Evaluation of the indirect measures of rock brittleness and fracture toughness in rock cutting

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Transaction Paper

Synopsis

Performance prediction models for partial face mechanical excavators, when developed in laboratory conditions, depend on relating the results of a set of rock property tests and indices to specific cutting energy (SE) for various rock types. There exist some studies in the literature aiming to correlate the geotechnical properties of intact rocks with the SE, especially for massive and widely jointed rock environments. However, those including direct and/or indirect measures of rock fracture parameters such as rock brittleness and fracture toughness, along with the other rock parameters expressing different aspects of rock behavior under drag tools (picks), are rather limited.

With this study, it was aimed to investigate the relationships between the indirect measures of rock brittleness and fracture toughness and the SE depending on the results of a new and two previous linear rock cutting programmes. Relationships between the SE, rock strength parameters, and the rock index tests have also been investigated in this study. Sandstone samples taken from the different fields around Ankara, Turkey were used in the new testing programme. Detailed mineralogical analyses, petrographic studies, and rock mechanics and rock cutting tests were performed on these selected sandstone specimens. The assessment of rock cuttability was based on the SE. Three different brittleness indices (B1, B2, and B4) were calculated for sandstones samples, whereas a toughness index (T_i), being developed by Atkinson *et al.*[1], was employed to represent the indirect rock fracture toughness. The relationships between the SE and the large amounts of new data obtained from the mineralogical analyses, petrographic studies, rock mechanics, and linear rock cutting tests were evaluated by using bivariate correlation and curve fitting techniques, variance analysis, and Student's t-test. Rock cutting and rock property testing data that came from well-known studies of McFeat-Smith and Fowell[2] and Roxborough and Philips[3] have also been employed in statistical analyses together with the new data.

Laboratory tests and subsequent analyses revealed that there were close correlations between the SE and B4 whereas no statistically significant correlation has been found between the SE and T_i. Uniaxial compressive and Brazilian tensile strengths and Shore scleroscope hardness of sandstones also exhibited strong relationships with the SE. NCB cone indenter test had the greatest influence on the SE among the other engineering properties of rocks, confirming the previous studies in rock cutting and mechanical excavation. Therefore, it was recommended to employ easy-to-use index tests of NCB cone indenter and Shore scleroscope in the estimation of laboratory SE of sandstones ranging from very low to high strengths in the absence of a rock cutting rig to measure it until the easy-to-use universal measures of the rock brittleness and especially the rock fracture toughness, being an intrinsic rock property, are developed.

Introduction

Rock cutting is mainly a process of chip formation resulting from crack initiation and propagation or crack interaction for many cutters breaking rock in concert. It is currently accepted that the chip formation under cutting tools is caused by primary or subsequent crack propagation with the generated crushing zone being restricted to a small area beneath the tool tip. This inevitably motivates the application of linear elastic fracture mechanics principles to the analysis of chip formation since they are able to deal with crack initiation and propagation[4]. Therefore, clear understanding of rock fracture mechanisms is of crucial importance in rock engineering applications such as mechanical rock excavation, civil engineering, and fragmentation works. That is why many investigators have studied rock fracture mechanics[5–12].

Brittle fracturing of rock is the one of the most popular research areas in rock mechanics since most of the rocks show brittle fracture when failed under loads. Materials such as cast iron and many rocks usually terminating by fracture at or only slightly beyond the yield stress are defined as brittle by Obert and Duvall[13]. Brittleness of rock materials is believed to have an impact on the rock cutting process. Many different ratios of σ_c to σ_t have been proposed by many researchers to calculate the rock brittleness. Rock fracture toughness is another significant parameter in fracture mechanics. Fracture toughness represents the ability of a material to resist the propagation of cracks. It is considered the inherent property of the material and it should not be affected by the configuration of the specimen and the loading method adopted in

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 SA ISSN 0038–223X/3.00 + 0.00. Paper received Dec. 2005; revised paper received Mar. 2006.

testing. The main use of this property is for classification of intact rock with respect to its resistance to crack propagation as seen in rock cutting. Among three modes, mode-I fracture toughness (K_{IC}) is considered the most important and most frequently encountered. However, fracture toughness is comparatively more difficult to obtain than standard laboratory rock properties such as uniaxial compressive and tensile strengths. Therefore, a rock toughness index related to sc and Young's modulus that was derived from stress-strain curves has been proposed to estimate rock fracture toughness[1,14,15].

This paper is concerned with establishing correlations between the SE, indirect measures of brittleness and fracture toughness in linear cutting of sandstones under standard cutting conditions by chisel-type picks. Relationships between the SE and the other geotechnical properties of rocks have also been investigated in this study. Representative samples of six different sandstones from the fields around Ankara, Turkey, have been subjected to a comprehensive rock cutting and rock property testing programme. Results of the two similar programmes previously conducted by different researchers on very low to high-strength sandstones were also employed in this study. Data obtained from those three programmes have been statistically analysed using bivariate correlation and curve fitting techniques, ANOVA (analysis of variance), and Student's t-test. Three different equations for quantifying rock brittleness were used to calculate the respective values of brittleness indices for the sandstones employed in this paper. The toughness index as described by Atkinson *et al.*[1] was used to quantify the rock fracture toughness.

Relationships between the SE and the other geotechnical properties of rocks have also been investigated in this study. Significances of the indirect measures of rock brittleness and rock fracture toughness in rock cutting along with the other geotechnical rock properties are discussed in this paper.

Cutting rocks with drag tools

Rock cuttability is the governing parameter in mechanical excavation, which determines the performance of the cutters during rock cutting. Linear rock cutting tests are carried out by cutting the core samples of 76 mm in diameter or block samples of proper dimensions using standard chisel picks on a rig for the applications where roadheaders, continuous miners, and shearers are employed. This test has been developed by Roxborough and Philips[16] to determine the cuttability characteristics of rocks such as SE and rock abrasivity, simulating the cutting action of picks.

When a pick is forced into the rock to break it into pieces, a highly stressed zone occurs under the pick tip. As the pick is kept pressed into the rock, the strength of the material is exceeded and the material is ground. Cracks are initiated and propagated through the free surface and laterally into the rock. Rock is fragmented whenever one of the main cracks reaches the free surface. There are two groups of fracture models, namely tensile and shear, which were proposed to describe the cutting action by picks. The tensile fracture model assumes that a tensile fracture develops along a circular path originating from the wedge tip and terminates at a free surface[17–19]. The chipping process is repeated as the pick continues to cut the rock material.

Rock brittleness

Brittleness is usually considered one of the most important mechanical properties of rocks. However, Denkhaus[20] takes the brittleness as a term describing the type of fracture for rocks contrary to widespread belief that the brittleness is a rock property. According to Denkhaus[20], when a fracture is accompanied by plastic deformation, it is called a ductile fracture and when plastic deformation is absent it is called a brittle fracture. The scale of brittleness must be arbitrarily defined by the ratio of elastic strain at the fracture to the plastic strain at the fracture. The higher this ratio, the higher is the brittleness of the fracture and the lower its ductility.

Another parameter the ratio of plastic deformation to total deformation; the higher this ratio, the more ductile the fracture and the less brittle it is. Brittleness may also be defined in terms of the ratio of specific elastic strain energy at the fracture to total specific strain energy at the fracture[20]. Morley[21] and Hetenyi[22] have defined the rock brittleness as the lack of ductility, and the ductility is defined as the ability of a material to endure a large inelastic deformation without losing its bearing capacity.

Different definitions of brittleness are summarized by Hucka and Das[23]. Singh[24] has proposed an indirect determination of brittleness as a measure of extracting coal by mechanical tools depending on the angle of internal friction of rocks. Hucka and Das[25] defined a brittleness index obtained from load–deformation curves. Following are the three equations mostly widely encountered in previous studies to quantify brittleness indirectly:

$$B1 = \frac{\sigma_c}{\sigma_t} \qquad [1]$$

$$B2 = \frac{\sigma_c - \sigma_t}{\sigma_c - \sigma_t} \qquad [2]$$

$$B3 = q \times \sigma_c \qquad [3]$$

where, B1, B2, and B3 are different brittleness indices, σ_c is uniaxial compressive strength, σ_t is tensile strength, and *q* is the percentage of fines formed in the Protodyakonov impact test.

Recently, Altindag[26] suggested a new brittleness index (B4) obtained from the uniaxial compressive and Brazilian tensile strengths. Altindag[26–27] found significant correlations between the B4 and penetration rate of percussive drills, drillability index for rotary drilling, and the specific drilling energy. B4, being defined as the area under the line of the compressive strength versus tensile strength, can be formulated as follows:

$$B4 = \frac{\sigma_c \times \sigma_t}{2} \qquad [4]$$

Evans and Pomeroy[28] theoretically showed that the impact energy of a pick is inversely proportional to the brittleness. Singh[24] indicated that cuttability, penetrability, and the Protodyakonov strength index of coal strongly depend on the brittleness index of coal. Singh[29] has shown that a directly proportional relation exists between *in situ* SE and the brittleness of three Utah coals.

