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Estimating specific energy from the brittleness indexes in cutting metallic ores

by R. Comakli*, S, Kahraman†, C. Balci‡, and D. Tumac‡

Synopsis

Specific energy (SE) is a very useful parameter for assessing rock excavation by machine. Predicting the SE from the brittleness will be practical, especially for preliminary studies, due to the fact that determining the SE from cutting tests is difficult and expensive. In this study, the predictability of the SE from different brittleness concepts was investigated for metallic ores such as chromite, haematite, galena, and smithsonite. Uniaxial compressive strength, Brazilian tensile strength, impact strength, and small-scale cutting tests were carried out in the laboratory. The SE values were calculated from the cutting tests and correlated with three different brittleness concepts. A significant correlation could not be found between the SE and the brittleness B_3 (the ratio of compressive strength minus tensile strength to compressive strength plus tensile strength). However, strong correlations were found between the SE and the both brittleness B_5 (the product of percentage fines in the impact strength test and compressive strength) and brittleness B_8 (half of the product of compressive strength and tensile strength). The validations of the derived equations were also checked. It is concluded that the SE in ore cutting can be reliably estimated from the brittleness concepts B_5 and B_8.

Keywords
specific energy, ore cutting, brittleness indexes, regression analysis.

Introduction

Specific energy (SE) is an important parameter in mechanical rock excavation. It can be simply used for predicting the performance of roadheaders (Rostami, Ozdemir, and Neil, 1994). However, obtaining the SE from small-scale or full-scale cutting tests is very difficult and expensive. For this reason, some researchers have investigated the relationships between SE and rock properties and suggested empirical equations for the estimation of SE. McFeat-Smith and Fowell (1979) carried out experimental studies for correlating the SE obtained by small-scale cutting tests with some rock properties such as cone indenter index, cementation coefficient, Schmidt hammer rebound value, and compressive strength. They stated that the cone indenter test consistently proved to be the best predictor for SE. Copur *et al.* (2001) correlated the SE with the UCS and BTS for some rock and ore types. They found good correlation between SE and both UCS and BTS. They also showed that the relation between SE and the product of UCS and BTS has a better correlation coefficient than that of the relations between SE and both UCS and BTS. Balci *et al.* (2004) tested 23 different rock and ore types and investigated the predictability of SE from physical and mechanical properties. They found good or very good correlations between the SE and rock properties such as UCS, Brazilian tensile strength, static and dynamic elastic moduli, and the Schmidt hammer value. Tiryaki and Dikmen (2006) carried out mineralogical and petrographic analyses, rock mechanics, and linear rock cutting tests on sandstones. They investigated the relations between SE and rock properties using regression analysis. They showed that the texture coefficient and feldspar content of sandstones affected rock cuttability, evidenced by significant correlations between these parameters and SE. However, the felsic and mafic mineral contents of sandstones exhibited no significant correlation with SE. On the other hand, cementation coefficient, effective porosity, and pore volume indicated good correlations with 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 with SE. Tumac *et al.* (2007) investigated the predictability of rock cuttability from Shore hardness and compressive strength. They showed that there was a relation between Shore hardness values, optimum specific energy, and compressive strength.

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* *Mining Engineering Department, Nigde University, Nigde, Turkey.*
† *Mining Engineering Department, Hacettepe University, Ankara, Turkey.*
‡ *Mining Engineering Department, Istanbul Technical University, Istanbul, Turkey.*
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Some researchers have investigated the relations between the cuttability or SE and brittleness. Singh (1986) indicated that cuttability, penetrability, and the Protodyakonov strength index of coal strongly depended on the brittleness of coal. Singh (1987) also showed that a directly proportional relation existed between *in situ* SE energy and the brittleness of three Utah coals. Goktan (1991) investigated the relation between SE and a brittleness concept derived from the UCS and BTS and concluded that the brittleness concept adopted in his study might not be a representative measure of specific energy consumption during rock cutting. Altindag (2003) investigated the relations between SE and brittleness concepts using the raw data obtained from previous experimental studies on rocks. He showed that the SE was strongly correlated with the brittleness B_3 (the area under the line relating compressive strength and tensile strength).

