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Effects of Rock Properties on Specific Cutting Energy in Linear Cutting of Sandstones by Picks

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Summary

Specific cutting energy (SE) has been widely used to assess the rock cuttability for mechanical excavation purposes. Some prediction models were developed for SE through correlating rock properties with SE values. However, some of the textural and compositional rock parameters i.e. texture coefficient and feldspar, mafic, and felsic mineral contents were not considered. The present study is to investigate the effects of previously ignored rock parameters along with engineering rock properties on SE. Mineralogical and petrographic analyses, rock mechanics, and linear rock cutting tests were performed on sandstone samples taken from sites around Ankara, Turkey. Relationships between SE and rock properties were evaluated using bivariate correlation and linear regression analyses.

The tests and subsequent analyses revealed that the texture coefficient and feldspar content of sandstones affected rock cuttability, evidenced by significant correlations between these parameters and SE at a 90% confidence level. Felsic and mafic mineral contents of sandstones did not exhibit any statistically significant correlation against SE. Cementation coefficient, effective porosity, and pore volume had good correlations against SE. Poisson's ratio, Brazilian tensile strength, Shore scleroscope hardness, Schmidt hammer hardness, dry density, and point load strength index showed very strong linear correlations against SE at confidence levels of 95% and above, all of which were also found suitable to be used in predicting SE individually, depending on the results of regression analysis, ANOVA, Student's t-tests, and R^2 values. Poisson's ratio exhibited the highest correlation with SE and seemed to be the most reliable SE prediction tool in sandstones.

Keywords: Specific cutting energy, linear rock cutting, picks, texture coefficient, rock properties, bivariate correlation, linear regression.

1. Introduction

Mechanical excavators employing picks have been widely used throughout the world in tunneling and mining for very low to medium-strength rocks including sandstones. Sandstones are frequently met in excavations for coal mining, as they are a part of the coal measures strata, and in civil tunneling. Roadheaders, continuous miners, and coal shearers are the mechanical excavators that cut sandstones in various mining and tunneling operations by means of picks mounted on their cutting heads or drums.

The benefits offered by these machines are maximized when they are matched against the properties of rock or coal to be excavated. Small changes in rock properties were reported to affect the performance of the mechanical excavators adversely (McFeat-Smith, 1977). Cutting rate, pick forces, SE, pick consumption, and cutting vibrations restrict their applications. These measures of machine performance are strongly related to the engineering properties of rocks. These properties such as strength, hardness, toughness, and brittleness are also functions of rock texture and mineralogy (Irfan and Dearman, 1978; Bell, 1978; Hugman and Friedman, 1979; Onodera and Asoka Kumara, 1980; Howarth, 1986; Howarth and Rowlands, 1986, 1987; Shakoor and Bonelli, 1991; Ulusay et al., 1994; Tugrul and Zarif, 1999). Therefore, selection of mechanical excavators for a particular operation must be based on a careful assessment of the properties of the rock environment. This must be achieved by practical means of rock property testing since downtimes with any mechanical excavation process can decrease the overall system efficiency and profitability.

Rock cuttability, an important parameter in mechanical excavation, can be determined through linear rock cutting tests in the laboratory. The cuttability of a rock by picks can be expressed by the forces acting on the pick and SE consumed during the tests. Rock cutting tests are carried out by cutting the rock samples of proper dimensions using a standard chisel pick on a test rig. These tests are expensive and time-consuming, and they require complicated laboratory facilities using high quality samples.

Since lower pick forces may accompany lower yield in some cases, they are not used alone to define the rock cuttability. SE is defined as the energy required to cut the unit volume (or mass) of rock material. It can be calculated using the mean cutting force measured during rock cutting tests. SE is recommended to express rock cuttability together with the pick forces (Barker, 1964; Hughes, 1972; Roxborough, 1973; Roxborough and Rispin, 1973; Evans and Pomeroy, 1973; Hurt, 1980).

It is of vital importance to predict the rock cuttability in order to prevent the mechanical excavator from harmful vibrations and excessive pick consumption when a rock with high strength is experienced in any excavation process. SE from laboratory linear cutting tests was reported to be in a good correlation with in-situ performance of roadheaders. Fowell and Pycroft (1980) developed a scale correlating the types of roadheaders with their possible performances regarding SE of the rock material. A reasonable relationship was found between laboratory and in-situ SE values for roadheaders used in coal measures strata (McFeat-Smith and Fowell, 1977). Some prediction models for laboratory SE were also developed for proper selection and optimization of mechanical excavators for particular rock conditions through previous studies, which involved rock properties as predictors. However, literature surveys revealed that some parameters involved, particularly in rock texture concept along with some of the compositional rock properties, were not taken into account during the development of such models.

This paper is concerned with the effects of textural, mineralogical, and engineering properties of very low to medium-strength sandstones on SE. For this purpose, comprehensive mineralogical-petrographic analyses, rock mechanics, and linear rock cutting tests were carried out. Sandstone samples from different sites around Ankara, Turkey were used in these experiments. Textural and mineralogical rock properties that were not considered in previous studies were taken into account with this study. Relationships between independent variables measured throughout the tests and SE were investigated statistically by using bivariate correlation and linear regression techniques. This study revealed that the textural and compositional rock properties affected SE, together with engineering properties of rocks.

2. Influences of Rock Properties in Linear Cutting of Rocks by Picks

When a pick is forced into the rock to break it into pieces, a highly stressed zone is produced under the pick tip. As the pick is kept pressed into the rock, pick forces exceed the strength of the material and material is cracked. Most of the mineralogical-petrographic and strength properties of rock are effective at this stage. Cracks are initiated and propagated through the free surface and laterally into the rock. Rock texture behaves like a physical barrier to crack propagation. In the final stage, rock is fragmented whenever one of the main cracks reaches the free surface.

McFeat-Smith and Fowell (1977) carried out the best-known study correlating the intact rock properties with SE, in which samples of coal and coal measures strata were subjected to linear cutting in the laboratory. Researchers tried to correlate SE and pick wear rate respectively with petrographic and a wide range of engineering properties of rocks. They have analyzed the test data using a stepwise curvilinear multiple regression technique and developed an equation for the prediction of laboratory SE. They have also developed 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 (UCS), cone indenter and Shore hardness indices of rocks in rock cutting.

Brittleness and toughness are known to be closely related to the rock cuttability although no generally accepted test procedures not requiring complicated laboratory facilities have been developed to determine these properties up to now. UCS has been used in assessing the cuttability of rock and in selecting the mechanical excavator especially for coal measures strata, as there was no reliable prediction model. UCS may be a reliable parameter to predict the rock cuttability for a particular rock type, since strong relationships are available between the UCS, toughness, and brittleness of different rocks for any rock type. However, reasonable correlations have not been reported between the UCS and rock cuttability for evaporates such as gypsum and anhydrite, although they are sedimentary rocks like coal measures strata. Cutting some evaporates by picks have been found to be more difficult than coal measures strata with similar UCS values. This may be attributed to the development and interlocking of the large grains that form evaporates during the deposition process, implying the significance of textural properties of rocks in rock cutting (Speight, 1997).

2.1 Rock Texture

Howarth and Rowlands (1986) developed a model to predict the drillability and strength properties of rocks through quantifying the rock texture by a dimensionless texture coefficient. This model depends on textural properties of rocks such as grain shape and orientation, degree of grain interlocking, and the packing density. All these parameters are determined through the mineralogical-petrographic examination of thin sections using an automatic microscopic image analysis system. A rock with a higher texture coefficient is assumed physically resistant to crack propagation initiated by a mechanical tool. Therefore, rocks with lower texture coefficient values are expected to have lower strength and to be drilled at higher rates relative to the rocks with higher texture coefficient values.

Howarth and Rowlands (1987) used three different rock types in their study and found good correlations between UCS, uniaxial tensile strength (UTS), modulus of elasticity, laboratory-drilling rate, and the rock texture coefficient. They reported that higher texture values were coupled with higher strength and low drilling rates for igneous rocks, whilst sandstone had lower values of strength and higher drillability with lower texture coefficients. Fracture modes of sandstones were predominantly intergranular and through the weakly cemented phillosilicate matrix, as intragranular fractures were dominant with igneous rocks. Relying upon these results and observations, they concluded that the rock texture was a physical barrier to the crack propagation and texture coefficient model could be considered as a measure of the resistance of the microstructure of rocks to crack propagation. Details of texture coefficient model can be found elsewhere (Howarth, 1986; Howarth and Rowlands, 1986, 1987).