Rock fracture toughness

Fracture toughness, K_{IC}, is an intrinsic material property and a measure of the energy required to create new surface areas in the material. Fracture toughness can also be defined as the ability of rock to resist fracturing and propagation of pre-existing cracks. In other words, it is the consumption rate of fracture energy required to create new surfaces.

Deliac[8] has extensively analysed the forms of major chipping due to drag tool cutting and proposed that there are two fundamental chipping modes referred to as mode A and mode B. Mode A is a typical shear and compressive fracture of rock and the chip formation can be approximately modelled by the Coulomb criterion. This is rather similar to the shear failure model proposed by Nishimatsu[30]. Mode A chip formation occurs when the pick is wide, the rock is relatively soft and the depth of cut is large. Mode B is a tensile crack propagation mode similar to Evans's tensile fracture model and the chip formation can be described by the fracture mechanics principles. Mode B chip formation is dominant when the pick is sharp and rigid; the rock is brittle and the depth of cut is small. Deliac[8] has derived an expression for the mean peak cutting force (MPCF) for this type of chip formation as follows, which returns values in close agreement with experimental results:

$$MPCF = C' \times K_{IC} \times d^{3/2} \qquad [5]$$

where K_{IC} is mode-I fracture toughness, C' is a coefficient depending on rock type and tool sharpness, and d is depth of cut.

Some researchers have also carried out investigations in an effort to establish relationships between the fracture toughness, hardness, and geotechnical properties of rocks and have found considerable correlations between them[31–33]. Fracture toughness was also found to be an important measure of coal grindability[34].

Numerous testing methods and specimen geometries have been used for the determination of fracture toughness of rocks[9,35–37]. Bearman[31] has listed the main testing methods for mode I fracture toughness. Although numerous testing methods have been used, ISRM has suggested the three testing methods for the determination of mode I fracture toughness, namely the short rod specimen method (SR), chevron bend specimen method (CB), and cracked chevron notched Brazilian disc method (CCNBD)[9,37]. However, these testing methods are not suitable to be performed in the field, which require sophisticated laboratory facilities. Atkinson *et al.*[1] have proposed the toughness index, as an indirect measure of the rock fracture toughness. The toughness index of rock is a derived parameter from the stress-strain curve, and is a measure of elastic energy requirements for deforming the rock with a cutting tool.

SE was reported to be related to the concept of rock fracture toughness, by a simple energy balance by using a toughness index in the form $\sigma^2_c / 2\text{x}E$ by Farmer and Garrity[14] and Poole[15]. The toughness index has been defined as the strain energy stored in a unit volume of rock just before the failure. Therefore, it is referred to as the amount of energy required to cause fracture, hence breakage. This is a direct function of compressive strength and elastic modulus. Both compressive strength and deformation modulus are determined by testing intact rock samples in the laboratory. Thus, an indication or indirect measure of fracture toughness of a rock can be obtained using the so-called toughness index.

The rock toughness index has been calculated from the measured values of the uniaxial compressive strength and Young's modulus in this study as shown by the following equation:

$$T_i = \frac{\sigma^2_c}{2 \times E} \times 100 \qquad [6]$$

where σ_c is the uniaxial compressive strength (MPa), E is Young's modulus (MPa) and the T_i is the toughness index of intact rock[1,14,15]. Atkinson *et al.*[1] has reported very close correlations between the area under the stress-strain curve (modulus of toughness) and the toughness index (Figure 1). Correlation coefficient between the predicted values of the toughness modulus is calculated from the regression model given in Figure 1 and those measured is 0.95. If T_i is greater than 27, the intact rock is assumed to reach its limit of cuttability and a field study is necessary to evaluate the joint pattern that can assist in excavating the rock mass[1].

Statistical analysis of the data

Relationships between the SE and the indirect measures of rock brittleness and fracture toughness of sandstones have been investigated depending on the results of three different programmes of linear rock cutting. Data obtained from the rock cutting and rock property determination tests that were

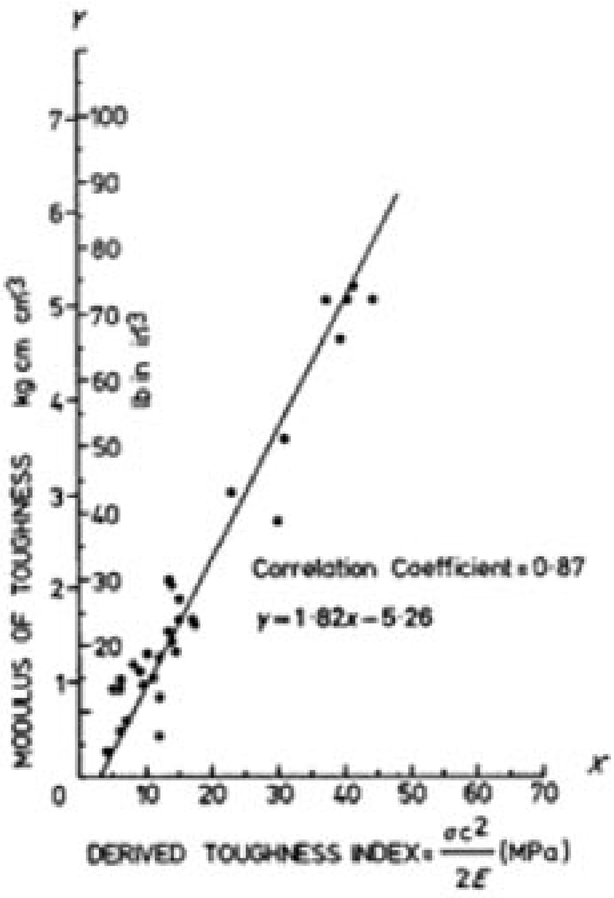

Figure 1—Relationship between the modulus of toughness and toughness index[1]

carried out on different sandstones, which are released by McFeat-Smith and Fowell[2] and Roxborough and Philips[3], have accompanied the new data to improve the accuracy of the statistical analyses. New data were obtained from the linear cutting tests on six different rock samples that were taken from fields around Ankara, Turkey. Those sandstones that are homogeneous without visible discontinuities occur extensively within the Salt Lake Basin in Central Anatolia in Turkey, which deposited in a flysch facies. The selection of the investigated field was based on the continuous occurrence of the sandstone sequences from the Upper Cretaceous to the end of the Paleocene. Comprehensive mineralogical analyses, petrographic studies, and rock mechanics tests were conducted on these samples. Details of those tests can be found elsewhere[38,39].

McFeat-Smith and Fowell[2] carried out a study in which samples of coal and coal measures strata that were widely encountered during roadway drivage operations the coal mines in England were subjected to linear rock cutting tests in the laboratory. Researchers tried to correlate the SE and pick wear rate with mineralogical-petrographic and a wide range of engineering properties of rocks. Roxborough and Philips[3] have given the results of rock cutting tests performed on core samples taken from igneous and sedimentary rocks in the Tyne-Tees Aquaduct tunnelling project in England. From borehole data and an appraisal of the detailed geological section along the line of the tunnel, it was possible to identify four different sandstones. The results of the rock cutting tests on Airy Holm sandstone (First grit) have not been involved in statistical analyses in this study since these tests were performed after either drying the samples or saturating them with water.

Geological and geotechnical properties of the sandstones employed in this study are given in Tables I and II. All the sandstones were also classified according to the engineering classification scheme of rocks as proposed by Deere and Miller[40] with particular reference to uniaxial compressive strength (σ_c) values (Table III). Linear rock cutting tests were performed on block samples of rocks in new testing programme to determine mean cutting forces (MCF) and SE, whereas McFeat-Smith and Fowell[2] and Roxborough and Philips[3] used core samples in linear cutting tests under the conditions similar to those given in Table IV. Brittleness and toughness indices of sandstones employed in the statistical analyses are given in Table V, which have been calculated using the Equations [1], [2], [4], and [6], respectively.

Correlation coefficients (Pearson's *r*-values) between the dependent variable and independent variables were determined using the SPSS 12 for Windows Software through the bivariate correlation technique. In this analysis, the correlation coefficients between the SE, being the dependent variable, and the other selected rock properties, being the independent variables, were investigated. In the further stage of statistical analyses, all the linear and nonlinear models were tried to fit the data. The coefficients of determination (R^2) were used to measure the goodness of the fit for the proposed regression models. Regression analyses were coupled with ANOVA or the F-test. ANOVA produced two values; the F-value showed how regression equation fitted the data, whereas the other one revealed the significance of the F-value. After the regression equations were determined and the regression models were verified through the F-test, Student's t-tests were used to determine whether those regression equations could be used to predict reliably the dependent variable for any independent variable from the population. In other words, significances of the constant and the regression coefficient in the regression equations were tested respectively at 95 per cent confidence level. Depending on the probability values (*p*- values) obtained, above-mentioned regression equation constants were considered either significant or not. If p-value (significance of *t*) is less than or equal to 0.05, then the relevant equation coefficient was taken significant, otherwise not significant.