In this study, eight different metallic ores such as chromite, haematite, galena, and smithsonite were tested in the laboratory and the predictability of the SE from different brittleness concepts was investigated.

Brittleness

There is no common agreement as to the definition, concept, or measurement of brittleness. Different researchers express and use the concept differently. Morley (1944) and Hetényi (1966) define brittleness as lack of ductility. Materials such as cast iron and many rocks, which usually fail by fracture at or only slightly beyond the yield stress, are defined as brittle by Obert and Duvall (1967). Ramsay (1967) defines brittleness as follows: 'when the internal cohesion of rocks is broken, the rocks are said to be brittle.' The definition of brittleness as a mechanical property varies from author to author. Different definitions of brittleness summarized by Hucka and Das (1974) are formulated as follows:

$$B_1 = \frac{\varepsilon_r}{\varepsilon_t} \qquad [1]$$

where B_1 is the brittleness determined from the percentage of reversible strain as determined from the stress-strain curve, ε_r is the reversible strain, and ε_t is the total strain.

$$B_2 = \frac{W_r}{W_t} \qquad [2]$$

where B_2 is the brittleness determined from the percentage of reversible energy as determined from the stress-strain curve, W_r is the reversible energy, and W_t is the total energy.

$$B_3 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \qquad [3]$$

where B_3 is the brittleness determined from the compressive and tensile strengths, σ_c is the uniaxial compressive strength, and σ_t is the tensile strength.

$$B_4 = sin\theta \qquad [4]$$

where B_4 is the brittleness determined from Mohr's envelope (at $\sigma_n = 0$) , and θ is the angle of internal friction.

$$B_5 = q\sigma_c \qquad [5]$$

where, B_5 is the brittleness from the Protodyakonov (1962) impact test, σ_c is the UCS, and q is the percentage of fines (-28 mesh) formed in the Protodyakonov impact test.

$$B_6 = \frac{H_\mu - H}{K} \qquad [6]$$

where B_6 is the brittleness from macro-hardness and micro-hardness, $H\mu$ is the micro-indentation hardness, H is the macro-indentation hardness, and K is a constant.

Hucka and Das (11975) defined a brittleness obtained from load-deformation curves. This definition of brittleness can be formulated as follows:

$$B_7 = \frac{W_{rs}}{W_t} \qquad [7]$$

where B_7 is the penetration brittleness determined from the percentage of reversible energy in the load-deformation curve, W_{rs} is the reversible strain energy just before failure, and W_t is the total energy supplied just before failure.

Altindag (2000) suggested a brittleness index obtained from compressive and tensile strength. This brittleness index is defined as the area under the curve of compressive strength versus tensile strength and can be formulated as follows:

$$B_8 = \frac{\sigma_c \sigma_t}{2} \qquad [8]$$

where B_8 is the brittleness determined from compressive and tensile strength, σ_c is the uniaxial compressive strength, and $\sigma\tau_c$ is the tensile strength.

Recently, Yagiz (2009) introduced a new brittleness index obtained from the punch penetration test:

$$B_9 = \frac{F_{\max}}{P} \qquad [9]$$

where B_9 is the brittleness determined from force-penetration curve, $F_{\max}$ is the maximum applied force on a rock sample (kN), and P is the corresponding penetration at maximum force (mm).

Sampling

Mineral deposits are common in the Taurus Mountain Belt, which runs from west to east in the south of Turkey. This mountain belt is subdivided into three parts: the western, the middle, and the eastern Taurus Mountains. The boundary between the middle and the eastern part is the Aladaglar region. Block samples of chromite, haematite, galena, and smithsonite were collected from eight different mines or outcrops in the Aladaglar region (Figure 1). The sampling locations are listed in Table I. Samples 70 mm in diameter were cored from the blocks for cutting tests, and 38 mm diameter samples for physico-mechanical tests.

Experimental studies

Uniaxial compressive strength (UCS) test

Uniaxial compressive strength tests were conducted on trimmed core samples, which had a diameter of 38 mm and a length-to-diameter ratio of 2–2.5. The stress rate was applied within the limits of 0.5–1.0 MPa/s. The tests were repeated at least five times for each ore type and the average value recorded as the UCS.

