 = 0.002\text{UCS} - 0.490\text{BTS} - 4.939\text{PLS} + 91.179. \quad (3)$$

As shown in Table 6, the regression coefficient (R^2) for this equation is 0.752. This indicates that the regression model above explains 75.2 % of the total variance of the 24 datasets. A simple t test and F test analysis of the results

Table 4 Brittleness values of rocks

Rock code number	Rock type	B_1	B_2	B_3	B_9	B_{9p}
1	Travertine	10.61	0.83	16.24	74.38	79.79
2	Travertine	9.37	0.81	40.50	73.54	71.62
3	Travertine	10.37	0.82	45.42	64.05	68.56
4	Travertine	8.62	0.79	60.27	74.41	69.96
5	Travertine	9.07	0.80	37.11	66.05	72.00
6	Travertine	9.34	0.81	42.31	67.96	67.49
7	Travertine	5.01	0.67	21.93	65.32	73.22
8	Travertine	6.89	0.75	26.81	64.02	71.78
9	Travertine	6.53	0.73	38.61	75.76	73.00
10	Travertine	6.65	0.74	59.76	68.04	65.51
11	Travertine	9.10	0.80	106.14	68.52	66.34
12	Marble	11.06	0.83	234.29	60.50	60.05
13	Marble	18.22	0.90	178.82	63.05	60.89
14	Marble	9.30	0.81	169.60	57.64	63.90
15	Marble	12.95	0.86	115.27	59.75	70.27
16	Marble	12.37	0.85	140.11	66.44	66.31
17	Marble	10.35	0.82	244.86	62.97	53.64
18	Tuff	10.04	0.82	19.28	80.86	75.25
19	Tuff	4.23	0.62	2.33	86.17	86.92
20	Tuff	5.65	0.70	5.46	89.14	84.74
21	Tuff	7.80	0.77	9.01	84.24	82.11
22	Tuff	7.06	0.75	8.93	86.04	82.62
23	Tuff	6.92	0.75	4.90	88.03	83.85
24	Tuff	5.25	0.68	8.32	86.86	83.96

Table 5 Pearson's correlation coefficients between B_9 and other selected rock properties

Independent variable	r -Value
UCS	-0.764
PLS	-0.866
BTS	-0.806

Correlation significant at the 0.01 level (one-tailed)

indicates that the correlations are real and the coefficients are true (Table 6). Equation (3) was used to predict the brittleness B_9 from the UCS, BTS, and PLS values of the rocks. The relation between the measured and predicted B_9 values was determined and is presented in Fig. 8.

6.2 Simple Regression Analysis

To develop the proposed models, the database composed of the brittleness values including B_1 , B_2 , B_3 , B_9 , and B_{9p} and the rock cutting properties including $SE1_{Mec}$, $SE1_{Elec}$, $SE2_{Mec}$, and $SE2_{Elec}$ values was used. The ranges of input parameters in the database, including 216 cases, and their basic descriptive statistics are given in Table 7. The correlation matrix was constructed for all data (Table 8) to

reveal the relations among the variables. All kinds of relations between the specific energy values and the brittleness values B_1 , B_2 , and B_3 were positive and statistically significant at $p = 0.01$ level, while those between specific energy values and the brittleness values B_9 and B_{9p} were inverse and significant (Table 8).

To establish predictive models among the parameters obtained in this study, simple regression analysis was performed. A series of simple regression analyses between the independent variables (B_1 , B_2 , B_3 , B_9 , and B_{9p}) and the dependent variables ($SE1_{Mec}$, $SE1_{Elec}$, $SE2_{Mec}$, and $SE2_{Elec}$) were conducted (Table 9). These simple regression analyses provide a means of summarising the relation between two variables. During the simple regression analyses, linear, power, logarithmic, and exponential curve-fitting approximations were executed, and the best approximation equation with the highest determination coefficient was determined for each regression. Statistically significant and strong correlations were then selected (Table 9), and regression equations were established among the brittleness values and specific energy values (Table 10). The different simple regression functions were determined for the different dependent and independent variables.