Rock brittleness indices

Table I

Physical and hardness properties of sandstones

Reference data	Sandstone sample	Quartz content (%)	Density (g/cm³)	Porosity (%)	NCB cone indenter hardness	Shore hard
From McFeat-Smith and Fowell[2]	Triassic L. Keuper 1	84	2.62	21.8	1.3	19
	Triassic L. Keuper 2	80	2.61	22.2	1.7	26
	Triassic L. Bunter 1	95	2.63	19	2.1	37
	Triassic M. Bunter 2	78	2.62	19	3	36
	Triassic M. Bunter 3	88	2.58	9.3	3.5	47
	Triassic U. Bunter 4	62	2.62	11	2.3	37
	Coal Measures 1	85	2.60	16.5	2.1	27
	Coal Measures 2	85	2.62	5.6	6.9	57
	Limestone Series 1	91	2.59	8.1	8.9	47
	Limestone Series 2	92	2.59	12.9	7.1	36
From Roxborough and Philips[3]	Coal sill (WT4/7)	93	2.60	8.30	3.50	38
	Letch house (TA2/7)	62	2.60	10.80	4.20	28
	Massive (WTC/1A)	80	2.60	6.90	10	42
New	L8A	38.65	2.45	5.4	4.42	41.55
	L8B	38.63	2.24	13.1	1.88	25.70
	L10	30.11	2.36	6.5	3.17	32.90
	L14	44.05	2.56	3.8	3.79	53.70
	L16	27.47	2.49	5.3	3.93	42.70
	L18	41.90	2.61	3.1	3.44	53.35

Table II

Mechanical and cuttability properties of sandstones

Reference data	Sandstone sample	σ_c (MPa)	σ_t (MPa)	E_{static} (MPa)	MCP (kN)	SE (MJ/m³)
From McFeat-Smith and Fowell[2]	Triassic L. Keuper 1	8	1.1	5 600	No data available	5.60
	Triassic L. Keuper 2	7	1	5 900		6.10
	Triassic L. Bunter 1	41	1.8	7 900		7.70
	Triassic M. Bunter 2	18	2.4	6 300		9.40
	Triassic M. Bunter 3	23	3.9	9 400		15.40
	Triassic U. Bunter 4	48	2.7	6 700		11.50
	Coal Measures 1	120	7.7	29 600		4.30
	Coal Measures 2	37	7.8	23 800		20.50
	Limestone Series 1	156	7.3	39 800		26.40
	Limestone Series 2	117	8.9	38 800		22.10
From Roxborough and Philips[3]	Coal sill (WT4/7)	122.7	6.2	33 100	1.88	23.80
	Letch house (TA2/7)	50.4	3.3	12 500	1.27	17.56
	Massive (WTC/1A)	84.2	6.7	31 200	2.22	32.67
New	L8A	6.20	3.51	8 454	1.08	9.75
	L8B	21.27	1.96	6 143	0.83	6.87
	L10	48.17	2.53	17 309	1.09	9.97
	L14	87.53	6.34	45 311	1.95	20.78
	L16	55.75	4.32	47 273	1.46	12.00
	L18	44.29	4.53	18 355	1.52	17.07

Table III

Classification of sandstones according to Deere and Miller[54]

Reference data	Sandstone sample	Description	Class
From McFeat-Smith and Fowell[2]	Triassic L. Keuper 1	Very low-strength	E
	Triassic L. Keuper 2	Very low-strength	E
	Triassic L. Bunter 1	Low-strength	D
	Triassic M. Bunter 2	Very low-strength	E
	Triassic M. Bunter 3	Very low-strength	E
	Triassic U. Bunter 4	Low-strength	D
	Coal Measures 1	High-strength	B
	Coal Measures 2	Low-strength	D
	Limestone Series 1	High-strength	B
	Limestone Series 2	High-strength	B
From Roxborough and Philips[3]	Coal sill (WT4/7)	High-strength	B
	Letch house (TA2/7)	Low-strength	D
	Massive (WTC/1A)	Medium-strength	C
New	L8A	Medium-strength	C
	L8B	Very low-strength	E
	L10	Low-strength	D
	L14	Medium-strength	C
	L16	Medium-strength	C
	L18	Low-strength	D

Table IV

Rock cutting conditions in core and block grooving tests

Cutting depth	5 mm
Cutting speed	150 mm/s
Rake angle	- 5°
Clearance angle	5°
Pick tip material	Tungsten carbide
Pick width	12.7 mm

There was found to be no correlation between the SE and both B1 and B2 for the range of the sandstones employed for the statistical analyses, as can be seen from Figures 2 (a) and (b) and Table VI. From these figures and tables, brittleness indices of B1 and B2 can be said not to demonstrate the differences in the SE values of sandstones with very low to high strengths. However, there was found to be a statically significant correlation between the SE and B4 at 99 per cent level with an r-value of 0.584 (Table VI). The regression curve established for the relationship between the SE and B4 through fitting a logarithmic model to the data is given in Figure 2 (c), whereas statistical parameters

Table V

Brittleness and toughness indices of sandstones

Reference data	Sandstone sample	B1	B2	B4	T_i (MPa)
From McFeat-Smith and Fowell[2]	Triassic L. Keuper 1	7.27	0.76	4.40	0.57
	Triassic L. Keuper 2	7	0.75	3.50	0.42
	Triassic L. Bunter 1	22.78	0.91	36.90	10.64
	Triassic M. Bunter 2	7.5	0.76	21.60	2.57
	Triassic M. Bunter 3	5.89	0.71	44.85	2.81
	Triassic U. Bunter 4	17.78	0.89	64.80	17.19
	Coal Measures 1	4.74	0.88	462.00	24.32
	Coal Measures 2	15.58	0.65	144.30	2.88
	Limestone Series 1	21.37	0.91	569.40	30.57
	Limestone Series 2	13.15	0.86	520.65	17.64
From Roxborough and Philips[3]	Coal sill (WT4/7)	19.79	0.9	380.37	22.74
	Letch house (TA2/7)	15.27	0.88	83.16	10.16
	Massive (WTC/1A)	12.57	0.85	282.07	11.36
New	L8A	1.77	0.28	10.89	0.23
	L8B	10.82	0.83	20.89	3.68
	L10	19	0.9	61.06	6.70
	L14	13.80	0.86	277.48	8.45
	L16	12.89	0.86	120.50	3.29
	L18	9.77	0.81	100.38	5.34

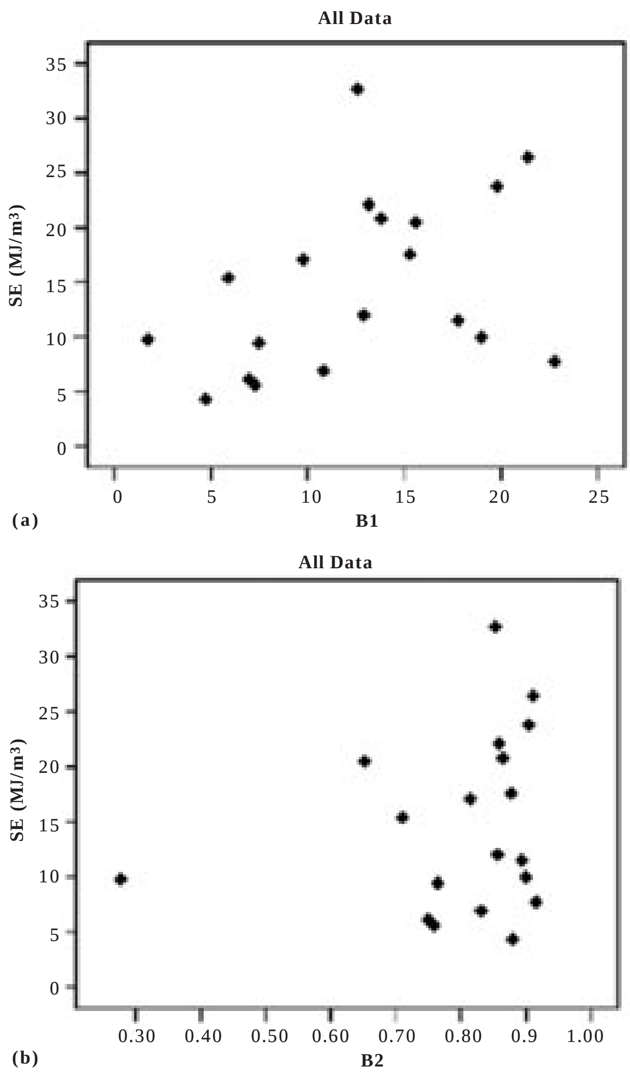

Figure 2—Relationships between the SE and (a) B1, and (b) B2, B4 for all the sandstones

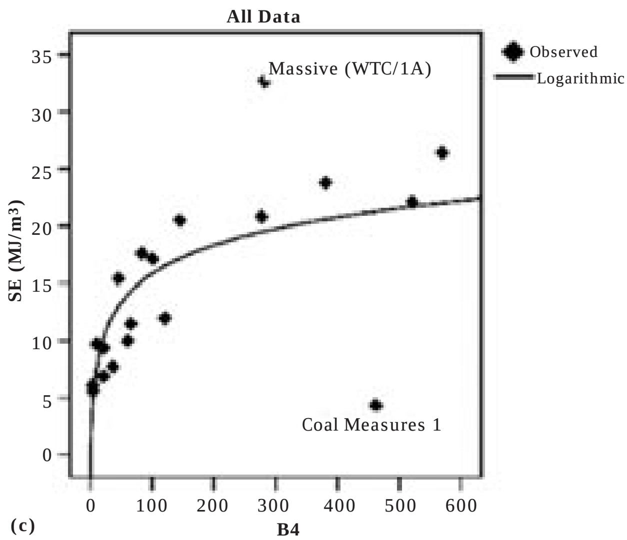

Figure 2 (continued)—Relationships between the SE and (c) B4 for all the sandstones

summarizing this model are given in Table VII.