Table I

Average results of physico-mechanical and cutting tests

Ore type	Location	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Impact strength index (%)	Specific energy (MJ/m³)
Hematite	Mentes/Yahyali	32.37	4.85	71.3	12.6
Hematite	Dundarli/Nigde	31.47	3.86	78.3	9.4
Hematite	Attepe/Yahyali	27.42	3.99	81.5	12.6
Chromite	Kapiz mine/Pozanti	66.27	7.44	72.1	28.1
Chromite	Guven mine/Aladag	7.89	1.12	40.9	10.1
Chromite	Andizli/Pozanti	58.98	5.98	68.6	20.1
Galena	Delikkaya/Yahyali	19.83	2.93	38.2	9.0
Smithsonite	Derebag/Yahyali	22.35	3.99	66.7	11.5

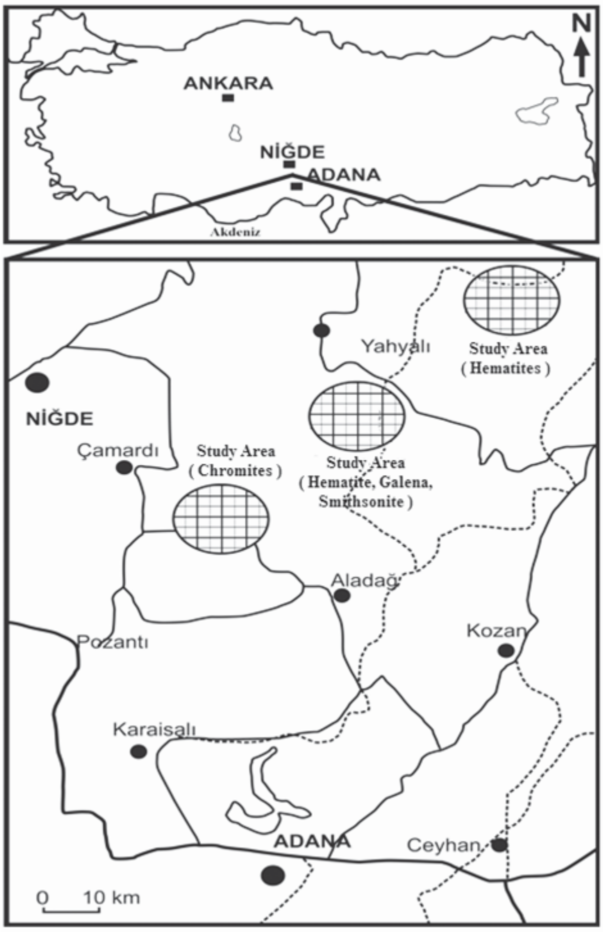

Figure 1—Location map of sampling area

Brazilian tensile strength (BTS) test

Brazilian tensile strength tests were conducted on core samples with a diameter of 38 mm and a height-to-diameter ratio of 0.5–1.0. A tensile loading rate of 200 N/s was applied until failure occurred. At least six samples were tested for each ore type and the results were averaged.

Impact strength test

The impact strength test was first developed by Protodyakonov (1962), and later modified by Evans and Pomeroy (1966). The device designed by Evans and Pomeroy (1966) was used in the impact strength tests in this study. A 100 g sample of rock in the size range 3.175–9.525 mm is placed inside a cylinder 42.86 mm in diameter and a 1.8 kg weight is dropped 20 times from a height of 30.48 cm onto the sample. The amount of rock remaining in the initial size range after the test is termed the impact strength index. The test was repeated three times for each ore type and the average value recorded as the impact strength index (I_S).

Small-scale cutting test

Details of this test were presented by McFeat-Smith and Fowell (1979). In the current study, 70 mm core samples were fixed in the table of a shaping machine (Figure 2) and cut by a chisel pick having a rake angle of –5 degrees, a clearance angle of 5 degrees, and a tool width of 12.7 mm. The depth of cut was selected as 5 mm. The tool forces in three directions were recorded (Figure 3) using a force dynamometer, and the SE calculated by dividing the mean cutting force by the yield (volume of cut material). The cutting tests were repeated three times for each rock type and the results were averaged.