Table 6 (a) Variables and summary of the model generated by regression analysis, (b) significance or t -value and coefficients for the generated model, (c) analysis of variance (ANOVA) for significance of regression of the generated model

(a) Model summary					
R	R^2	Adjusted R^2	Std. error of the estimate		
0.867	0.752	0.714	5.41029		
(b) Coefficients					
	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error			
(Constant)	91.179	2.961		30.793	0.000
UCS	0.002	0.119	0.005	0.019	0.985
BTS	-0.490	1.934	-0.796	-0.253	0.803
PLS	-4.939	1.806	-0.081	-2.735	0.013
(c) ANOVA					
	Sum of squares	df	Mean square	F	Sig.
Regression	1771.072	3	590.357	20.169	0.000
Residual	585.425	20	29.271		
Total	2356.497	23			

According to the simple regression analyses for all data, the power function showed significant relation between B_1 values and all the specific energy values. The power and exponential functions showed significant relation between B_2 values and SE_{Mec} and SE_{Elec} values. The logarithmic and power functions showed significant relation between

B_3 values and specific energy values obtained from unrelied and relieved cutting modes. The linear function showed significant relation between B_{9p} values and $SE1_{Mec}$ and $SE2_{Mec}$ values. The logarithmic function showed significant relation between B_{9p} and $SE1_{Elec}$, and the exponential function showed significant relation between B_{9p} values and $SE2_{Elec}$ values. Only the exponential function showed significant relation between B_9 values and all the specific energy values.

7 Comparison of Models and Discussion

In the present study, simple regression relation systems were constructed to predict the cuttability from measured and calculated brittleness indices. For the prediction of cuttability, the $SE1_{Mec}$, $SE1_{Elec}$, $SE2_{Mec}$, and $SE2_{Elec}$ values were predicted from the B_1 , B_2 , B_3 , B_9 , and B_{9p} brittleness values. In this section, some performance indices such as root mean square error (RMSE) and variance accounted for (VAF) are calculated and compared. All specific energy values were evaluated separately with brittleness values using the simple regression method. A total of 20 different predictive models were applied. To justify the accuracy of the developed equations, the F test was applied with a 90 % confidence level to three of the relations, revealing statistically significant correlations.

To check and compare the prediction performance of the simple regression-based models, the variance accounted for (VAF, Eq. 4) and the root mean square error (RMSE, Eq. 5) performance indices were used:

Fig. 8 B_9 predicted by multiple regression analysis versus measured values

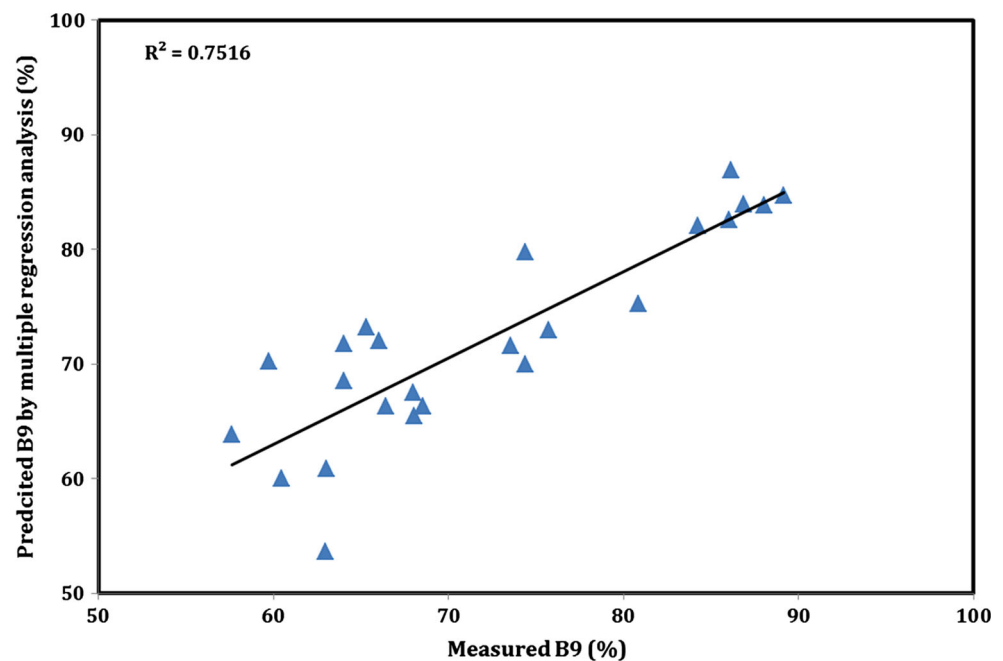


Table 7 Basic descriptive statistics for dependent and independent variables

	B_1	B_2	B_3	B_9 (%)	B_{9p} (%)	SE1 _{Mec} (MJ/m ³)	SE1 _{Elec} (MJ/m ³)	SE2 _{Mec} (MJ/m ³)	SE2 _{Elec} (MJ/m ³)
Minimum	4.23	0.62	2.33	57.64	53.64	5.68	8.22	5.28	7.49
Maximum	18.22	0.90	244.86	89.14	86.92	63.45	60.13	61.37	56.27
Mean	8.87	0.78	68.18	72.24	72.24	32.56	31.31	28.63	27.18
Median	9.09	0.80	39.56	68.28	71.70	32.43	31.33	30.17	25.75
Std. deviation	3.04	0.07	73.99	10.12	8.77	18.47	16.14	16.43	14.70
Variance	9.27	0.004	5474.06	102.46	76.99	341.31	260.43	270.05	216.16