The study of Azzoni et al. (1996) on rocks with four lithotypes produced similar results to those obtained by Howarth and Rowlands (1987). They found a direct relationship between the texture coefficient and UCS values for the rocks included in any lithotype. When all rocks from different lithotypes were considered together, this relationship was less evident. Azzoni et al. (1996) reported that texture coefficient model can be used as a parameter to classify rocks with respect to their lithotypes, but cannot be used to predict precisely their mechanical properties, since this model does not include the significant petrographic parameters of porosity and mineralogical composition.

Ersoy and Waller (1995) found a direct relationship between the texture coefficient and drilling rate for sandstone, which is contrary to findings of Howarth and Rowlands (1987). Ersoy and Waller (1995) reported that higher texture coefficient for the low strength sandstone with weakly bonded large grains, higher packing density, and higher porosity was accompanied with higher drilling rates and lower strength. Since the sandstone was large grained and had a higher packing density, it had a higher texture coefficient. A similar result was also observed with a limestone of identical textural and physical properties as for sandstone, which was also cemented with very soft calcite. Both sandstone and limestone were drilled at rates higher than rocks with lower texture coefficients. Ersoy and Waller (1995) attributed these unusual results for sandstones to the high porosity, weak bonding between grains and weak matrix, all accounting for the lower strength and higher drillability of the sandstones used in their study. The type and degree of cementation is also an additional factor leading the limestone to have a lower strength and higher drillability. Therefore, Ersoy and Waller

(1995) proposed to take into consideration the bonding structure and type and degree of cementation together with the other properties of rock constituents in textural characterization of rocks.

3. Experimental Studies

The effects of textural, compositional, and engineering properties of rocks on cuttability were investigated (Dikmen, 2002). For this purpose, detailed mineralogical analyses, petrographic studies, rock mechanics, and linear rock cutting tests were performed on selected sandstone specimens.

A total of 18 different rock samples, which are homogeneous without visible discontinuities, were taken from sites around Ankara, Turkey. These sites have been investigated both geologically and tectonically in detail. Detailed mineralogical analyses, petrographic studies, and rock mechanics tests were carried out. Then, preliminary linear rock cutting tests were performed on all samples to select the rock samples on which standard rock cutting tests could be conducted properly within the power capacity of the rock cutting rig available. These tests revealed that samples with the exception of sandstones coded L8A, L8B, L10, L14, L16, and L18 were not suitable for mechanical excavation using light or medium duty roadhaders. Coordinates of sampling locations for the sandstone samples employed in further analyses and tests, which were determined by a global positioning system device, are given in Table 1.

3.1 Mineralogical and Petrographic Studies

X-ray fluorescence (XRF) analysis results of test samples are given in Table 2. Thin sections belonging to each sample were prepared for petrographic and modal analyses

Table 1. Sampling locations of sandstones

Rock sample	Rock type	Region	Global position		
			east	north	altitude (m)
L8A	sandstone	Haymana-Cayraz	59922	69348	1097
L8B	sandstone	Haymana-Cayraz	59922	69348	1097
L10	sandstone	Haymana	58267	70118	1068
L14	sandstone	Memlik-Degirmentepe	80186	37051	1203
L16	sandstone	Bala (Northern)	81045	38875	1210
L18	sandstone	Memlik-Saribeyler	80782	40495	1224

Table 2. Results of XRF analysis

Rock sample	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	P_2O_5 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)	SO_3 (%)	Fire loss (%)
L8A	0.63	2.38	10.70	61.07	0.00	2.50	15.57	0.00	0.00	4.50	0.09	2.47
L8B	0.66	3.17	13.68	62.38	0.00	4.01	6.90	0.00	0.00	6.06	0.09	4.55
L10	0.60	2.56	12.01	64.26	0.00	3.30	10.35	0.00	0.00	4.92	0.13	2.20
L14	1.86	2.89	9.79	62.37	0.10	1.86	10.82	0.93	0.10	4.74	0.00	4.12
L16	1.75	5.26	9.79	63.92	0.10	1.03	8.04	1.13	0.10	6.80	0.00	1.88
L18	2.06	3.61	9.18	61.34	0.10	1.13	12.89	0.72	0.10	5.36	0.00	4.84

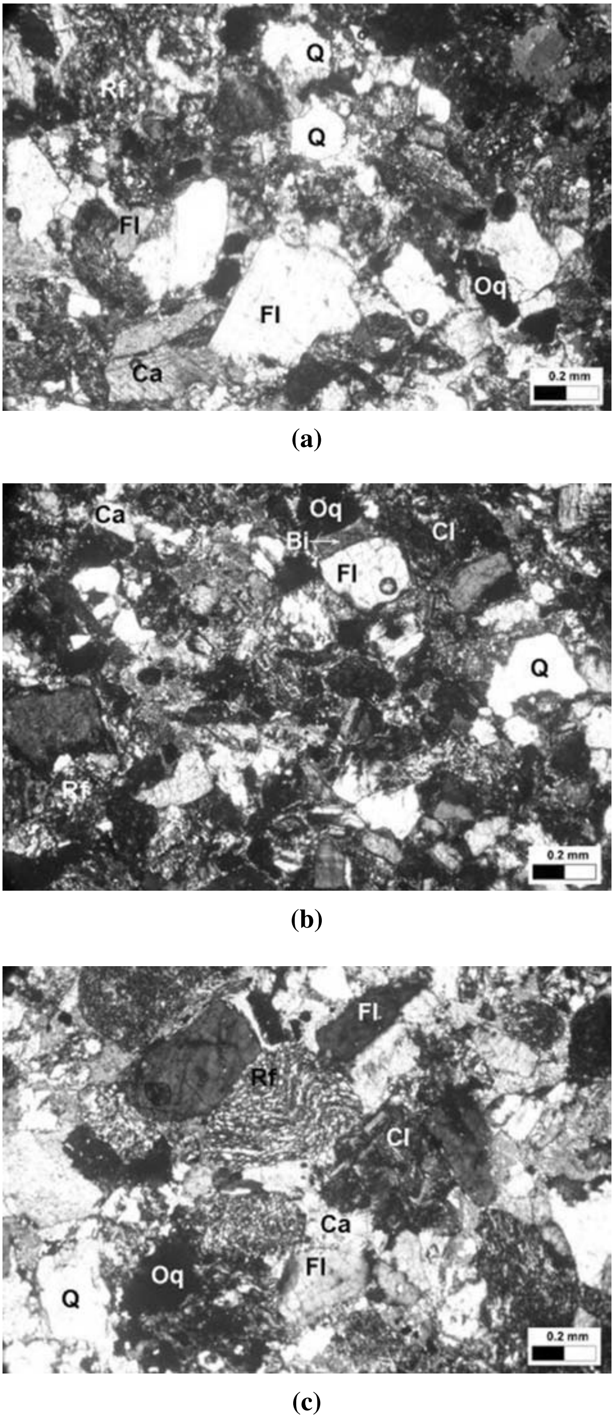
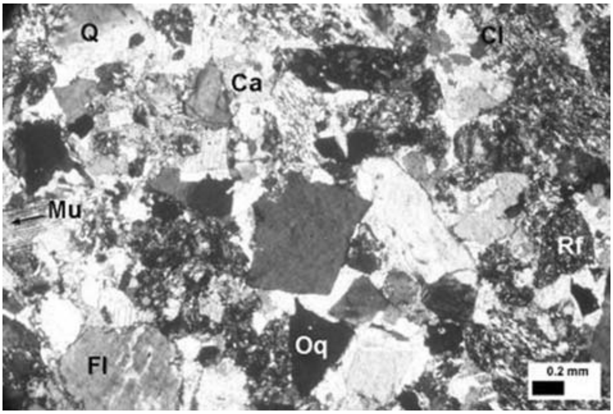


Fig. 1. Photomicrographs of thin sections: (**a**) L8A (**b**) L8B (**c**) L10 (**d**) L14 (**e**) L16 (**f**) L18, *Q*: Quartz, *Ca*: Calcite, *Rf*: Rock fragments, *Ep*: Epidote, *Oq*: Opaque mineral, *Cl*: Chlorite, *Fl*: Feldspar, *Mu*: Muscovite, *Bi*: Biotite



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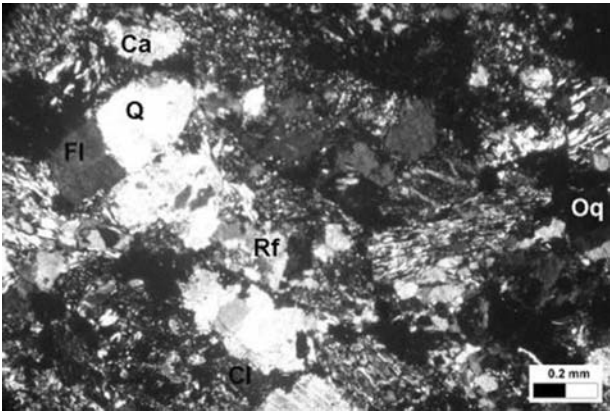