Evaluation of the results

Table I presents the average results of all tests. As shown, the UCS values range from 7.89 MPa for the Guven Mine/Aladag chromite to 66.27 MPa for the Kapiz Mine/Pozanti chromite. The BTS values range from 1.12 MPa for the Guven Mine/Aladag chromite to 7.44 MPa for the Kapiz Mine/Pozanti chromite. I_S values range from 38.2% for the Delikkaya/Yahyali galena to 81.5 % for the Attepe/Yahyali haematite.

The brittleness concepts B_3, B_5, and B_8 were used in the statistical analysis. The calculated brittleness values are given in Table II. The brittleness values and SE values were analysed using least squares regression. Linear, logarithmic, exponential, and power curve fitting approximations were executed and the best approximation equation with the highest correlation coefficient was determined for each regression. No significant correlation between SE and brittleness B_3 was found (Figure 4). However, a strong correlation between SE and brittleness B_5 was found (Figure 5). The relationship follows an exponential function. The SE increases with increasing brittleness B_5. The equation of the curve is

$$SE = 7.64e^{0.0002\,B_5} \qquad r = 0.89 \qquad [10]$$

where SE is the specific energy (MJ/m^3) and B_5 is the brittleness.

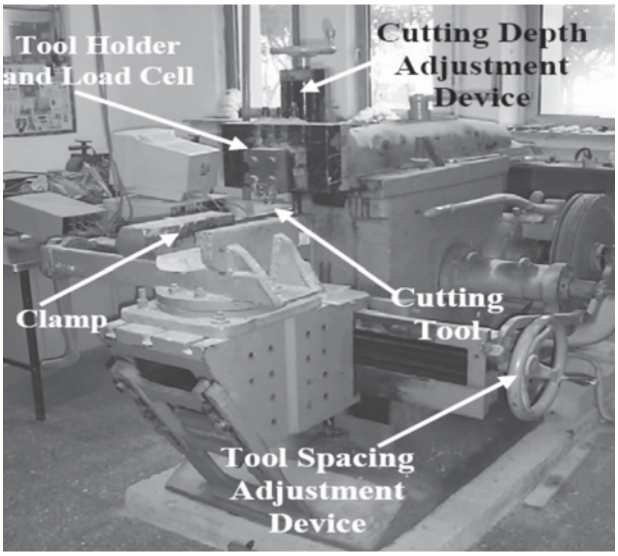

Figure 2—Small-scale cutting rig

Table II

Brittleness values

Ore type	Ore location	B_3	B_5	B_8
Hematite	Mentes/Yahyali	0.74	2308.0	78.5
Hematite	Dundarli/ Nigde	0.78	2463.2	60.7
Hematite	Attepe/ Yahyali	0.75	2233.6	54.7
Chromite	Kapiz mine/ Pozanti	0.80	4775.4	246.5
Chromite	Guven mine/ Aladag	0.76	322.4	4.3
Chromite	Andizli/ Pozanti	0.82	4043.7	176.4
Galena	Delikkaya/ Yahyali	0.74	757.5	29.1
Smithsonite	Derebag/ Yahyali	0.70	1490.7	44.6