Table 8 Pearson’s correlation coefficients of the dependent and independent variables

	SE1 _{Mec}	SE1 _{Elec}	SE2 _{Mec}	SE2 _{Elec}	B_1	B_2	B_3	B_9	B_{9p}
SE1 _{Mec}	1	0.988	0.977	0.984	0.668*	0.665*	0.877*	-0.885*	-0.934*
SE1 _{Elec}		1	0.972	0.989	0.660*	0.663*	0.900*	-0.860*	-0.922*
SE2 _{Mec}			1	0.979	0.538*	0.580*	0.848*	-0.894*	-0.918*
SE2 _{Elec}				1	0.623*	0.629*	0.903*	-0.864*	-0.916*
B_1					1	0.926	0.639	-0.567	-0.614
B_2						1	0.601	-0.592	-0.649
B_3							1	-0.703	-0.859
B_9								1	0.867
B_{9p}									1

* Correlation significant at 0.01 level

Table 9 Correlation coefficients of the simple regression between SE1_{Mec}, SE1_{Elec}, SE2_{Mec}, and SE2_{Elec} and the independent variables (brittleness values)

Dependent variable	Independent variable	Linear	Power	Logarithmic	Exponential
SE1 _{Mec}	B_1	0.668	0.693*	0.681	0.644
	B_2	0.665	0.704*	0.657	0.704
	B_3	0.877	0.935	0.943*	0.731
	B_9	0.885	0.906	0.885	0.918*
	B_{9p}	0.934*	0.897	0.930	0.919
SE1 _{Elec}	B_1	0.660	0.686*	0.678	0.648
	B_2	0.663	0.681	0.655	0.686*
	B_3	0.900	0.933	0.934*	0.787
	B_9	0.860	0.898	0.862	0.906*
	B_{9p}	0.922	0.907	0.922	0.922*
SE2 _{Mec}	B_1	0.538	0.630*	0.577	0.571
	B_2	0.580	0.648*	0.577	0.646
	B_3	0.848	0.930*	0.925	0.724
	B_9	0.894	0.920	0.896	0.930*
	B_{9p}	0.918*	0.895	0.911	0.917
SE2 _{Elec}	B_1	0.623	0.654*	0.642	0.619
	B_2	0.629	0.650	0.622	0.654*
	B_3	0.903	0.936*	0.934	0.793
	B_9	0.864	0.908	0.869	0.914*
	B_{9p}	0.916	0.908	0.914	0.924*

* Statistically significant at $p = 0.05$ level. Bold values indicate the strongest relation

Table 10 Predictive models for assessing the specific energy values

Model	Predictive model	R ² (%)
1	SE1 _{Mec} = 0.915B ₁ ^{1.574}	0.48
2	SE1 _{Mec} = 122.269B ₂ ^{6.117}	0.50
3	SE1 _{Mec} = 13.296ln(B ₃) - 14.594	0.89
4	SE1 _{Mec} = 3818.431e ^{-0.069B₉}	0.84
5	SE1 _{Mec} = 174.688 - 1.967B _{9p}	0.87
6	SE1 _{Elec} = 1.931B ₁ ^{1.236}	0.47
7	SE1 _{Elec} = 0.201e ^{6.275B₂}	0.47
8	SE1 _{Elec} = 11.499ln(B ₃) - 9.470	0.87
9	SE1 _{Elec} = 1331.247e ^{-0.054B₉}	0.82
10	SE1 _{Elec} = 546.761 - 120.636ln(B _{9p})	0.85
11	SE2 _{Mec} = 1.113B ₁ ^{1.421}	0.40
12	SE2 _{Mec} = 94.184B ₂ ^{5.593}	0.42
13	SE2 _{Mec} = 3.426B ₃ ^{0.536}	0.87
14	SE2 _{Mec} = 3447.859e ^{-0.069B₉}	0.87
15	SE2 _{Mec} = 152.855 - 1.720B _{9p}	0.84
16	SE2 _{Elec} = 1.656B ₁ ^{1.235}	0.43
17	SE2 _{Elec} = 0.172e ^{6.274B₂}	0.43
18	SE2 _{Elec} = 4.622B ₃ ^{0.452}	0.88
19	SE2 _{Elec} = 1422.213e ^{-0.057B₉}	0.84
20	SE2 _{Elec} = 2820.055e ^{-0.067B_{9p}}	0.85