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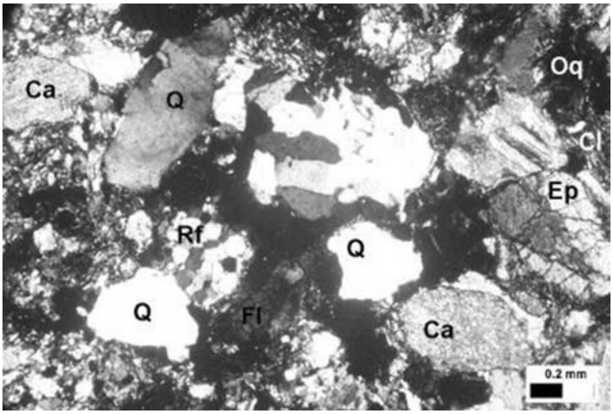

(f)

Fig. 1 (*continued*)

and the determination of textural rock characteristics including the texture coefficient. Photographs of each thin section were taken using a digital camera together with an Optiphod – Polarized microscope. Petrographic images of thin sections are given in Fig. 1. Primary and secondary minerals were identified and their grain sizes evaluated. Two thin sections were produced for each sandstone sample, parallel and normal to the direction of mechanical tests. Since the direction of thin section preparation for sandstones did not affect their textural properties, no thin sections in random directions were prepared, based on the study of Howarth and Rowlands (1987). Visual analysis of thin sections confirmed this, revealing that the parameters determined in thin section analysis were not influenced by the direction of thin section preparation, with the exception of sample L8B whose thin section, taken in direction parallel to mechanical property testing, contained basalt particles that were not visible in a thin section taken in normal direction (Table 3). Therefore, thin sections prepared normal to the direction of mechanical tests for each sample were used in subsequent mineralogical and petrographic studies. Cementation coefficients of sandstone samples were determined according to McFeat-Smith (1977).

Results of the modal analysis of thin sections are given in Table 4. In studying thin sections for texture coefficient determination, a reference area that included 100 mineral grains and rock fragments was chosen. For every grain and particle within this area, geometrical parameters required for calculations were determined. Rock texture coefficients for each thin section were calculated using the equation given by Howarth and Rowlands (1987).

Two texture coefficient values were calculated for each thin section (Table 5). The first coefficient (TC I) was determined using the method proposed by Howarth and Rowlands (1987); whilst a new method was adopted to calculate the second coefficient (TC II). The TC II values given in Table 5 were calculated by taking into account the mineral grains existing within the rock fragments in thin sections, incorporation with the matrix structures for both the overall thin section and rock fragments and bonding between the grains, rock fragments, and the matrix.

3.2 Engineering Properties of Sandstones

According to the engineering classification of intact rock based on the UCS value, as proposed by Deere and Miller (1966), sandstone samples L8A, L14, and L16 are medium strength rocks, L10 and L18 are low strength rocks, whilst L8B is a very low strength rock (Jumikis, 1979). Tests for determining the engineering properties of sandstones were conducted following the mineralogical and thin section examinations. All tests carried out for the determination of engineering properties of sandstones, except the Schmidt hammer tests, were carried out in laboratory. Schmidt hammer tests were carried out in the field on fresh outcrops of sandstone layers. Sandstone blocks sampled from sites around Ankara, Turkey were coated with microcrystalline wax using layers of muslin and were then transported to the Rock Mechanics Laboratory at the Mining Engineering Department of Hacettepe University.

Cylindrical core specimens were prepared from block samples for physical property testing and compression, Brazilian, Shore scleroscope, and point load

Table 3. Petrographic analysis of thin sections

Rock sample	Mineral content	Type of cementation	Cementation coefficient	Rock fragments	Mean grain size (mm)	Percentage of grains and rock fragments (%)	Percentage of matrix (%)	Chracteristics property
L8A (N-P)	calcite, feldspar, quartz, serisite, chlorite, opaque mineral	ferruginous and clay	3	basalt, chert, limestone	0.19	87	13	high percentage of feldspar
L8B (N-P)	feldspar, calcite, quartz, serisite, muscovite, chlorite, opaque mineral	ferruginous and clay	3	chert, limestone (+Basalt (P))	0.18	85	14	high percentage of feldspar
L10 (N-P)	calcite, quartz, feldspar, serisite, chlorite, opaque mineral	silica and carbonate	7	chert, limestone, basalt	0.29	92	8	remarkable orientation
L14 (N-P)	calcite, quartz, feldspar, muscovite	silica	8	basalt, limestone, marble, chert	0.32	93	7	high percentage of calcite and small amount of bonding material
L16 (N-P)	quartz, feldspar, calcite, chlorite, muscovite, serisite, opaque mineral	silica	8	marble, chert, basalt	0.52	72	28	large grained
L18 (N-P)	quartz, feldspar, chlorite, pyroxene, serisite, opaque mineral	silica	8	quartzite, basalt, chert, limestone	0.21	75	25	high percentage of pyroxene

N: Normal to the direction of mechanical property testing.
P: Parallel to the direction of mechanical property testing.

Table 4. Results of the modal analysis

Rock sample	Quartz (%)	Feldspar (%)	Muscovite (%)	Biotite (%)	Chlorite (%)	Serisite (%)	Calcite (%)	Pyroxene (%)	Opaque minerals (%)	Epidote (%)	Mafic minerals (%)	Felsic minerals (%)	Mineral grains (%)	Rock fragments (%)
L8A	38.65	38.65	0.39	3.86	2.32	2.13	6.38	3.70	3.38	0.19	8.50	84.06	95.94	4.06
L8B	38.63	36.87	0.53	3.86	5.62	2.63	5.97	0.0	3.42	0.35	12.47	82.00	97.89	2.11
L10	30.11	23.16	0.23	1.04	3.59	1.39	37.06	0.0	0.87	1.16	7.18	90.56	98.61	1.39
L14	44.05	14.68	5.58	1.76	1.62	1.32	27.75	0.0	1.17	0.15	4.85	92.07	98.09	1.91
L16	27.47	41.21	0.55	0.27	3.30	1.37	10.44	0.0	0.82	0.27	5.22	79.67	85.71	14.29
L18	41.90	13.97	0.84	0.28	3.91	1.12	24.58	0.0	0.56	6.98	12.29	81.28	94.13	5.87

Table 5. Parameters related to determination of texture coefficient

Rock sample	$\frac{N_0}{N_0+N_1}$		$\frac{1}{FF_0}$		$\frac{N_1}{N_0+N_1}$		AR_1		AF_1		Packing density (AW)		Texture coefficient (TC)	
	I	II	I	II	I	II	I	II	I	II	I	II	I	II
L8A	0.69	0.69	8.120	8.65	0.31	0.31	2.40	2.21	1.72	1.79	0.29	0.312	1.989	2.246
L8B	0.71	0.71	8.270	9.26	0.29	0.29	2.31	2.26	1.54	1.75	0.32	0.315	2.196	2.432
L10	0.21	0.21	6.320	39.81	0.79	0.79	2.73	3.21	1.36	1.38	0.36	0.402	1.609	4.767
L14	0.45	0.45	7.760	19.42	0.45	0.55	2.32	2.91	1.23	1.12	0.452	0.520	1.012	5.476
L16	0.35	0.35	9.960	24.88	0.576	0.65	2.31	2.31	1.10	1.09	0.36	0.208	1.846	2.152
L18	0.40	0.40	8.970	66.35	0.587	0.60	2.32	2.61	1.13	1.05	0.315	0.212	1.674	5.973

tests, whilst specific specimen preparation steps were followed for the NCB cone indenter tests. Core specimens NX (54 mm) and BX (41 mm) in diameter for tests were obtained by drilling the sandstone samples in laboratory in such a way that the drilling direction was perpendicular to the plane of thin sections taken from the samples. Disc specimens for the Brazilian test were machined from cylindrical core specimens. Specimens for the compression and Brazilian tests were trimmed and processed using abrasive materials in an effort to ensure them having parallel ends.

All the test specimens were oven-dried at 105 °C for 24 h before testing except the point load tests, which were performed at natural water content. The standard testing procedures suggested by the ISRM (International Society for Rock Mechanics) for testing physical and mechanical properties of rocks were followed throughout the tests, with the exception of the NCB cone indenter tests (Brown, 1981).

3.2.1 Physical Properties

Physical properties of sandstones were determined by water saturation and caliper techniques on BX size specimens, by using at least five specimens each time. Dry and saturated densities, pore volume, and effective porosity of sandstone samples were determined on cylindrical rock specimens in accordance with the procedures suggested by ISRM (Brown, 1981). The mean values of the relevant physical properties are summarized in Table 6.