R^2 in Table VII reveals that almost 47 per cent of the observed variability in the SE is explained by B4. Adjusted R^2 that is an estimate of how well the model would fit another data set from the same population is also equal to 0.44385, which is not very high. The estimate of the variance of the dependent variable for each value of the independent variable (standard error of the estimate) is about 6, as seen in Table VII. As can be understood from Table VII, the model summarizes the relationship between the SE and B4 by fitting a regression line to the sample data. In order to ensure that this model is also valid for predicting SE values in the population from which the sample was selected, F and t- tests were performed about the population regression line. Since the observed significance level is less than 0.05 for the F-test, the null hypothesis that there is no relationship between

Table VI

Bivariate correlation analysis for the SE, B1, B2, and B4 for all the sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
SE (MJ/m3)	14.7089	7.99308	19
B1	12.5666	5.95723	19
B2	0.8037	0.14733	19
B4	168.9053	187.47060	19

Correlations		
Variables		**SE (MJ/m3)**
B1	Pearson Correlation	0.404
	Significance (2-tailed)	0.086
B2	Pearson Correlation	0.195
	Significance (2-tailed)	0.425
B4	Pearson Correlation	0.584 (*)
	Significance (2-tailed)	0.009

*Correlation is significant at the 0.01 level (2-tailed)

the SE and B4 in the model can be rejected (Table VII).

From Table VII, it can be understood that the null hypothesis that the regression coefficient for B4 is zero can be rejected since observed significance levels of t-statistics for the independent variable is less than 0.05. However, this value is not less than 0.05 for the regression constant and the null hypothesis cannot be rejected for the regression constant. The values obtained for the regression coefficient and the constant are based on one sample from the population. If a different sample were taken from the same population, different values would have been obtained for those coefficients and the constant. The distributions of all possible values of the coefficients and the constant are normal if the regression assumptions are met. The standard deviations of these distributions, called the standard errors of the regression coefficient, and the constant are given under the column labelled Std. Error B in Table VII. Again, the corresponding standard error for the regression constant is not low enough to make sure that the accuracy of the regression model is high enough to estimate the SE values from the population by using B4 values for all the sandstones employed in this study.

Therefore, it was decided to establish separate regression models for sandstones with high strength and those with strength values varying from very low to medium. The correlation coefficient between SE and B4 for very low to medium strength sandstones is 0.886, which is statistically significant at 99 per cent confidence level, indicating a strong correlation between those variables for very low to medium strength sandstones used in this study (Table VIII). R^2 that was found from the variance analysis as given in Table VIII reveals that 78.4 per cent of the observed variability in the SE is explained by B4. Adjusted R^2 is equal to 0.76759, which is high enough. The standard error of the estimate is 3.52069, as seen in Table VIII. As can be understood from Table VIII, the relationship between the SE and B4 can be summarized by fitting a liner regression model to the sample data. The regression curve drawn for this linear model is given in Figure 3.

F and t-tests were performed about the population regression line for this model. Since the observed significance level is less than 0.05 for the F-test, the null hypothesis that there is no relationship between the SE and B4 in the model

Table VIII

Bivariate correlation analysis for the SE and B4 for very low to medium-strength sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
B4	85.1187	89.66959	15
SE (MJ/m3)	13.5247	7.30297	15

Correlations		
Variables		**SE (MJ/m3)**
B4	Pearson Correlation Correlation	0.886 (*)
	Significance (2-tailed)	0.000

*Correlation is significant at the 0.01 level (2-tailed)

Table VII

Curve fit results for the SE and B4 for all the sandstones

Multiple R	0.68902	Regression equation: SE = 3.555 x Ln(B4)–0.5736
R^2	0.47475	
Adjusted R^2	0.44385	
Standard error of estimate	5.96088	

Analysis of variance			
	Degree of freedom	**Sum of squares**	**Mean square**
Regression	1	545.96104	545.96104
Residuals	17	604.04554	35.53209
F = 15.36529 Sig. F = 0.0011			

Variables in the regression equation					
Variable	**B**	**Std. Error B**	**Beta**	**T**	**Sig. T**
B4	3.555552	0.907061	0.689018	3.920	0.0011
(Constant)	-0.573620	4.131634	-	-0.139	0.8912

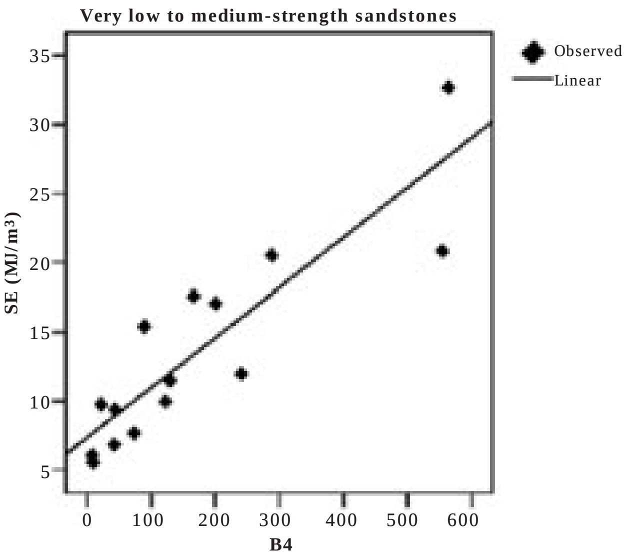

Figure 3—Relationship between the SE and B4 for very low to medium-strength sandstones

can be rejected. The null hypothesis that the regression coefficient and the constant for B4 is zero can also be rejected since observed significance levels of t-statistics for the independent variable were less than 0.05. The corresponding standard errors for the regression coefficient and constant are low enough to make sure that the accuracy of the regression model is high enough to estimate the SE values from the population by using B4 values for all the sandstones employed in the statistical analyses (Table IX).

When the data from McFeat-Smith and Fowell[2] have been considered, it can be seen that high strength and very low to medium strength sandstones have grouped separately (Figure 4). It can also be seen from Figure 4 that a linear model can fit the data from very low to medium strength sandstones very well, whereas a quadratic model summarizes the relationship between the SE and B4 with an R^2 value of 1 for high strength sandstones.

Rock toughness index

There was found to be no statistically significant correlation between the SE and T_i for the range of sandstones employed for the statistical analyses even though very low to medium strength sandstones have also been subjected to a separate bivariate correlation analysis, as can be seen from Figures 5 (a) and (b) and Tables X and XI. From these figures and tables, the toughness index can be said not to demonstrate the differences in the SE values of sandstones employed in the statistical analyses.

The relationship between the T_i and MCF has also been investigated in the extent of this study. Besides MCF being used to calculate the SE, it is also used to decide if the target rock is suitable for mechanical excavation in terms of the machine weight necessary to overcome the reaction forces in practice and the cutting motor power requirements. Since McFeat-Smith and Fowell[2] released no data on MCF, only the MCF data obtained from the new testing programme, being coupled with data from Roxborough and Philips[3], have been utilized for this purpose. There was found to be no statically significant correlation between the T_i and MCF even though very low to medium strength sandstones have also been subjected to a separate bivariate correlation analysis.

However, drawing the MCF values against T_i for all the sandstones on the same graph revealed that two groups of sandstones behaved separately from each other (Figure 6). In Figure 6, with the exception of the coal sill, all other sandstones are of very low to medium strength rocks. When Brazilian tensile strength (σ_t) values of those sandstones are considered, except the value for coal sill that is high-strength sandstone, this grouping of sandstones seemed to be due to the differences in Brazilian tensile strength of very low to medium strength sandstones.