$$VAF = \left(1 - \frac{\text{var}(o_i - t_i)}{\text{var}(o_i)} \times 100 \% \right), \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (o_i - t_i)^2}, \tag{5}$$

where “var” indicates the variance, *o_i* is the measured value, *t_i* is the predicted value, and *N* is the number of samples.

The interpretation of the performance indices above is as follows: the higher the VAF, the better the model performs; For example, a VAF of 100 % means that the measured output has been predicted accurately. VAF = 0 means that the model performs as poorly as a predictor using simply the mean value of the data. The lower the RMSE, the better the model performs (Grima and Babuska 1999; Gokceoglu 2002; Gokceoglu and Zorlu 2004). Contrary to the VAF, the RMSE also accounts for a bias in the model, i.e., an offset between the measured and predicted data. Theoretically, excellent prediction capacities are 100 % for VAF, 0 for RMSE, and 1 for *r*.

Considering the VAF and RMSE performance indices for each predictive model (Table 11), it is clear that the

Table 11 Results of statistical performance analysis for the generated models

Model	Specific energy value (MJ/m ³)	VAF (%)	RMSE	<i>R</i>	<i>R</i> ²	Adj. <i>R</i> ²	Standard error of estimation	<i>p</i> -Value
1	SE1 _{Mec}	79.54	14.93	0.69	0.48	0.46	0.561	0.000
2	SE1 _{Mec}	81.66	13.74	0.70	0.50	0.47	0.552	0.000
3	SE1 _{Mec}	96.68	6.00	0.94	0.89	0.89	6.270	0.000
4	SE1 _{Mec}	91.75	9.55	0.92	0.84	0.84	0.308	0.000
5	SE1 _{Mec}	96.20	6.44	0.93	0.87	0.87	6.729	0.000
6	SE1 _{Elec}	84.61	12.38	0.69	0.47	0.45	0.449	0.000
7	SE1 _{Elec}	85.36	11.94	0.69	0.47	0.45	0.449	0.000
8	SE1 _{Elec}	96.85	5.65	0.93	0.87	0.87	5.901	0.000
9	SE1 _{Elec}	93.28	8.20	0.91	0.82	0.81	0.261	0.000
10	SE1 _{Elec}	96.33	6.11	0.92	0.85	0.84	6.383	0.000
11	SE2 _{Mec}	74.58	14.81	0.63	0.40	0.37	0.599	0.001
12	SE2 _{Mec}	77.08	13.72	0.65	0.42	0.39	0.588	0.001
13	SE2 _{Mec}	93.43	7.55	0.93	0.87	0.86	0.283	0.000
14	SE2 _{Mec}	92.98	7.75	0.93	0.87	0.86	0.283	0.000
15	SE2 _{Mec}	95.28	6.37	0.92	0.84	0.84	6.656	0.000
16	SE2 _{Elec}	81.75	11.72	0.65	0.43	0.40	0.489	0.001
17	SE2 _{Elec}	82.43	11.37	0.65	0.43	0.40	0.489	0.001
18	SE2 _{Elec}	97.26	4.50	0.94	0.88	0.87	0.228	0.000
19	SE2 _{Elec}	93.23	7.14	0.91	0.84	0.83	0.262	0.000
20	SE2 _{Elec}	91.37	8.29	0.92	0.85	0.85	0.248	0.000

developed simple regression models employing the B_3 , B_9 , and B_{9p} values give better performance predictions than the other developed models employing B_1 and B_2 . Furthermore, the simple regression models developed employing the B_3 , B_9 , and B_{9p} values have lower standard error of estimation and higher correlation coefficient (r) than the other models employing the B_1 and B_2 values. Therefore, it can be said that simple regression methods are the best prediction models for estimation of $SE1_{Mec}$, $SE1_{Elec}$, $SE2_{Mec}$, and $SE2_{Elec}$ values from B_3 , B_9 , and B_{9p} values in this study.

