Estimation of optimum specific energy based on rock properties for assessment of roadheader performance

by C. Balci*, M.A. Demircin†, H. Copur*, and H. Tuncdemir*

Synopsis

Specific energy is defined as the amount of work required to break a unit volume of rock and is used to predict the performance of mechanical miners. It is obtained from full-scale rock cutting experiments, which require large block samples, experienced personnel and expensive equipment found in only a few research centres in the world.

Estimation of the optimum specific energy, at which a given geological formation is excavated at optimum cutting geometry in the most energy efficient manner, from mechanical rock properties to predict the performance/efficiency of roadheaders is the basic aim of this study. The mechanical rock property tests require only core samples, which are easier to obtain and to test. In this context, full-scale rock cutting tests are performed on 23 different rock, mineral and ore samples including sandstone, claystone, tuffite, chromite, trona and copper collected from some operating mines in Turkey. The optimum specific energy values are obtained for each sample. Physical and mechanical property tests are performed on the core samples obtained from the same samples to determine uniaxial compressive strength, indirect (Brazilian) tensile strength, static and dynamic elasticity moduli, Schmidt hammer rebound values, density, and Cerchar abrasivity index. The relationships between the optimum specific energy and the mechanical rock properties are analysed using statistical methods.

The results indicate strong relationships between the optimum specific energy and the mechanical rock properties. The strongest relationships are found by using uniaxial compressive strength and tensile strength. The performance models developed in this study are in good agreement with the empirical models previously developed for roadheaders and can be used reliably for prediction purposes.

Keywords: Mechanical excavation, roadheader, performance prediction, rock cutting, optimum specific energy, mechanical properties of rocks.

Introduction

Prediction of the excavation performance of any mechanical excavator such as roadheaders, continuous miners and shearers for any geological formation is one of the main concerns in determining the economics of a mechanized mining and/or tunnelling operation. There are several methods of performance prediction and the best approach may be the use of more than one of these methods. These methods may be generally classified as full-scale linear cutting test, small-scale cutting test (core cutting), empirical approach, semi-theoretical approach and field trial of a real machine.

The full-scale linear cutting test is widely accepted and a precise approach, since a large block of rock of size 1×1×0.6 m is cut in the laboratory with an industrial cutter. The cutting force, normal force, sideways force and specific energy values are obtained for different cut spacing and depth values. The production rate of a mechanical miner is calculated based on the optimum specific energy or by using a computer model/simulation requiring forces acting on the cutters. The basic disadvantage of the full-scale rock cutting test is that it requires large blocks of rock samples, which are usually difficult, too expensive or impossible to obtain. Also, this type of testing equipment is found in only a few research centres in the world[1–3]. Therefore, the core sample based cuttability tests are preferred in many cases, even though their predictive abilities are lower than the full-scale rock cutting tests.

The small-scale cutting test (core cutting) was developed by Fowell and McFeat (1976, 1977)[4,5]. A core sample of 7.6 cm in diameter or a small rock sample of 20×10×10 cm is fixed in a table of a shaping machine and cut by a chisel pick having a rake angle of -5°, a clearance angle of 5°, tool width of 12.7 mm and at a cutting depth of 5 mm. The test results are classified as index values and evaluated according to previously accumulated field performance data. The basic disadvantage is that the predictions using this method are based on an index cutter instead of an actual

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cutter. In addition, the database is based on only the field performance of light and medium weight roadheaders used in coalmines in England.

Empirical performance prediction models are mainly based on past experience and the statistical interpretation of previously recorded case histories[6–9]. Therefore, collection of field data becomes very important for developing empirical performance prediction models. The accuracy and reliability of these models depend on the quality and amount of the data. It is usually difficult to collect large amount of and high quality data in the field, and the details of the data are only known by the researcher who develops the model.

A deterministic computer simulation is used in the semi-theoretical approach. Performance prediction and machine and cutterhead design are possible with this method. The method is proven to be precise and reliable, provided that cutter forces are determined precisely. Many machine manufacturers, research institutes and consultants have their own computer models for this purpose[10–12]. However, many contractors and design companies do not have such sophisticated models.