Uniaxial compressive and Brazilian tensile strengths

There was found to be a statically significant correlation between the SE and σ_c at 99 per cent level with an *r*-value of 0.597 for the range of the sandstones employed for the statistical analyses (Table XII). The regression curve

Table IX

Curve fit results for the SE and B4 for very low to medium-strength sandstones

Multiple R	0.88554	Regression equation: SE = 0.0721 x B4 + 7.3857
R^2	0.87419	
Adjusted R^2	0.76759	
Standard error of estimate	3.52069	

Analysis of variance

	Degree of freedom	Sum of squares	Mean square
Regression	1	585.52823	585.52823
Residuals	13	161.13874	12.39529

F = 47.23797 Sig. F = 0.0000

Variables in the regression equation

Variable	B	Std. error B	Beta	T	Sig. T
B4	0.072121	0.010493	0.885545	6.873	0.0000
(Constant)	7.385781	1.274418	–	5.795	0.0001

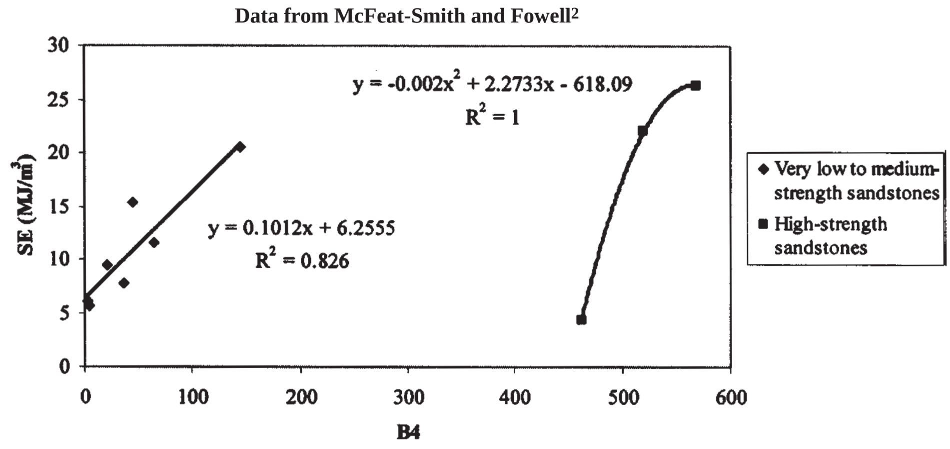

Figure 4—Relationships between the SE and B4 for sandstones with different strengths (from McFeat-Smith and Fowell[2])

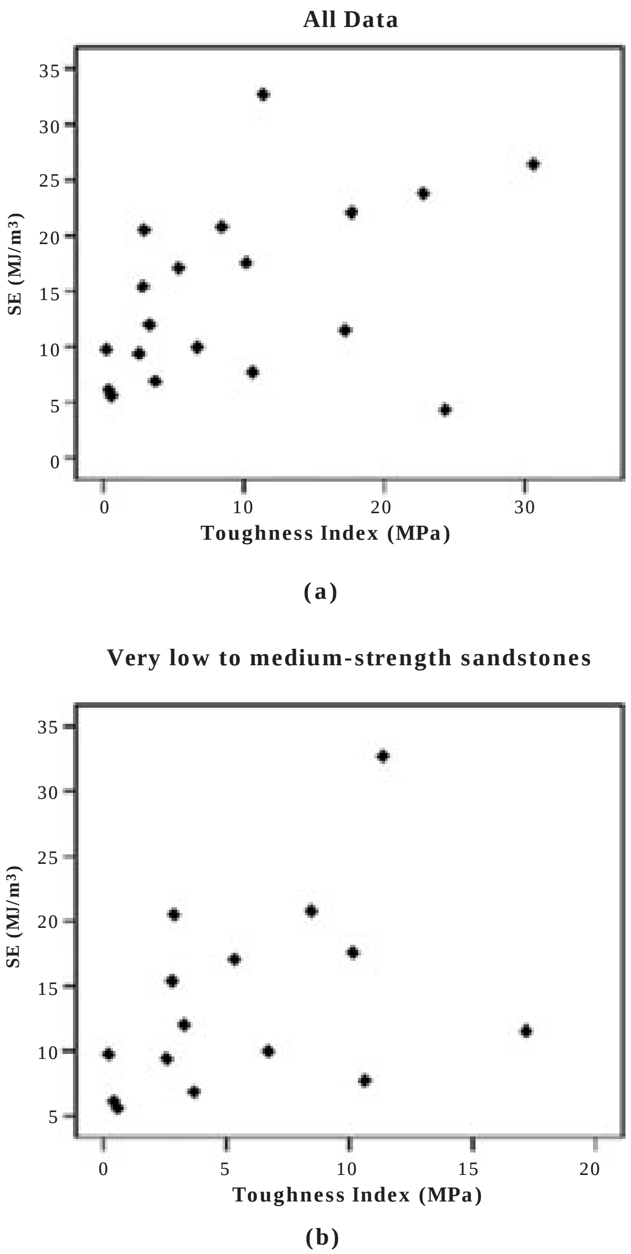

Figure 5—Relationship between the SE and T_i for (a) all the sandstones (b) very low to medium-strength sandstones

Table X

Bivariate correlation analysis for the SE and T_i for all the sandstones

	Descriptive statistics		
Variables	**Mean**	**Std. dev.**	**No. of samples**
T_i (MPa)	9.5553	8.98456	19
SE (MJ/m³)	14.7089	7.99308	19

	Correlations	
Variables		**SE (MJ/m³)**
T_i (MPa)	Pearson correlation	0.413
	Significance (2-tailed)	0.079

Table XI

Bivariate correlation analysis for the SE and T_i for very low to medium-strength sandstones

	Descriptive statistics		
Variables	**Mean**	**Std. dev.**	**No. of samples**
T_i (MPa)	5.7520	4.90782	15
SE (MJ/m³)	13.5247	7.30297	15

	Correlations	
Variables		**SE (MJ/m³)**
T_i (MPa)	Pearson correlation	0.389
	Significance (2-tailed)	0.152

established for the relationship between the SE and σ_c through fitting a logarithmic model to the data is given in Figure 7, whereas statistical parameters summarizing this model are given in Table XIII.

R^2 in Table XIII reveals that almost 37 per cent of the observed variability in the SE is explained by σ_c, which is quite small. F and t-tests that were performed about the population regression line have not given enough evidence to make sure that the accuracy of the regression model is high enough to estimate the SE values from the population by

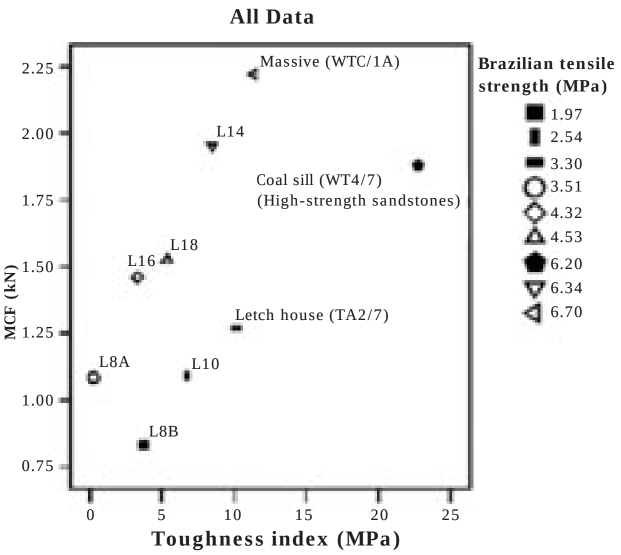

Figure 6—Relationship between the MCF and T_i for all the sandstones

using σ_c values for all the sandstones employed in the statistical analyses.

The correlation coefficient for the relationship between the σ_t determined through the Brazilian tests and the SE is 0.685 at 99 per cent confidence level indicating the significance of σ_t in rock cutting (Table XIV). This also confirms the results of the previous studies in this area. The regression curve established for the relationship between the SE and σ_t through fitting a logarithmic model to the data is given in Figure 8. The best-fit logarithmic model established for the relationship between the SE and σ_t also seems to be statistically accurate enough to estimate SE values from the population by using σ_t values (Table XV).

The correlation coefficient for the relationship between the porosity and the SE is -0.587 at 99 per cent confidence level indicating the close correlation between these two parameters are in line with the previous studies in this area (Table XVI). The regression curve established for the relationship between the SE and the porosity through fitting a logarithmic model to the data is given in Figure 9. The best-fit exponential model established for the relationship between the SE and the porosity seems to be statistically

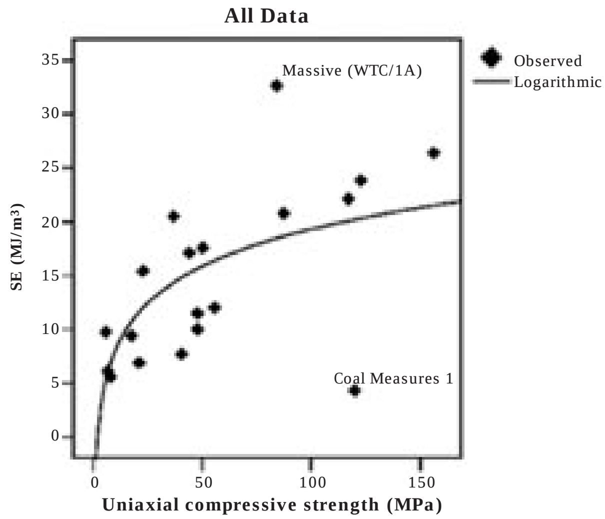

Figure 7 Relationship between the SE and σ_c for all the sandstones

Table XII

Bivariate correlation analysis for the SE and σ_c for all sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
σ_c (MPa)	57.6586	44.60144	19
SE (MJ/m^3)	14.7089	7.99308	19

Correlations		
Variables		**SE (MJ/m^3)**
σ_c (MPa)	Pearson correlation	0.597(**)
	Significance (2-tailed)	0.007

**Correlation is significant at the 0.01 level (2-tailed)

Table XIII

Curve fit results for the SE and σ_c for all the sandstones

Multiple R	0.61168	Regression equation:
R^2	0.37415	SE = 4.9831 x Ln(σ_c) – 3.6628
Adjusted R^2	0.33734	
Standard error of estimate	6.50670	