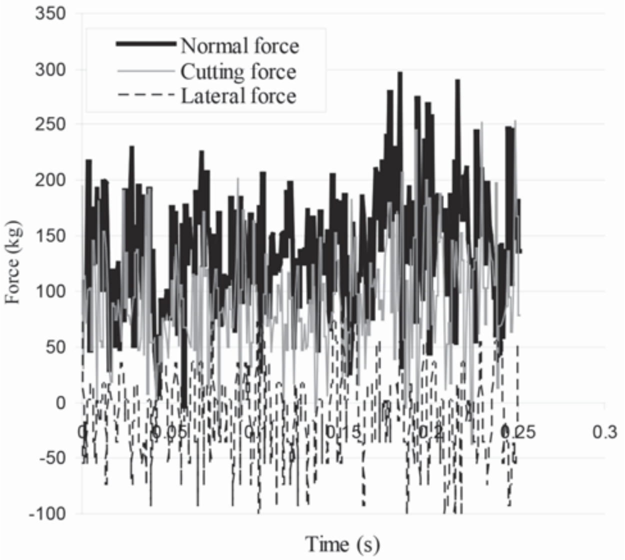

Figure 3—Tool forces in three directions

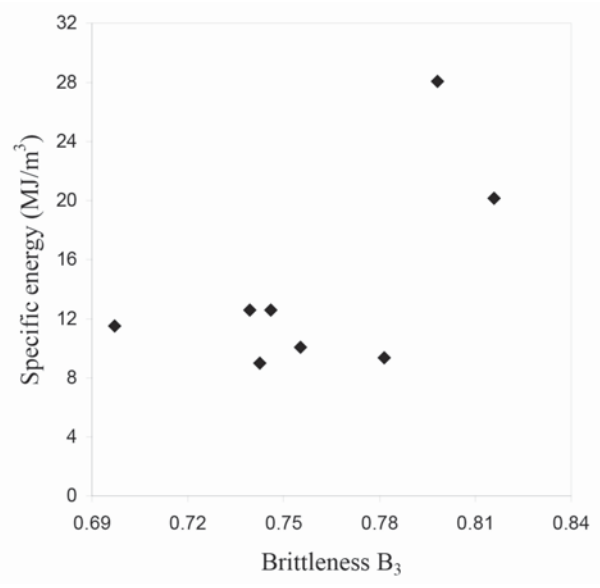

Figure 4—Correlation between specific energy and brittleness B_3

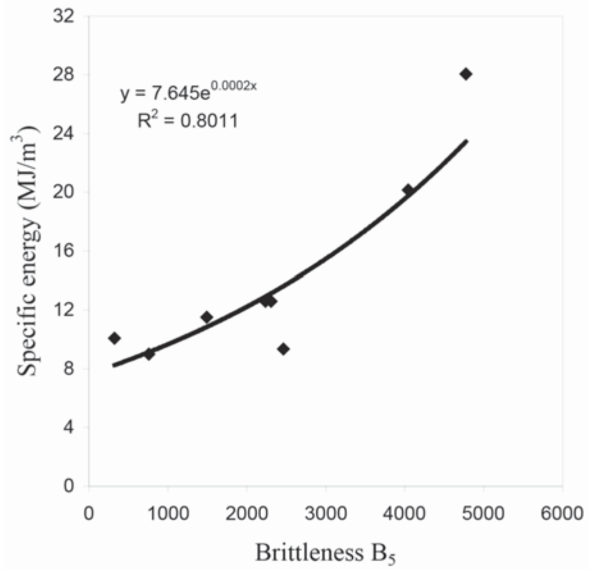

Figure 5—Correlation between specific energy and brittleness B_5

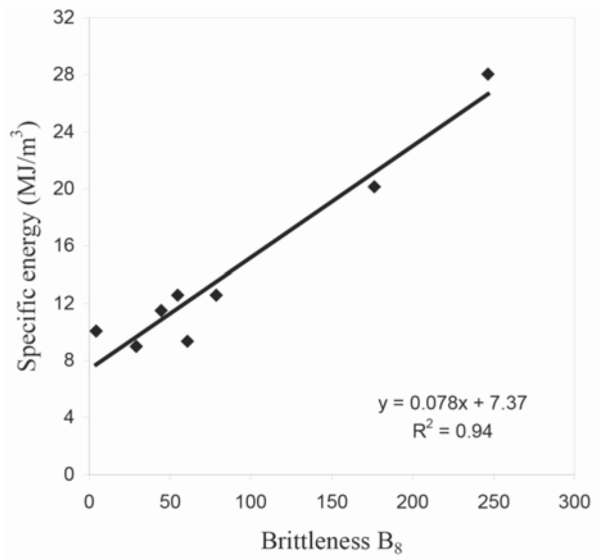

Figure 6—Correlation between specific energy and brittleness B_8

A very strong correlation between SE and the brittleness B_8 was also found (Figure 6). The relation follows a linear function. SE increases with increasing brittleness B_8. The equation of the line is

$$SE = 0.078B_8 + 7.37 \qquad r = 0.97 \tag{11}$$

where SE is the specific energy (MJ/m³) and B_8 is the brittleness.