Table 6. Physical properties of sandstone specimens

Rock sample	Dry density (gr/cm^3)	Saturated density (gr/cm^3)	Pore volume (cm^3)	Effective porosity (%)
L8A	2.45	2.73	2.93	5.4
L8B	2.24	2.8	8.75	13.1
L10	2.36	2.77	4.87	6.5
L14	2.56	2.77	1.3	3.8
L16	2.49	2.84	6.87	5.3
L18	2.61	2.76	4.43	3.1

Table 7. Mechanical properties of sandstone specimens

Rock sample	UCS (MPa)	UTS (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
L8A	62.030	3.510	8.454	0.18
L8B	21.267	1.965	6.143	0.10
L10	48.173	2.535	17.309	0.14
L14	87.533	6.340	45.311	0.35
L16	55.750	4.323	47.273	0.18
L18	44.287	4.533	18.355	0.31

3.2.2 Mechanical Properties

Mechanical properties of rocks were determined according to ISRM specifications using cylindrical core specimens of sandstone (ISRM, 1978b, 1979; Brown, 1981). UCS, elasticity modulus, and Poisson's ratio values were determined on a stiff testing machine with a capacity of 3000 kN at a loading rate of 0.05 kN/sec. Cylindrical specimens NX in diameter with a length to diameter ratio of 2.5:1 were used. UTS was determined by using the Brazilian testing method. Disc specimens NX in diameter with a thickness to diameter ratio of 1:2 were loaded using a MTS-type hydraulic machine with a capacity of 10 ton at very low machine-controlled loading rates. The results obtained are summarized in Table 7.

3.2.3 Index Properties

Shore scleroscope, Schmidt hammer hardness, point load, and dry unit weight values of sandstone specimens were determined in accordance with the suggestions of ISRM (ISRM, 1978a; Brown, 1981; ISRM, 1985). Instructions from NCB were followed for the determination of cone indenter values for sandstone specimens (NCB, 1977). Results of the relevant index tests are given in Table 8.

Shore scleroscope tests were conducted on the flat surfaces of cylindrical core specimens of sandstones using a Model C-2 shore scleroscope. Five specimens were tested for each sandstone sample. Twenty individual tests were conducted on each specimen, separated by at least 0.5 cm. Shore hardness of each specimen was determined by averaging the mean values obtained from individual test specimens. Schmidt hammer rebound tests were carried out on fresh surfaces of outcrops of sandstones by

Table 8. Engineering index properties of sandstone specimens

Rock sample	Shore scleroscope hardness	Schmidt hammer hardness	NCB cone indenter hardness	Point load strength index (MPa)	Dry unit weight (kN/m^3)
L8A	41.55	35	4.422	1.69	24.035
L8B	25.70	36	1.880	1.16	21.974
L10	32.90	38	3.168	1.70	23.152
L14	53.70	52	3.797	3.02	25.114
L16	42.70	34	3.934	3.10	24.427
L18	53.35	43	3.440	2.93	25.604

using a calibrated L-type Schmidt hammer in the field. Twenty individual tests were conducted on these surfaces, separated by at least a plunger diameter, in which the longitudinal axis of the hammer was perpendicular to the outcrop surface. Schmidt hammer hardness values of sandstones were determined by averaging the mean values obtained from individual test areas.

Cone indenter tests were conducted on the small pieces of specimens $12 \times 12 \times 6\,\text{mm}$ in size for each sandstone sample using a standard NCB cone indenter apparatus. Ten tests were carried out for each sandstone sample to determine the cone indenter hardness. The mean cone indenter hardness of each sample was then calculated.

Point load tests were conducted on cylindrical sandstone specimens BX in diameter. Axial tests were performed on specimens with length to diameter ratio between 0.3–1.0. Ten tests were carried out for each sandstone sample. The point load strength index ($I_{s(50)}$) was determined by compressing the rock specimens between two standard conical platens. Dry unit weight of sandstone samples were determined on cylindrical rock specimens in accordance with the procedures suggested by ISRM (Brown, 1981).

3.3 Rock Cutting Tests

A rock cutting test rig, which is a modified MKE HS 600 shaping machine, having a stroke of 625 mm and a power of 4 kW was used. Details of the test rig can be found elsewhere (Ozlen, 1992). Rock cutting tests were carried out using the standard cutting picks on blocks of rock under the conditions given in Table 9. Two tests were carried out on each sandstone sample in which cutting forces were recorded. After each cutting test, the length of cut was measured and the debris produced by the cut was collected and weighed for the determination of SE. Specific cutting energy is calculated by using the formula below:

$$SE = \frac{F_C \times L}{V} \times 10^{-1} \tag{1}$$

where:

SE: Specific cutting energy (MJ/m^3)
F_C: Mean cutting force (kN)
L: Cutting length (cm)
V: Volume cut, cm^3 ($V = Y/D$)
Y: Yield (gr)
D: Density (gr/cm^3).

Results of the rock cutting tests are given in Table 10.

Table 9. Rock cutting test conditions

Cutting depth	5 mm
Cutting speed	150 mm/sec
Rake angle	−5°
Clearance angle	5°
Pick tip material	Tungsten carbide (cobalt of 10%)
Pick width	12.7 mm

Table 10. Results of the rock cutting tests

Rock sample	Mean cutting force (kN)	Specific cutting energy (MJ/m^3)
L8A	1.084	9.753
L8B	0.832	6.872
L10	1.090	9.972
L14	1.953	20.782
L16	1.460	12.001
L18	1.525	17.070

4. Statistical Analysis of Experimental Results

Data gained from the tests performed on sandstone specimens were subjected to a comprehensive statistical analysis. Results of the basic descriptive statistical analysis performed on the test data are given in Table 11. Correlations between SE and the petrographic, mineralogical, and engineering properties of rocks tested are given and discussed in this section. Bivariate correlation and linear regression analyses were em-

Table 11. Basic descriptive statistics for test data

All variables	Mean	Standard deviation	Number of test specimens	Number of samples (N)
Specific cutting energy (MJ/m^3)	12.742	5.196	12	6
Texture coefficient I	1.721	0.408	6	6
Packing density I	0.350	0.057	6	6
Texture coefficient II	3.841	1.759	6	6
Packing density II	0.328	0.119	6	6
Cementation coefficient	6.167	2.483	6	6
Mean grain size (mm)	0.285	0.128	6	6
Percentage of grains and rock fragments (%)	84	8.718	6	6
Percentage of matrix (%)	15.833	8.750	6	6
Percentage of quartz (%)	36.802	6.590	6	6
Percentage of feldspar (%)	28.090	12.363	6	6
Percentage of calcite (%)	18.697	12.928	6	6
Percentage of rock fragments (%)	4.938	4.876	6	6
Percentage of opaque mineral (%)	1.703	1.329	6	6
Percentage of mafic mineral (%)	8.418	3.344	6	6
Percentage of felsic mineral (%)	84.941	5.157	6	6
Percentage of mineral grains (%)	95.064	4.874	6	6
Dry density (gr/cm^3)	2.452	0.135	30	6
Saturated density (gr/cm^3)	2.778	0.038	30	6
Pore volume (cm^3)	4.858	2.674	30	6
Effective porosity (%)	6.2	3.592	30	6
Shore scleroscope hardness	41.650	11.083	600	6
Schmidt hammer hardness	39.667	6.831	120	6
NCB cone indenter hardness	3.440	0.877	60	6
Point load strength index (MPa)	2.267	0.846	60	6
Dry unit weight (kN/m^3)	24.051	1.327	30	6
UCS (MPa)	53.173	21.851	18	6
UTS (MPa)	3.867	1.568	30	6
Modulus of elasticity (GPa)	21.395	16.891	12	6
Poisson's ratio	0.210	0.098	12	6

ployed in determining the relationship between SE and the rock properties mentioned above. Some parameters in Table 11, which were evaluated to be not necessarily significant in rock cutting process, were not taken into account in the statistical analyses.

4.1 Bivariate Correlation Analysis

Correlation coefficients between dependent variable and independent variables were determined using SPSS 11 for Windows Software through the bivariate correlation technique (Norusis, 2002). In this analysis, the correlation coefficients between SE, the dependent variable, and the other selected rock properties, the independent variables, were investigated. Data gained from the mineralogical and petrographic analyses, engineering and cuttability tests were arranged to produce a rock property matrix. A correlation matrix was obtained as a result of applying the bivariate correlation technique to the test data. Pearson's correlation coefficients (*r*-values) between SE and the other independent variables are given in Table 12. Significances of Pearson's correlation coefficients were evaluated by hypothesis testing coupled with the critical values of *r* as given by Johnson (1998).