Analysis of variance			
	Degree of freedom	**Sum of squares**	**Mean square**
Regression	1	430.27589	430.27589
Residuals	17	161.13874	42.33710
	F = 10.16309	Sig. F = 0.0000	

Variables in the regression equation					
Variable	**B**	**Std. error B**	**Beta**	**T**	**Sig. T**
σ_c	4.983052	1.563085	0.611679	3.188	0.0054
(Constant)	-3.662762	5.953033	–	–0.615	0.5465

Table XIV

Bivariate correlation analysis for the SE and σ_t for all the sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
σ_t (MPa)	4.4214	2.48527	19
SE (MJ/m³)	14.7089	7.99308	19

Correlations		
Variables		**SE (MJ/m³)**
σ_t (MPa)	Pearson correlation	0.685(**)
	Significance (2-tailed)	0.001

**Correlation is significant at the 0.01 level (2-tailed)

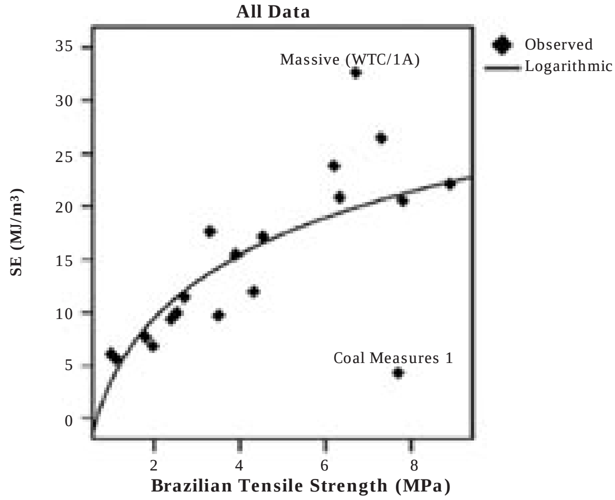

Figure 8—Relationship between the SE and st for all the sandstones

Table XV

Curve fit results for the SE and σ_t for all the sandstones

Multiple R	0.70727	Regression equation: SE = 8.5601 x Ln(σ_t) + 3.542
R^2	0.50023	
Adjusted R^2	0.47083	
Standard error of estimate	5.81447	

Analysis of variance			
	Degree of freedom	**Sum of squares**	**Mean square**
Regression	1	575.26923	575.26923
Residuals	17	574.73735	33.80808
F = 17.01573	Sig. F = 0.0007		

Variables in the regression equation					
Variable	**B**	**Std. error B**	**Beta**	**T**	**Sig. T**
σ_t	8.560065	2.075161	0.707270	4.125	0.0007
(Constant)	3.542046	3.017924	–	1.174	0.2567

Table XI

Bivariate correlation analysis for the SE and porosity for all the sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
Porosity (%)	10.9789	6.10688	19
SE (MJ/m³)	14.7089	7.99308	19

Correlations		
Variables		**SE (MJ/m³)**
Porosity (%)	Pearson correlation	–0.587(**)
	Significance (2-tailed)	0.008

**Correlation is significant at the 0.01 level (2-tailed)

accurate to estimate the SE values from the population by using the porosity values (Table XVII).

NCB cone indenter and Shore scleroscope hardness

There was found to be very close correlations between the hardness values determined from NCB cone indenter and Shore scleroscope tests and the SE (Tables XVIII to XXI). These two testing devices are very well known to return

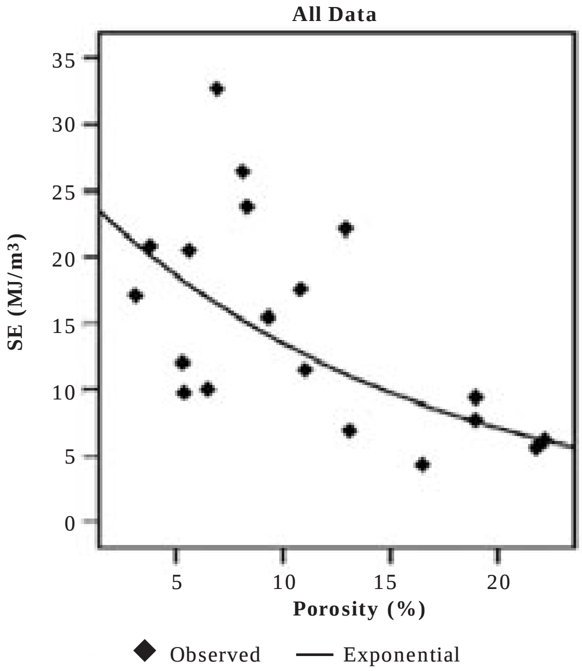

Figure 9—Relationship between the SE and porosity for all the sandstones

Table XVII

Curve fit results for the SE and porosity for all the sandstones

Multiple R	0.67856	Regression equation:
R^2	0.46045	$SE = 25.698\ xe^{-0.0645 \times Porosity}$
Adjusted R^2	0.42871	
Standard error of estimate	0.43898	

Analysis of variance

	Degree of freedom	Sum of squares	Mean square
Regression	1	2.7957020	2.7957020
Residuals	17	3.2760224	0.1927072

F = 14.50751 Sig. F = 0.0014

Variables in the regression equation

Variable	B	Std. error B	Beta	T	Sig. T
Porosity	–0.064534	0.016943	–0.678562	–3.809	0.0014
(Constant)	25.697542	5.435807	–	4.727	0.0002

Table XVIII

Bivariate correlation analysis for the SE and NCB cone indenter hardness for all sandstones

Descriptive statistics

Variables	Mean	Std. dev.	No. of samples
NCB cone indenter hardness	4.0653	2.44839	19
SE (MJ/m^3)	14.7089	7.99308	19

Correlations

Variables		SE (MJ/m^3)
NCB cone indenter hardness	Pearson correlation	0.865(**)
	Significance (2-tailed)	0.000

**Correlation is significant at the 0.01 level (2-tailed)

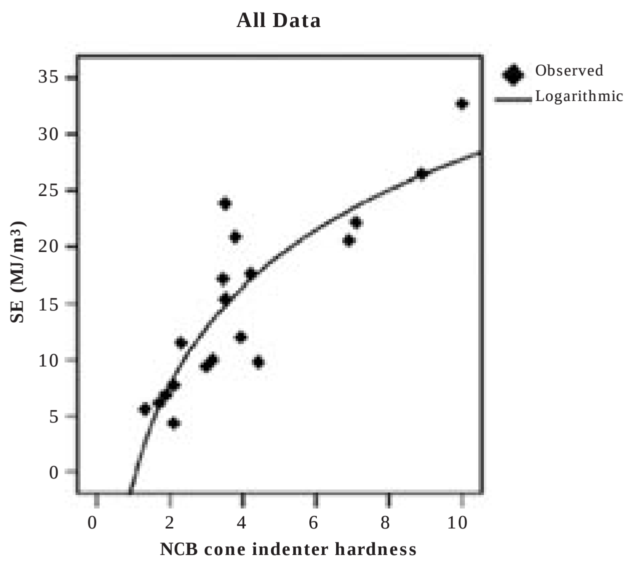

Figure 10—Relationship between the SE and NCB cone indenter hardness for all the sandstones

Table XIX

Curve fit results for the SE and NCB cone indenter hardness for all the sandstones

Multiple R	0.86826	Regression equation:
R^2	0.75388	SE = 12.373 x Ln(NCB) – 0.7506
Adjusted R^2	0.73940	
Standard error of estimate	4.08037	

Analysis of variance

	Degree of freedom	Sum of squares	Mean square
Regression	1	866.96630	866.96630
Residuals	17	283.04028	16.64943

F = 52.07184 Sig. F = 0.0000

Variables in the regression equation

Variable	B	Std. error B	Beta	T	Sig. T
NCB cone indenter hardness	12.373115	1.714658	0.868262	7.216	0.0000
(Constant)	–0.750645	2.337965	–	–0.321	0.7521

Table XX

Bivariate correlation analysis for the SE and Shore hardness for all sandstones

Descriptive statistics			
Variables	**Mean**	**Std. dev.**	**No. of samples**
Shore hardness	38.2579	10.45584	19
SE (MJ/m^3)	14.7089	7.99308	19

Correlations		
Variables		**SE (MJ/m^3)**
Shore hardness	Pearson correlation	0.587(**)
	Significance (2-tailed)	0.008

**Correlation is significant at the 0.01 level (2-tailed)

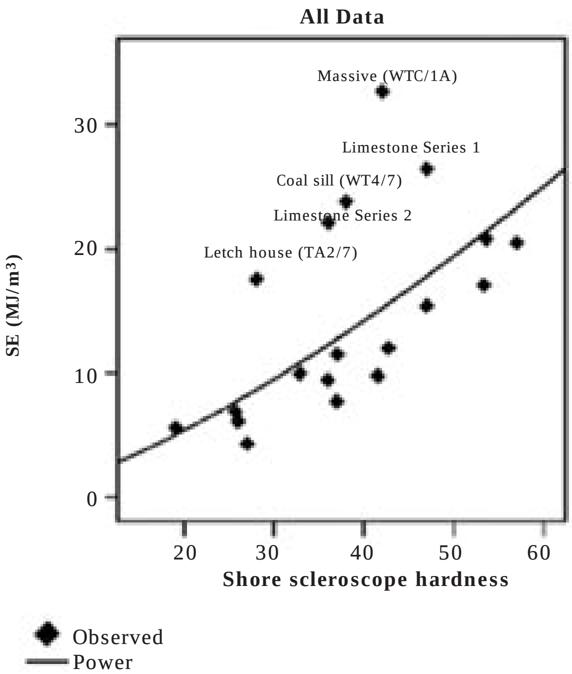

Figure 11—Relationship between the SE and Shore hardness for all the sandstones

information about different aspects of the rock strength and rock behavior under mechanical cutting tools (Figures 10 and 11).