Altindag (2003) combined some data for the regression analysis and derived the following equation between SE and brittleness B_8:

$$SE = 1.005B_8^{0.61} \qquad r = 0.84 \tag{12}$$

where SE is the specific energy (MJ/m³) and B_8 is the brittleness.

Figure 7 was plotted to compare Equations [11] and [12]. Although Equation [11] is a linear relation and Equation [12] is a power relation, there is not a large difference between the two trends, as shown in Figure 7. The difference between the two trends may be due to the fact that Altindag's data covers a wide strength range. The ores tested in this study have UCS values less than 66 MPa and brittleness B_8 values less than 300. However, Altindag's data includes UCS values up to 559 MPa and brittleness B_8 values up to 2491. An important point is that Altindag's data shows an almost linear trend for rock with brittleness values less than 300. On the other hand, some of the methods for measuring SE are different in Altindag's study. For example, Altindag used published data and some of his data is derived from to disc cutter tests, not a chisel pick test.

As shown above, the correlation coefficients of Equations [10] and [11] are very good, but they do not necessarily identify the valid model. Validation of these equations was checked by the *t*-test and the *F*-test.

The significance of *r*-values can be determined by the *t*-test, assuming that both variables are normally distributed and the observations are chosen randomly. The test compares the computed *t*-value with the tabulated *t*-value using the null hypothesis. In this test, a 95% level of confidence was chosen. If the computed *t*-value is greater than tabulated *t*-value, the null hypothesis is rejected. This means that *r* is significant. If the computed *t*-value is less than the tabulated *t*-value, the null hypothesis is not rejected. In this case, *r* is not significant. As seen in Table III, the computed *t*-values

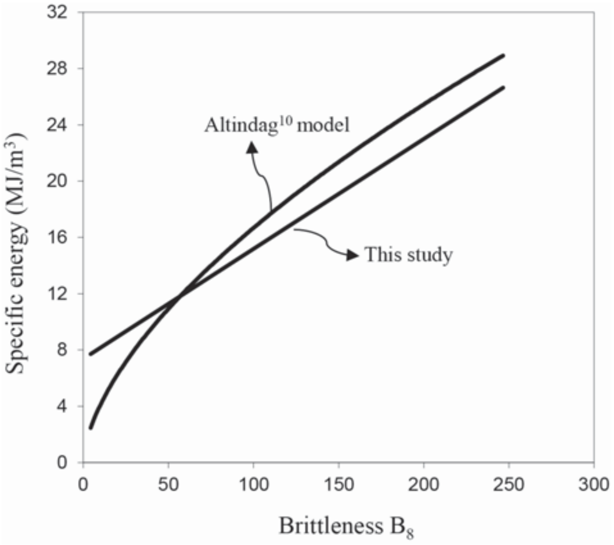

Figure 7—Comparison between Equations [11] and [12]

Table III

t- and F-test results

Equation no.	Tabulated *t*-value	*t*-value	Tabulated *F*-ratio	*F*-ratio
10	± 2.36	4.27	4.60	18.11
11	± 2.36	2.71	4.60	6.22

are greater than the tabulated t-values for Equations [10] and [11]. Equation [10] and [11] are therefore valid according to the t -test.

The significance of regressions was determined by analysis of variance. In this test, a 95% level of confidence was chosen. If the computed F-value is greater than tabulated F-value, the null hypothesis is rejected, and there is a real relation between the dependent and independent variables. Since the computed F-values are greater than the tabulated F-values for Equations [10] and [11], the null hypothesis is rejected (Table III). Therefore, it is concluded that Equations [10] and [11] are valid according to the F-test.

Conclusions

The prediction of specific energy (SE) from three different brittleness concepts was investigated for metallic ores such as chromite, haematite, galena, and smithsonite. It was concluded that there is no correlation between SE and the brittleness B_3. However, strong correlations were found between SE and brittleness concepts B_5 and B_8. The derived equations were also checked by the t- and F-tests and the models were shown to be valid. It was concluded that SE in ore cutting can be reliably predicted from brittleness concepts B_5 and B_8.

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