Table 12. Pearson's correlations between SE and the other rock properties

Independent variables	*r*
Texture coefficient I	−0.876*
Packing density I	0.666
Texture coefficient II	0.746+
Packing density II	0.340
Cementation coefficient	0.729+
Mean grain size	0.201
Percentage of grains and rock fragments	0.0230
Percentage of matrix	0.003
Percentage of mineral grains	−0.0140
Percentage of rock fragments	0.0140
Percentage of quartz	0.523
Percentage of feldspar	−0.772+
Percentage of mafic mineral	−0.347
Percentage of felsic mineral	0.371
Dry density	0.862*
Saturated density	−0.155
Pore volume	−0.706
Effective porosity	−0.761+
Shore scleroscope hardness	0.920**
Schmidt hammer hardness	0.890*
NCB cone indenter hardness	0.416
Point load strength index	0.823*
Dry unit weight	0.862*
UCS	0.723
UTS	0.942**
Modulus of elasticity	0.650
Poisson's ratio	0.982**

+ Statistically significant at 0.1 level (2-tailed).
* Statistically significant at 0.05 level (2-tailed).
** Statistically significant at 0.01 level (2-tailed).

Correlation coefficients greater than ±0.811 were taken as statistically significant at 95% confidence level, whereas those greater than ±0.917 were statistically significant at 99% confidence level, with four degrees of freedom for a two-tailed test (Johnson, 1998). Although the correlation coefficients between ±0.729 and ±0.811 were also statistically significant at 90% level, they were only considered to provide rough estimates of SE. Correlation coefficients with an asterisk (*) were considered significant at 0.05 level and those with two asterisks (**) were considered significant at 0.01 level, whereas plus sign is used to pinpoint the r-values with 0.1 confidence level in Table 12.

4.1.1 Influence of Petrographic Properties

As shown in Table 12, two different methods for calculating the texture coefficient resulted in two contradictory findings. SE is shown to be indirectly proportional to the TC I ($r = -0.876$). According to the negative correlation between the two variables, a linear decrease is expected in the energy required to cut the unit volume of rock material, as the TC I increases. The texture coefficient concept originally proposes a remarkable increase in the resistance of rock material to the forces applied on it, as the texture coefficient of rock material increases. Therefore, as the texture coefficient increases, pick forces are also expected to increase in linear rock cutting. However, as shown in Tables 5 and 10, there is an indirect relationship between mean cutting forces and the TC I values. Nevertheless, increases in the pick forces do not necessarily bring up an increase in SE, since higher pick forces may accompany with higher yield as seen in practice. Also contrary to this, an increase with the mean cutting forces is coupled with an increase in SE at a constant depth of cut in this study as shown in Table 10.

Regardless of the pick geometry and the direction of loading, rock texture resists to the rock breakage by picks due to some geometrical features of its constituents e.g. mineral grains and rock fragments. Therefore, it is reasonable to expect an increase in resistance of rock to breakage, and hence, with the pick forces required to cut the rock, as the texture coefficient being described by its developers as a measure of the resistance of a rock to crack propagation increases. From this point of view, it can be evaluated that the strong correlation found between SE and the TC I is statistically significant but has no physical meaning.

A similar result was also obtained with the TC I by Ersoy and Waller (1995). The sandstone with weakly bonded grains and a weak matrix had a higher texture coefficient due to its larger grains coupled with higher packing density. This sandstone was drilled with higher penetration rates, despite the fact that texture coefficient concept proposed a higher mechanical strength and hence low penetration rates in drilling rocks of higher texture coefficients. This can be attributed to some deficiencies in the calculation of the TC I, especially for sandstones, in terms of the mineral grains located in the rock fragments in thin sections and the matrix structures of both thin section and rock fragments.

It was therefore decided to use the TC II values to represent the texture coefficient for sandstones, which was in a direct relationship with SE values ($r = 0.746$). A positive linear relationship between these two variables occurred by taking the mineral grains within rock fragments as independent mineral grains in calculations based upon the evaluation of the matrix structures for both the thin section and the rock fragments and bonding between the grains and matrix. Therefore, the TC I and packing density I values were eliminated and the TC II and packing density II values were used in further regression analyses.

The TC II values calculated by using the new method resulted to be much greater than calculated by the original method, especially for thin sections of L10, L14, and L18 with a silica matrix. Rock fragments in these cases consist of metamorphic quartz grains, large-thin in shape and highly interlocked due to metamorphisms. A rock fragment would behave as a group of mineral grains rather than a single grain, when forced by a cutting pick, because of the matrix structure and the highly interlocked nature of mineral grains. In this case, the tensile cracks will be intragranular rather than intergranular. These grains were evaluated as individual mineral grains and employed in the calculations for the TC II values for the thin sections of L10, L14, and L18. The same methodology was also applied to L8A, L8B, and L16, independent of the different characteristics in terms of mineral grains and matrix structure. Therefore, the difference between the TC I and TC II values for this second group of thin sections is not as significant as for L10, L14, and L18 (Table 5).

There is a rough linear relationship between the packing density and SE, which is probably because the packing density is the multiplier of all other parameters in the texture coefficient equation. However, a positive correlation was found between cementation coefficient and SE, which is statistically significant at 90% confidence level ($r = 0.729$). This result complies with the previous studies in this area. McFeat-Smith (1977) revealed that the pick consumption rate of roadheaders employed in excavation of Bunter and Keuper sandstones are much more related to the intensity of cementation rather than the quartz content. He has then proposed a classification system for sedimentary rocks in order to quantify the type and degree of cementation with respect to cementation coefficient. Studies of McFeat-Smith and Fowell (1977) revealed the significance of cementation coefficient on both SE and pick wear rate as a result of laboratory rock cutting tests. The curvilinear regression analysis they have performed resulted in two different prediction models, one for SE and the other for pick wear rate, both included the cementation coefficient as a parameter.

There is no statistically significant relationship between mean grain sizes, percentage of grains and rock fragments, percentage of matrix and SE possibly because all those parameters are secondary measures of rock strength, hence rock cuttability (Table 12). Their influences on SE should be better to be evaluated together with the other textural rock properties.

4.1.2 Influence of Mineralogy

Feldspar and quartz content in sandstone were found to influence SE (Table 12). A strong negative correlation ($r = -0.772$) was found between the feldspar content of the thin sections and SE. This linear correlation is meaningful, as feldspars are reported to play an important role in reducing the strength of rocks (Tugrul and Zarif, 1999). Some discontinuities in feldspars were also reported to reduce the tensile strength, which is the main rock property resisting the breakage by pick action especially for brittle rocks (Onodera and Asoka Kumara, 1980). Relying upon this result, a remarkable decrease can be expected in SE, as the percentage of feldspar increases.

The influence of quartz content of sandstones on SE is not as significant as that of feldspar (Table 12). However, quartz content is the most widely known parameter in searching for the effects of rock composition on mechanical strength, drillability, and cuttability characteristics of rocks (West, 1986). Fahy and Guccione (1979) and Shakoor and Bonelli (1991) have found a considerable relationship between UCS and quartz content of sandstones. Tugrul and Zarif (1999) reported that as the quartz content of granites increased, their measures of strength also increased. Bell (1978) could not find any correlation between the quartz content and mechanical properties of Fell sandstones. It was proposed that degree of interlocking with quartz particles is much more effective on mechanical rock properties than their percentage in rock (Bell, 1978; Barbour et al., 1979).

Mafic minerals, which include iron and magnesium, are easily weathered by physical and chemical processes, thus lowering the strength of rock materials. Therefore, it can be assumed that SE is indirectly proportional to the mafic mineral content. However, no statistically significant relationship could be found between SE and mafic mineral content of sandstones (Table 12). The effect of felsic minerals on rock cuttability is not known; hence, it was investigated with this study. The relationship between the felsic mineral contents and SE of sandstones exhibits a positive linear correlation that is not statistically significant. This is probably because those minerals include both feldspar and silica within their structures along with the others; former reduces the rock strength whilst latter is known to increase it.

4.1.3 Influence of Engineering Properties

According to the correlation analysis, all the physical properties of the sandstones, with the exception of saturated density, used in this study had a considerable influence on SE (Table 12). Dry density is the most significant property affecting SE amongst the others with a *r*-value of 0.862 at 95% confidence level, indicating its direct relationship with SE. SE decreased as both the effective porosity and pore volume increased. Porosity is one of the most important physical properties affecting the engineering behaviour of rock materials. It is very well known that the pore spaces in rock texture reduce rock strength significantly (Jumikis, 1979). Since SE is known to be directly proportional to the rock strength especially for the coal measures strata, any increase in effective porosity or the pore volume of sandstone is likely to cause a corresponding decrease in SE (Rostami et al., 1993; Speight, 1997). There is also a very close relationship between the density or unit weight of the rock and its porosity. Rock density is inversely proportional to its porosity (Jumikis, 1979; Tugrul and Zarif, 1999). Therefore, it is meaningful that SE had strong correlations with dry density and porosity of sandstones.