In this work, rock cutting tests were performed on only three types of rock having different strength values. According to this, the prediction models developed in this paper (Table 10) can be used for estimation of cuttability for similar rock types such as marble, tuff, and travertine. In addition, practitioners should take rock mass, rock texture, and petrographic and mineralogical features of rocks into consideration as well, because discontinuities of the rock or rock mass, stress state, contents of abrasive mineral of rocks, and other rock conditions usually play a relevant role in actual excavation performance.

The values of B_1 brittleness ranged from 4.23 to 18.22, whereas the values of B_2 brittleness ranged from 0.62 to 0.90. The lack of correlation between the specific energy values and the B_1 and B_2 brittleness values may be a result of the rock types and mineralogical and petrographic properties of the rock samples, or may be because of this narrow range (for B_2). Three different rock types including marble, travertine, and tuff were tested in this study with UCS in the range of 4.44–80.73 MPa and BTS in the range of 1.05–6.88 MPa. This is probably due to the fact that rock types having different strengths may have a similar ratio, similar brittleness, and specific energy values. Moreover, Altindag (2003), Goktan and Yilmaz (2005b), and Tiryaki (2006) could not find a relation between specific energy and the B_1 and B_2 brittleness values. On the other hand, Altindag (2003) and Tiryaki (2006) indicated that there was strong correlation between specific energy and B_3 brittleness. Consequently, it can be said that the results of this study parallel those of previous studies.

$S_{20} = B_9$ has been used as a method for TBM performance prediction testing and drillability testing by different researchers. However, relations between the brittleness B_9 and the cuttability have not been investigated in detail so far. The major difference between this study and previous studies is that the rock cuttability is directly predicted using the B_9 and B_{9p} brittleness values.

8 Conclusions

Rock cuttability is a key parameter in mechanical excavation projects. However, to obtain the mean cutting force and specific energy from small- or full-scale cutting tests is

very difficult and expensive. For this reason, we investigated the relations between cuttability and brittleness and suggest some empirical models for estimation of the specific energy. Twenty-four different rock samples with different strength values for marble, travertine, and tuff were tested in the laboratory to investigate the relations between the specific energy and different brittleness values.

Simple regression analyses were performed to determine the best and most reliable correlations between the specific energy and the brittleness values derived. Approximately 20 predictive models were determined. The performance of these models was checked by using the coefficient of determination, VAF, and RMSE statistical performance indicators. According to these performance indicators, the prediction performance of the predictive models including B_3 , B_9 , and B_{9p} was found to be better than for the other models including B_1 and B_2 . The proposed simple regression-based models (including B_3 , B_9 , and B_{9p} brittleness) were shown to perform best, with VAF varying between 91.37 and 97.26 %, RMSE between 4.50 and 9.55, standard error of estimation between 0.228 and 6.729, and correlation coefficients between 0.91 and 0.94.

The results of this study were compared with results previously obtained by different researchers, showing agreement between this and previous studies. The conclusion is that B_3 , B_9 , and B_{9p} can be used for assessment of rock cuttability.

This paper aims to develop easy and inexpensive prediction models to help performance prediction. The simple regression technique used in this paper demonstrated very satisfactory results in predicting specific energy values. Relatively few published studies are available on the relation between rock brittleness and rock cutting efficiency. B_9 has been used as a method for TBM performance prediction testing and drillability testing. However, in this study, B_9 is used for prediction of specific energy obtained from small-scale rock cutting tests. Specific energy values obtained from small-scale linear cutting experiments are used for predicting the performance of roadheaders and simulation of the cutting action of chain saw machines, being one of the activities performed in this research differentiating it from similar works done in the past.

It is concluded that the developed prediction models can be used for prediction of cuttability. Therefore, it is recommended to test the target rock using B_3 , B_9 , and B_{9p} values for cuttability when encountered in tunneling or roadway development works in mining. It is believed that the $SE1_{Mec}$, $SE1_{Elec}$, $SE2_{Mec}$, and $SE2_{Elec}$ values obtained by employing B_3 , B_9 , and B_{9p} as predictors through the simple regression methods will help field engineers to determine whether a target rock is suitable for mechanical excavation with tungsten carbide-tipped picks. The

statistical models developed in this study are valid for these types of rock. These models can be reliably used for estimation of specific energy in preliminary studies. It should be pointed out that the basic aim of this study was to analyze the fundamental relation between rock brittleness and specific energy based on laboratory experiments, without taking into account the possible effects of various in situ conditions. While this is shown to be a promising technique, it is emphasized that the validity of the presented approach should be further investigated for other rock types and cutting conditions.

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