Discussion

Statistical analyses on the data have shown that there were close relationships between the SE of the sandstones employed in this study and their B4 values. B4 seemed even to be able to classify the sandstones with respect to the SE, being the measure of the rock cutting efficiency, as measured in linear cutting tests using chisel picks (Figure 4). However, despite this close relationship between the SE and B4, it is very difficult to accept B4 as a measure of rock brittleness. Although, different ratios of σ_c to σ_t have been proposed by many researchers, rock brittleness values obtained from these ratios have been reported not to represent fully the brittleness concept[41]. Goktan[42] investigated the relations between the laboratory-measured SE and the brittleness index as proposed by Hucka and Das[23] for rocks and coals using the results of rock cutting tests carried out by other researchers. He has found no statistically significant correlations between the SE and that measure of rock brittleness. His conclusion was that the brittleness concept adopted in his study might not be a representative measure of the SE. Rostami *et al.*[41] reported that this lack of correlation was due to the variations between the direct and indirect tensile measurements using the Brazilian test. However, Kahraman[43] has found that each method of measuring brittleness has its own use in rock excavation, i.e. one method of measuring brittleness shows good correlation with the penetration rate of rotary drills, while the other method does not.

Altindag[26–27] has reported that there were significant correlations between the B4 and some specific drillability parameters. However, Denkhaus[20,44] has reported that the B4 was lacking a theoretical base for representing the rock brittleness. This is mainly because B4 has nothing to do with the relation of elastic to plastic strain. It is well known that the higher the ratio of σ_c to σ_t the greater the brittleness of fracture for the rock under normal conditions. Denkhaus[20] has employed two rocks with the same uniaxial compressive

Table XXI

Curve fit results for the SE and Shore hardness for all the sandstones

Multiple R	0.69763	Regression equation: SE = 0.0826 x Shore$^{1.3952}$
R^2	0.48668	
Adjusted R^2	0.45649	
Standard error of estimate	0.42818	

Analysis of variance			
	Degree of freedom	**Sum of squares**	**Mean square**
Regression	1	2.9549982	2.9549982
Residuals	17	3.1167262	0.1833368
	F = 16.11786	Sig. F = 0.0009	

Variables in the regression equation					
Variable	**B**	**Std. error B**	**Beta**	**T**	**Sig. T**
Shore hardness	1.395237	0.347532	0.697626	4.015	0.0009
(Constant)	0.082600	0.103840	–	0.795	0.4373

strength but with different tensile strengths to discuss the validity of B4 in representing the brittle behaviour of rocks. As can be seen in Denkhaus[44], the area under the line for σ_c against σ_t is higher for the rock with a σ_c to σ_t ratio of 5. That is why that rock is more brittle than the rock with a σ_c to σ_t ratio of 20 according to the B4 approach. This contradicts the general knowledge in this area as stated above. Since the σ_c to σ_t ratio of the second rock is higher than the first rock, it is expected to show more brittle behaviour than the latter one at fracture as opposed to what B4 concept proposes. Denkhaus[20] has emphasized that the B4 approach was purely phenomenological and the physical meaning of the product $\sigma_c \times \sigma_t$ was not clear. Nevertheless, B4 seems to rely on the assumption stating that the uniaxial compressive strength of rocks is always proportional to their tensile strengths, which is not true[20,44].

Brittleness of rock materials is believed to have an impact on the rock cutting process. However, there is no universally accepted means to quantify rock brittleness. The main reasons are that the apparent brittleness of a rock depends on the material properties, the geometry and size, and on the loading conditions and it is rock behaviour rather than an intrinsic rock property. These make it very difficult to find a proper relationship, which incorporates all the above-mentioned influences[20,45].

No correlations have been found between the toughness index and the rock cutting efficiency as represented by the SE. However, Poole[15] has reported that the pattern of the relation between the performances of roadheaders and TBMs and estimates of toughness index were in good agreement. When cutting a rock face, the volume of rock influenced by a single tool is still relatively small, so the size effect, when cutting a rock mass, is not thought to diminish the validity of the results based on the laboratory tests. Being parallel to this, McFeat-Smith and Fowell[2] revealed that the SE values found in the laboratory conditions were in close correlation with those measured in the field, especially for widely jointed or massive rock masses. Therefore, a similar correlation has been expected between the SE values obtained from the linear cutting tests on intact sandstone samples and the toughness index in this study.

Farmer and Garrity[14] have proposed that the estimates of the fracture toughness made from measured values of uniaxial compressive strength and deformation modulus should not be confused with the apparent SE calculated from measured values of machine head power consumption and the volume excavation rate by ignoring the energy transfer ratio. SE measured in this way did not correlate well with excavation rates since the former was calculated from the measurements of the latter by the study of McFeat-Smith and Fowell[2].

Farmer and Garrity[14] have proposed that apparent SE is not, therefore, a particularly useful concept when considering the excavation performance. However, Poole[15] has reported that the pattern of the relation between the performance of two powerful roadheaders and estimates of toughness index values indicated an energy transfer ratio of the order of 1–2 per cent, indicating that the toughness index may be a good measure of rock cuttability, especially for partial face machines.

However, the laboratory tests that must be conducted to obtain the parameters in a toughness index equation are static in nature, not entirely reflecting the dynamic nature of the rock cutting process with picks. Additionally, σ_c is just one of the rock properties affecting rock cuttability and it cannot be used to predict the cuttability solely. σ_c has been used in both assessing the cuttability of rock and selecting the mechanical excavator, especially for coal measures strata, as there was no universal prediction model. σ_c is one of the major rock properties in rock cutting since a significant amount of cutting energy available in the system is consumed in overcoming the σ_c of rock for producing a crushed zone under the pick tip at the very beginning of the rock cutting process (indentation). Being parallel to this, a statistically significant correlation has been found between the SE and σ_c in this study. However, σ_c may be a reliable parameter to predict the rock cuttability for a particular rock type, since there are strong relationships between the σ_c, toughness, and brittleness of different rocks for any rock type. In addition, rocks of a particular type, which have similar depositional and mineralogy characteristics, seem to have identical values for toughness and abrasiveness. Strong correlations were found between the σ_c and laboratory SE for coal measures strata, confirming the usage of σ_c for predicting the cuttability and the performances of the roadheaders for this type of rocks[41,46]. However, similar correlations were not found between the σ_c and the rock cuttability for evaporites such as gypsum and anhydrite, despite the fact that they are sedimentary rocks like coal measures strata[46].

Nevertheless, the way in which the toughness index of individual rocks is derived also brings up some problems in representing the rock fracture toughness. The toughness index is calculated from the area under the stress-strain curves as obtained in laboratory uniaxial rock compression tests. Brittle rocks exhibit higher axial strain with lower σ_c values when compared to ductile rocks. Brittle rocks have a small or large region of elastic behaviour but only a small region of ductile behaviour before they fracture. Ductile rocks have a small region of elastic behaviour and a large region of ductile behaviour before they fracture. Therefore, the common shapes of stress-strain curves for brittle and tough rocks are different from each other, as seen in Figure 12. Despite the fact that the ratio of σ_c to ε (strain) is specific for all individual rocks, a ductile rock as a given σ_c value may have the same toughness index with a brittle rock with the same σ_c according to the toughness index approach, depending on the strain value corresponding to the ultimate stress at the time of failure. This may lead to improper evaluation of the deformation, hence the brittleness characteristics of those two rocks.

Furthermore, the effects of temperature, confining stress, composition, and the strain rate on rock fracture behaviour are not taken into account in the toughness index equation. However, the higher the temperature, the more ductile and less brittle a solid becomes. Rocks are brittle at the Earth's surface, but at depth, where temperatures are high because of the geothermal gradient, rocks become ductile. Some minerals, like quartz, olivine, and feldspars, are very brittle. Others, like clay minerals, micas, and calcite, are more ductile. This is due to the chemical bond types that hold them together. Thus, the mineralogical composition of the rock will be a factor in determining the deformational behaviour of the

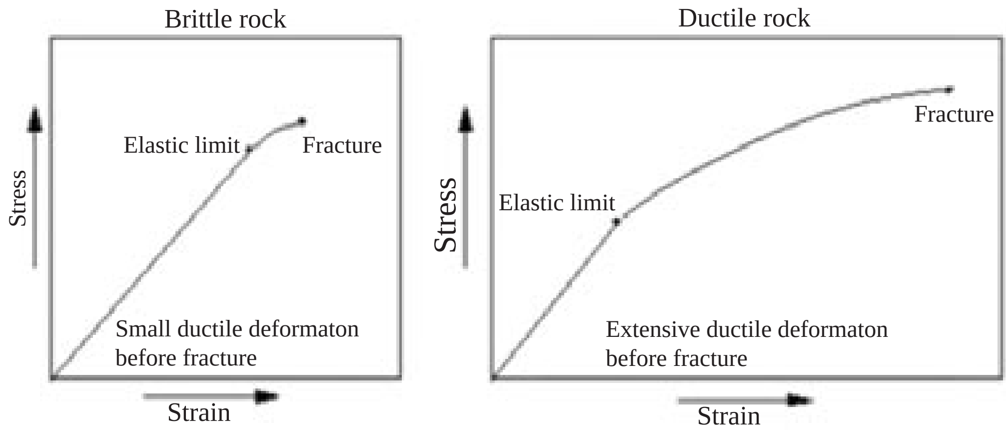

Figure 12 Typical stress-strain curves for brittle and ductile rocks

rock.