Very strong correlations were found between the index properties of sandstones, except cone indenter hardness, and their specific cutting energies (Table 12). SE increases with dry unit weight with an *r*-value of 0.862 at 95% confidence level.

SE was found to be directly proportional to Shore scleroscope hardness with a correlation coefficient of 0.920 at a significance level of 99% (Table 12). Shore scleroscope test is widely employed in mechanical excavation applications in order to measure the rebound hardness of intact rock. It was reported to provide the rock hardness concerning its mineral content, elasticity, and cementation characteristics (McFeat-Smith, 1977). Previous studies also revealed the potential of Shore scleroscope test for the assessment of the plasticity and UCS of rocks (McFeat-Smith, 1977; Holmgeirsdottir and Thomas, 1998). Laboratory rock cutting studies conducted by McFeat-Smith and Fowell (1977) indicated the importance of Shore scleroscope hardness in predicting SE and pick wear rate. Fowell (1970) also stated that Shore scleroscope test could be utilized to asses the cuttability of rocks by mechanical tools.

SE increased as the Schmidt hammer hardness value increased with a correlation coefficient of 0.890 at 95% confidence level for the range of sandstones tested (Table 12). Schmidt hammer is another rebound hardness test originally developed to predict the UCS of concrete. Afterwards, a procedure was suggested by ISRM to utilize this test for determining the hardness of rock materials (Brown, 1981). Schmidt hammer test has also been reported to have a possible use for the prediction of machine performance in mechanical excavation (Goktan and Ayday, 1993).

The correlation between cone indenter hardness and SE was not found as statistically significant as Shore scleroscope and Schmidt hammer hardness (Table 12). Test apparatus for cone indenter hardness was developed at the NCB to determine the indentation hardness and UCS of rock through measuring its resistance to indentation by a hardened tungsten carbide cone (NCB, 1977). Cone indenter hardness was previously found to be in good correlations with laboratory SE and roadheader performance, especially in coal-measures strata (McFeat-Smith and Fowell, 1977; NCB, 1977). Additionally, cone indenter hardness has been used for predicting UCS of rocks for many years (NCB, 1977). However, Bilgin and Shahriar (1986) indicated that the region of rocks plays an important role in relating cone indenter hardness with either of the above parameters.

The correlation analysis showed that point load strength index was directly proportional to SE with an *r*-value of 0.862 at 95% confidence level (Table 12). The point load test, almost a simulation of a laboratory compression test intended for use in the field, is very useful for strength classification of intact rocks. Point load strength values are also known to correlate well with UCS and UTS of a wide range of rocks. It has been widely used as a rock strength index for many years with great accuracy (Broch and Franklin, 1972; Bieniawski, 1975; Arthur, 1996). It was originally developed to determine the tensile strength of rocks (Hoek, 1977). This is because, when a brittle rock is compressed between two conical plates, the minimum principal stress that is generated along a plane between the conical plates refers to as a near-uniform tensile stress. Rock failure occurs if this minimum principal stress equals to the tensile strength of the rock (O'Rourke, 1989). Since the main cracks leading the intact rock under a pick to produce rock chips are tensile cracks, an increase can be expected with SE as point load strength index of rock increases.

UCS correlates well with SE with a correlation coefficient of 0.723 that is very close to the critical value of 0.729 (Table 12). This critical value is used to decide whether the target correlation is statistically significant or not at 90% confidence level for the data set used in this study. According to this, a linear increase can be expected in SE as UCS increases, complying with the most of the previous studies in this area. UCS is the one of the major rock properties affecting rock cuttability because a considerable amount of the cutting energy is consumed in overcoming the UCS of rock for producing a crushed zone under the pick tip at the beginning of the rock cutting process. Strong positive correlations have been previously found between UCS and laboratory SE for coal measures rocks, confirming the practicability of UCS for predicting the cuttability of this type of rocks (Rostami et al., 1993; Speight, 1997). However, cutting some evaporates by mechanical tools were reported to be more difficult than coal measures rocks with similar UCS values under the same cutting conditions. This reveals the lack of correlation between the UCS and rock cuttability for all kinds of rocks.

Correlation coefficient between UTS and SE is 0.942 at 99% confidence level, which shows the strong relationship between these two parameters (Table 12). This result is in line with the previous studies in this area. It is very well known that as UTS increases, a corresponding increase occurs in SE for the most of the rocks. Brittle rocks were reported to show tensile failure, whilst tougher rocks fail in shear mode. However, the failure cracks in a rock forced by a pick are tensile in nature regardless of the rock type (Evans and Pomeroy, 1973; Roxborough, 1973; Nishimatsu, 1979; Hood and Roxborough, 1992).

Modulus of elasticity is positively correlated with SE with $r = 0.650$, which is not statistically significant even at 90% confidence level (Table 12). Modulus of elasticity is directly proportional to SE, since it is known as an important parameter in evaluating the deformations in rock in relation to various loading conditions. This property is also reported to change with mode of formation, porosity, particle size, and the water content (Jumikis, 1979). Rock cutting can also be assumed a kind of deformation process intended to produce rock chips. However, the correlation coefficient found between the modulus of elasticity and SE is lower than it was expected. This is possibly because the modulus of elasticity of a particular rock type depends upon its depositional characteristics and mineralogy. Therefore, rocks of a particular type from different depositional regions have different modulus of elasticity values.

Poisson's ratio is in almost perfect linear correlation with SE with $r = 0.982$ that is statistically significant at 99% confidence level (Table 12). Poisson's ratio and modulus of elasticity, the most widely used elastic constants, are very well known to relate to each other. Factors influencing the modulus of elasticity value for a particular rock type mentioned above also cause some changes in Poisson's ratio values. However, Poisson's ratio had a stronger relation with SE when compared to modulus of elasticity. This is possibly because the differences in dimensional considerations taken in determinations for Poisson's ratio and modulus of elasticity. Poisson's ratios of sandstones were calculated using the deformations measured in two dimensions, perpendicular and parallel to the direction of loading. However, modulus of elasticity values were calculated depending on the deformations measured only in one dimension.

4.2 Linear Regression Analysis

Rock properties that were found to be in statistically significant correlations with SE were subjected to a linear regression analysis. UCS has also been included in this study. This is because the correlation coefficient between SE and UCS is very close to the critical value of 0.729 (Table 12). Linear regression analysis is one of the most widely employed analysis methods in order to fit a straight line to data sets which belong to two variables that are in a statistically significant linear correlation. Value of the

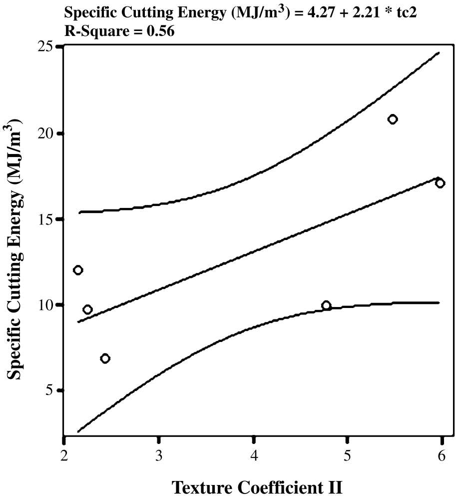

Fig. 2. Linear regression line with 95% mean prediction interval curves. Texture coefficient II (tc2)

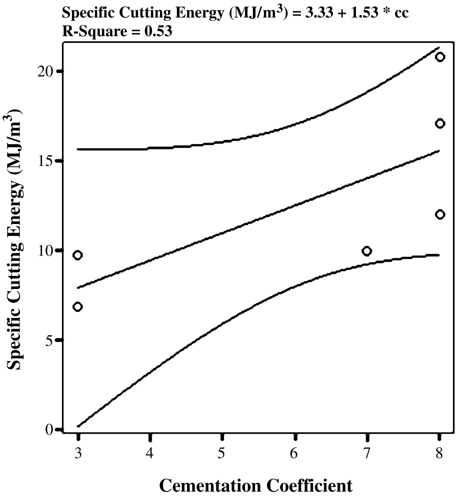

Fig. 3. Linear regression line with 95% mean prediction interval curves. Cementation coefficient (cc)

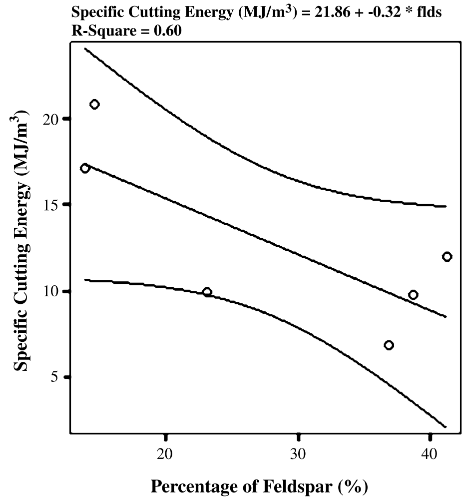

Fig. 4. Linear regression line with 95% mean prediction interval curves. Percentage of feldspar (flds)

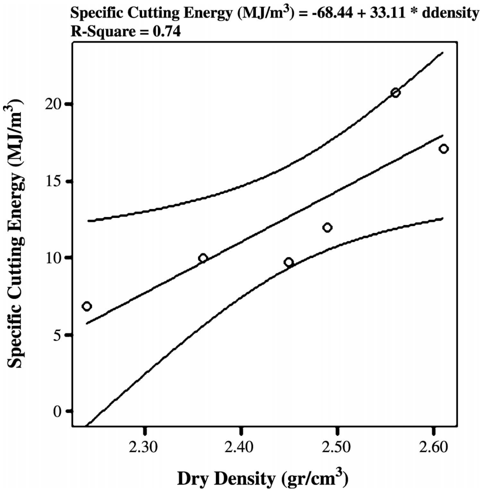

Fig. 5. Linear regression line with 95% mean prediction interval curves. Dry density (ddensity)

dependent variable can be predicted for any value of independent variable by using the regression model fitted. A linear regression analysis that is based on the least square method has been applied on the data obtained in this study. Regression lines and equations (models) established through linear regression analysis are given in Figs. 2 to 12. Statistical parameters summarizing these models are also given in Table 13.

Regression analyses were coupled with the analysis of variance (ANOVA) or the F-test. ANOVA is used to determine the significance of the deviation from linearity for the regression lines that were established. In other words, ANOVA help decides

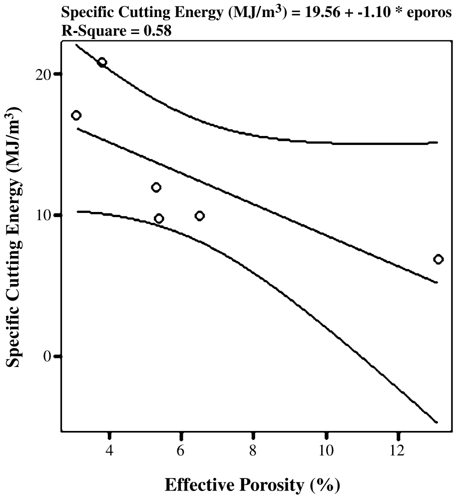

Fig. 6. Linear regression line with 95% mean prediction interval curves. Effective porosity (eporos)

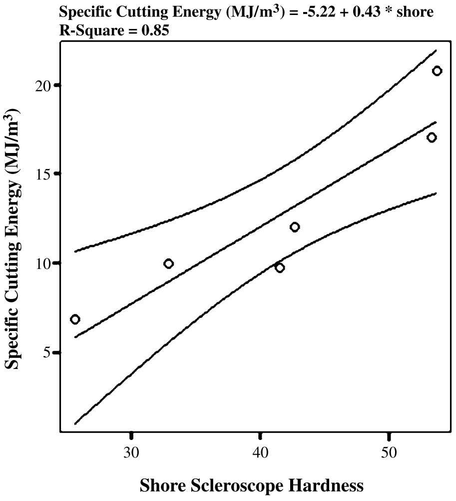

Fig. 7. Linear regression line with 95% mean prediction interval curves. Shore scleroscope hardness (shore)

whether the regression line is the best curve representing the relationship between the sample data sets of two correlated variables. Hypothesis designated by $R^0_{pop} = 0$, which states that there is no linearity between two variables has been tested through ANOVA. ANOVA produced two values for each model; F value showed how regression equation fitted the data, whereas the other one revealed the significance of F value. When the latter was less than 0.05, then $R^0_{pop} = 0$ was rejected. This meant that the relationship between SE and the target independent variable could be

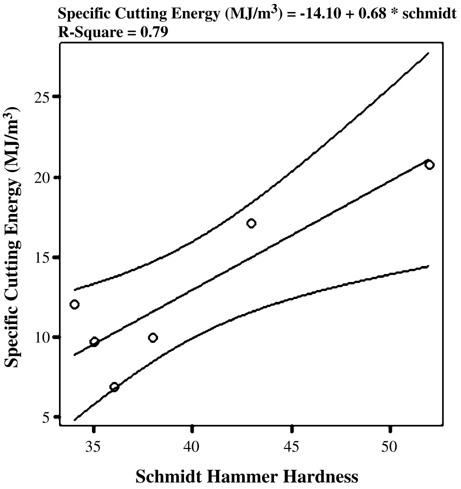

Fig. 8. Linear regression line with 95% mean prediction interval curves. Schmidt hammer hardness (schmidt)

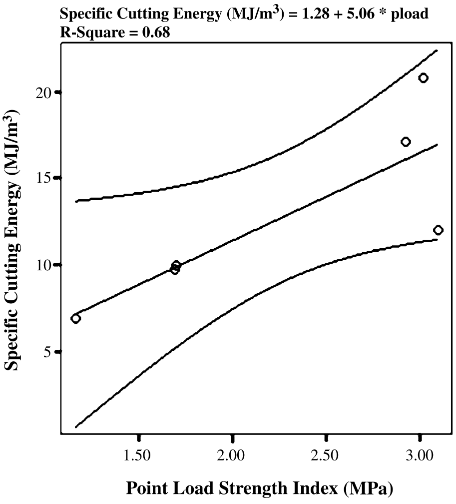

Fig. 9. Linear regression line with 95% mean prediction interval curves. Point load strength index (pload)

expressed as a linear equation at 95% confidence level. Otherwise, it was assumed that this relationship could not be represented as a linear regression model (Johnson, 1998; Walpole, 1998). Obviously, this does not mean that there is no relationship between any two variables under investigation. A nonlinear function may be suitable to represent the relationship between such variables as a nonlinear regression equation in such cases.

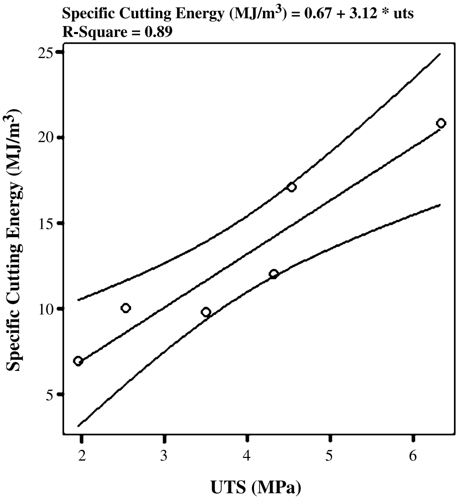

Fig. 10. Linear regression line with 95% mean prediction interval curves. Tensile strength (uts)

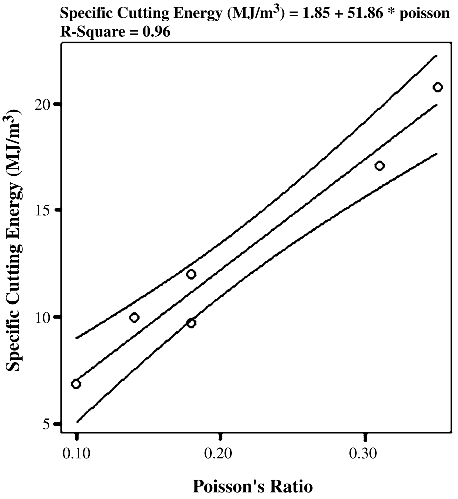

Fig. 11. Linear regression line with 95% mean prediction interval curves. Poisson's ratio (poisson)

Results of ANOVA are given in Table 14. Depending on these results, models including the Poisson's ratio, UTS, Shore scleroscope hardness, Schmidt hammer hardness, dry density, and point load strength index as predictors respectively were found statistically significant in terms of linearity.