Another aspect is presence or absence of water. Water appears to weaken the chemical bonds and forms films around mineral grains along which slippage can take place. Thus, wet rock tends to behave in a ductile manner, while dry rocks tend to behave in a brittle manner. The lower the strain rate, the greater the tendency for ductile deformation to occur.

Because of the above reasons, the toughness index approach does not seem to have a wide application in rock excavation for the estimation of rock cuttability and likely excavation rates of partial face machines. The above reasons also explain why B4 must not be employed to evaluate how much a rock exhibits brittle behaviour under loading. However, this, of course, does not necessarily diminish the significance of fracture characteristics of rocks in rock cutting and mechanical rock excavation. According to Sun *et al.*[4], fracture properties rather than mechanical properties of rocks are the governing parameters of the rock fracture mechanism involving crack initiation and propagation. Being in line with this approach, cutting some evaporites by mechanical tools were reported to be found more difficult than coal measures strata with the similar σ_c values, indicating the lack of correlation between the σ_c and cuttability for all rocks. This may be attributed to the development and interlocking of the large grains that form evaporites during the deposition process. Furthermore, unlike the coal measures strata, evaporites are tough rocks[46]. These differences between coal measures and evaporites raise difficulties for the growth and propagation of cracks that lead to fragmentation of rock, revealing the significance of toughness. However, no generally accepted test procedures that do not also require complicated laboratory facilities have been developed to determine this parameter yet.

There were close relationships found between the SE, σ_t, NCB cone indenter and Shore hardness values, and the porosity in this study. It is very well known that as tensile strength increases, a corresponding increase occurs in SE for most of the rocks. Brittle rocks were reported to show tensile failure, while 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[18, 28,47].

NCB cone indenter apparatus is widely employed in selecting the roadheader and pick type and model for both civil tunnelling projects and roadway drivage applications in coalmines. Test apparatus for cone indenter hardness was developed at the National Coal Board of England to determine both the indentation hardness and σ_c of rock through measuring its resistance to indentation by a hardened tungsten carbide cone. The basic principle of this apparatus is to measure the penetration depth of the cone into rock for a known applied force. The indentation hardness measured in this test provides an accurate and meaningful measure of resistance of rocks to indentation. Results of this indentation test have been found applicable to rock cutting since the cutting action of picks is known to include an indentation action at the beginning of the cutting process. NCB cone indenter values were determined to be in good correlation with laboratory and field specific cutting energy values in previous studies, especially for the coal measures strata. In addition, the equation proposed by NCB for predicting σ_c of rock from cone indenter hardness came up with satisfactory results for some sedimentary rocks[2,48].

The Shore scleroscope is widely employed in mechanical excavation applications in order to measure the rebound hardness of intact rock. Shore hardness provides the rock hardness concerning the mineral content, elasticity, and cementation characteristics of it. Previous studies also revealed the potential of the Shore scleroscope test for the assessment of the plasticity of rocks[49]. Laboratory rock cutting studies conducted by McFeat-Smith and Fowell[2] put forward the importance of the Shore scleroscope hardness in the prediction of SE and pick wear rate.

Tiryaki *et al.*[39] have found that the SE decreases as the effective porosity increases for the sandstones. Porosity is considered as the ratio between the solids and pores in rock. It is very well known that the pore spaces, being non-uniformities in the texture of rocks, reduce their strength significantly. Since SE is directly proportional to the rock strength, especially for the coal measures strata, any increase in the porosity of sandstones is likely to cause a corresponding decrease in the SE. Therefore, it is meaningful that SE has had a close negative relationship with the porosity of sandstones employed in this study.

Conclusions

Very low to medium-strength sandstones from different sites around Ankara, Turkey were subjected to a series of comprehensive rock mechanics and rock cutting tests and mineralogical and petrographic analyses. Relationships between the indirect measures of rock brittleness and fracture toughness, along with the other engineering rock properties and SE were investigated statistically by using bivariate correlation and curve fitting techniques, ANOVA, and Student's t-test. Data from previous well-known studies in this area have also been involved in statistical analyses. The following results and conclusions can be drawn from the present study of the evaluation of indirect measures of rock brittleness and fracture toughness in cutting sandstones by drag tools:

- Close correlations have been found between the laboratory SE and B4. However, this does not necessarily mean accepting B4 as a measure of rock brittleness. It along with the other brittleness indices, should be considered as different combinations of ratios and products of σ_c and σ_t unless their significances in representing the rock brittleness are justified in a theoretical sense by further investigations.
- There was no statistically significant correlation between the SE and the toughness index for the sandstones employed in this study. The only remarkable evidence indicating the significance of the toughness index in rock cutting is the close correlation found between the T_i and MCF for very low to medium strength sandstones. Therefore, the toughness index, being proposed as an indirect measure of rock fracture toughness, seems to be useless to represent reliably the rock fracture toughness of the sandstones employed in this study.
- Rock brittleness must be taken as a rock behaviour rather than an intrinsic rock property.
- Further studies including the determination of the fracture toughness by different methods for the sandstones employed in this study can be useful in clarifying the relationships between the fracture toughness, being an intrinsic rock property, its indirect measures, and the SE.
- Regardless of the depositional properties of sandstones, strength parameters of σ_c, σ_t, and hardness characteristics of the NCB cone indenter and Shore scleroscope, and the porosity have been very well correlated with the SE, especially for the very low to medium-strength sandstones.
- Brazilian tensile strength is a good predictor of the laboratory SE for the range of sandstones included in this study.
- NCB cone indenter and Shore scleroscope hardness tests, being easy-to-use rock index tests, can be used to estimate the laboratory SE, which can be applied in the field, especially for the excavations in massive or widely jointed rock masses of sandstones. The NCB cone indenter test had the greatest influence on the SE among the other engineering properties of rocks, confirming the previous studies in rock cutting and mechanical excavation.

The rock cutting process is mainly a process of fragmenting the rock by mechanical tools, in which elastic properties of rock materials play a very important role. Therefore, rock brittleness and fracture toughness have been reported to be very significant in rock cutting by many researchers. In particular, fracture toughness, being an intrinsic rock property, has a great potential in estimating the SE for a wide range of rocks. However, until an easy-to-use field test is developed for this parameter, standard rock index tests and well-known rock parameters can be used to estimate laboratory SE.

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Mintek develops more cost-effective grinding media*

Mintek, specialists in mineral and metallurgical research and development (R&D), technology transfer and beneficiation, in association with industry and university partners, has begun a major project to develop a more cost-effective type of grinding ball for the minerals industry.

With a budget of R5 million spread over three years, the project is funded by the National Research Foundation's (NRF) Innovation Fund. Anglo Platinum, the University of Pretoria, and Prima Industrial Holdings are Mintek's project partners.

The programme will initially focus on developing a grinding ball for the platinum group metals (PGM) industry, which could later be expanded to include other sectors. 'Grinding, including the energy input, typically constitutes about fifty per cent of the total costs of metallurgical processing,' said Dr Jones Papo, head of Base Metals in Mintek's Advanced Materials Division (AMD). 'South Africa's PGM industry consumes more than 70 000 tons of grinding media each year, at an annual cost of about R500 million. If a ball can be developed that exceeds the performance of current products at a more competitive price, it would result in a significant reduction in processing costs. A high quality product such as this would also create an excellent export opportunity.'

Quality control work on sectioned grinding ball in Mintek's metallographic laboratory

A drop tester (right) and grinding ball mill used at Mintek for impact and wear tests

Mintek has been involved in R&D on grinding media, including quality control work for producers and consumers, for more than twenty years. During this time, a large amount of information has been built up on the effects of different compositions, microstructures, and heat treatments on grinding ball performance.

For the current project, five promising alloy compositions have been selected for initial investigations. Samples produced in laboratory-scale melts are undergoing screening for their mechanical and metallurgical characteristics, and their microstructures will be optimized for the best combination of impact and wear resistance. Balls cast from the three most promising materials will then be evaluated through Mintek's own quality control system.

In the subsequent stages of development, pilot-scale batches of balls will undergo marked-ball tests in an industrial mill, to compare their wear rates with those of commercial grinding media. For the final evaluation, full-charge performance trials will be undertaken on one or more milling circuits over a period of about nine months. ◆

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