After these regression models were verified through ANOVA, Student's t-tests were used to determine whether they could be used to predict SE from the population reliably. In other words, significances of the model components (equation constant and the regression coefficient in each regression model) were tested respectively at 95%

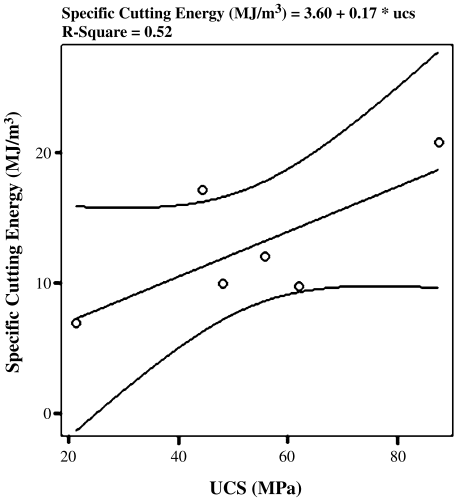

Fig. 12. Linear regression line with 95% mean prediction interval curves. Uniaxial compressive strength (ucs)

Table 13. Regression model summaries

Predictors	R	R^2	Adjusted R^2	Std. error of estimation
Texture coefficient II	0.746	0.557	0.446	3.866093
Cementation coefficient	0.729	0.532	0.415	3.97339
Percentage of feldspar	0.772	0.597	0.496	3.689333
Dry density	0.862	0.743	0.679	2.944442
Effective porosity	0.761	0.579	0.473	3.770873
Shore scleroscope	0.920	0.846	0.808	2.276326
Schmidt hammer	0.890	0.791	0.739	2.653742
Point load strength	0.823	0.678	0.597	3.29702
UTS	0.942	0.887	0.859	1.952433
Poisson's ratio	0.982	0.964	0.955	1.098927
UCS	0.723	0.523	0.404	4.011935

confidence level. Depending on the probability values (*p* values) obtained, each of above-mentioned model components were considered either significant or not. If *p* value was less than or equal to 0.05, then the relevant model component was taken significant, otherwise not significant. All the regression models that were verified through ANOVA were understood to have components that were also statistically significant (Table 15). This reveals the practicability of these models in predicting SE values from the population.

Upper and lower boundaries of these regression models in estimating the mean values of SE from the population were also calculated considering the standard errors of estimations that are given in Table 13. The boundaries for the models are given in Table 15 and illustrated in Figs. 2 to 12.

Furthermore, the coefficients of determination (R^2) were used to measure the goodness of the fit for the proposed regression models. R^2 is equal to the square of

Table 14. ANOVA results

Predictors	Sum of squares		df	Mean square	F	Significance of F
Texture coefficient II	regression	75.196	1	75.196	5.031	0.088
	residual	59.787	4	14.947		
	total	134.983	5	–		
Cementation coefficient	regression	71.831	1	71.831	4.55	0.10
	residual	63.151	4	15.788		
	total	134.983	5	–		
Percentage of feldspar	regression	80.538	1	80.538	5.917	0.072
	residual	54.445	4	13.611		
	total	134.983	5	–		
Dry density	regression	100.304	1	100.304	11.569	0.027
	residual	34.679	4	8.670		
	total	134.983	5	–		
Effective porosity	regression	78.105	1	78.105	5.493	0.079
	residual	56.878	4	14.219		
	total	134.983	5	–		
Shore scleroscope	regression	114.256	1	114.256	22.050	0.009
	residual	20.727	4	5.182		
	total	134.983	5	–		
Schmidt hammer	regression	106.813	1	106.813	15.167	0.018
	residual	28.169	4	7.042		
	total	134.983	5	–		
Point load strength	regression	91.501	1	91.501	8.41	0.044
	residual	43.481	4	10.870		
	total	134.983	5	–		
UTS	regression	119.735	1	119.735	31.410	0.005
	residual	15.248	4	3.812		
	total	134.983	5	–		
Poisson's ratio	regression	130.152	1	130.152	107.774	0.000
	residual	4.831	4	1.208		
	total	134.983	5	–		
UCS	regression	70.600	1	70.600	4.386	0.104
	residual	64.382	4	16.096		
	total	134.983	5	–		

df: Degree of freedom.

the correlation coefficient between the observed and predicted values of the dependent variable. R^2 equals one (plus or minus) if all the predicted values are over the regression line. Adjusted R^2 is also used together with R^2 in an effort to evaluate the validity of regression models at a higher accuracy (Johnson, 1998; Walpole, 1998; Norusis, 2002). Values of these two parameters that were calculated for each model are given in Table 13. According to these values, most of the changes in SE values are successfully expressed by the Poisson's ratio, UTS, Shore scleroscope hardness, Schmidt hammer

Table 15. Significance of model components and confidence intervals

Regression models	Unstandardized coefficients		Standardized coefficients	t	Significance of t	95% Confidence interval for B	
	B	Std. error	Beta			Lower bound	Upper bound
(Constant)	−68.438	23.897	–	−2.864	0.046	−134.787	−2.090
Dry density	33.112	9.735	0.862	3.401	0.027	6.084	60.141
(Constant)	−5.223	3.937	–	−1.327	0.255	−16.153	5.708
Shore scleroscope	0.431	0.092	0.920	4.696	0.009	0.176	0.686
(Constant)	−14.096	6.976	–	−2.021	0.113	−33.464	5.272
Schmidt hammer	0.677	0.174	0.890	3.895	0.018	0.194	1.159
(Constant)	1.283	4.173	–	0.307	0.774	−10.302	12.868
Point load strength	5.055	1.742	0.823	2.901	0.044	0.218	9.893
(Constant)	0.671	2.297	–	0.292	0.785	−5.706	7.047
UTS	3.122	0.557	0.942	5.604	0.005	1.575	4.668
(Constant)	1.852	1.141	–	1.623	0.180	−1.316	5.019
Poisson's ratio	51.856	4.995	0.982	10.381	0.000	37.988	65.725

hardness, dry density, and point load strength index, individually, in line with the ANOVA and Student's t-test.

5. Conclusions

Sandstone samples taken from different sites around Ankara, Turkey were subjected to a comprehensive mineralogical-petrographic analysis, rock mechanics, and linear rock cutting tests by picks. Effects of textural and mineralogical properties of sandstones on SE were investigated, along with a broad range of rock engineering properties. Some parameters related to rock texture and composition such as texture coefficient and feldspar, mafic, and felsic mineral contents, which were ignored in previous studies, were considered. The applicability of texture coefficient concept to linear cutting of sandstones by picks was investigated. The significance of rock texture coefficient and feldspar content on the cuttability of sandstones was highlighted, along with the other rock properties.

The relationships between SE and textural, compositional, and engineering properties of sandstones were evaluated through bivariate correlation and linear regression analyses using the SPSS 11 software package. Statistical analyses revealed that the texture coefficient concept, as developed by Howarth and Rowlands (1987) in order to estimate the drillability and strength characteristics of rocks, could also be used in rock cutting for sandstones. Depending on the correlation analysis, a statistically significant correlation between the TC II and SE values at 90% confidence level ($r = 0.746$) was found.

It is understood that some benefits are obtained when the TC II is adopted as the texture coefficient for sandstones, which is calculated by taking into account the mineral grains located within the rock fragments and the matrix characteristics in thin sections. A higher TC I value in a previous study had been coupled with a higher drilling rate, which is inconsistent for low strength sandstones with weak matrix and large grains. A similar unusual correlation has also occurred between SE and texture coefficient as presented by the TC I values in linear cutting tests in this study. However, this was not observed to occur between SE and texture coefficient when the TC II values are adopted instead of the TC I values.

When assessing the practicability of adopting the TC II values as the texture coefficients of sandstones, samples L10, L14, and L18 with the greatest TC II values were found to require the highest specific cutting energies. This validates the approach developed in this study, which proposes one to employ the mineral grains within the rock fragments in thin sections when calculating the texture coefficients, especially for sandstones with strong matrices. However, the linear regression analyses showed that the TC II could not be used to predict SE for sandstones using a simple linear regression model.

The effect of feldspar content on cuttability characteristics of rocks, which is known to reduce the tensile strength of rock materials, was investigated. It was found that SE is inversely correlated to the feldspar content. The cementation coefficient, reported to be responsible for pick wear in cutting sandstones, was determined to be in a significant positive linear correlation with SE at 90% confidence level. The effective porosity, which may be considered to be a textural and physical property of rock materials, also had a remarkable inverse correlation with SE, with a correlation coefficient of 0.761 that is statistically significant at 90% confidence level. In line with the effective porosity, the pore volume also showed a considerable negative correlation with SE with r equal to 0.706.

UCS, which is at present the most widely used prediction tool for SE, was shown not to be statistically significant even at 90% confidence level. On the contrary, Poisson's ratio, UTS, Shore scleroscope hardness, Schmidt hammer hardness, dry density, and point load strength index exhibited very strong linear correlations with SE. Dry density, Schmidt hammer hardness, and point load strength index were in positive correlations statistically significant with SE at 95% confidence level, whereas positive correlations that are statistically significant at 99% confidence level were found between Poisson's ratio, UTS, Shore scleroscope hardness, and SE. These rock properties were also found statistically significant in estimating SE individually, depending on the results of linear regression analysis, ANOVA and Student's t-tests, and R^2 values. Poisson's ratio appeared to be the most important parameter in linear cutting of sandstones by picks, relying upon the statistical analyses performed in this study.

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