Another method of performance prediction is to test an actual used or new machine in the field. This is a very expensive and time-consuming approach, but it is the most precise one[13].

Specific energy values were correlated, in the past, with rock properties by different researchers[4,5,14–24]. Evans[22,24] developed theoretical relationships between the cutting force for wedge and conical-type cutters, which were directly related to specific energy, and the uniaxial compressive and tensile strength of coals and soft rocks. Nishimatsu[23] developed a theoretical relationship between cutting and normal force for wedge-type cutters, and shear strength of soft rocks. Fowell and McFeat-Smith[4,5] performed experimental studies to correlate specific energy obtained by small-scale cutting tests to some rock properties such as cone indenter index, cementation coefficient, Schmidt hammer rebound value and compressive strength. Singh[20] performed experimental studies to find out relationships between in-seam coal cutting performance and brittleness index related to compressive strength and tensile strength. Goktan[18] researched the relationship between specific energy obtained from small-scale rock cutting tests and the brittleness index related to compressive and tensile strength. Deketh *et al.*[21] performed experimental studies to correlate the rock cutting performance to the failure envelope obtained from triaxial compression tests. Balci and Bilgin[14,15] researched relationships between optimum specific energy obtained by full-scale cutting tests and different rock properties such as compressive strength, tensile strength, and static and dynamic elasticity moduli. Copur *et al.*[16] searched for relationships between optimum specific energy obtained by full-scale cutting tests and compressive and tensile strength. They also searched for relationships between a brittleness index obtained from macro-scale indentation tests and rock cutting efficiency including specific energy and cutter forces[17]. Altindag[19] researched relationships between specific energy obtained by small-scale cutting tests and brittleness index related to compressive and the tensile strength.

Previous studies were usually limited to one rock type, one machine type and/or one index rock property. This study focuses on the prediction of optimum specific energy based on core-based index tests on a wide range of rock, mineral and ore types. Full-scale rock cutting tests and physical and mechanical property tests are performed on 23 different samples collected from different mining sites. The relationships between the optimum specific energy and the mechanical rock properties such as uniaxial compressive strength, tensile strength, dynamic and static elasticity moduli and Schmidth hammer rebound values are investigated by using statistical methods. The results are compared to empirical performance prediction models previously developed for roadheaders.

Experimental set-up and procedures

The laboratory testing programme includes full-scale rock cutting and physical and mechanical property tests. The tests are performed in the laboratories of Istanbul Technical University, Mining Engineering Department. Testing equipment, procedures and parameters are introduced in this section.

Full-scale linear rock cutting test

Full-scale cutting forces acting on an actual cutter are measured with the linear cutting tests while cutting an actual rock. Full-scale testing minimizes the uncertainties of scaling and any unusual rock cutting behaviour. The test results can be used for selection and design of a mechanical miner and cutter, definition of optimum cutting geometry, and prediction of performance and cost.

The linear rock cutting machine used in this study was recently built based on a project supported by NATO[1]. It includes a stiff reaction frame on which cutter and dynamometer (load cell) are mounted. The triaxial pillar-type dynamometer with 50 tons of thrust capacity monitors orthogonal forces acting on the cutter. The cutter is calibrated with the dynamometer prior to testing by applying certain amount of loads with a hydraulic jack. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. Casting can be applied in any desired dip angle or parallel or perpendicular (usually the case) to the bedding planes in order to simulate the actual cutting conditions of the deposit. A schematic drawing of the linear cutting machine used is presented in Figure 1.

A servo-controlled hydraulic actuator forces the sample through the cutter at a preset depth of cut, width of spacing and constant velocity. The dynamometer measures the normal, drag and sideways forces acting on the cutter during the cut. The rock box is moved sideways after each cut by a preset spacing to duplicate the action of the multiple cutters on a mechanical miner.

Data acquisition system includes a dynamometer, amplificator and personal computer. The data is handled by commercial software. The data acquisition card includes eight independent channels, and monitors and collects data from the dynamometer. Excitation voltage ranges between 0 and 10 V. The Data sampling/recording rate is adjustable up to 50 000 Hz. The recorded data is evaluated using a custom-made macro program.

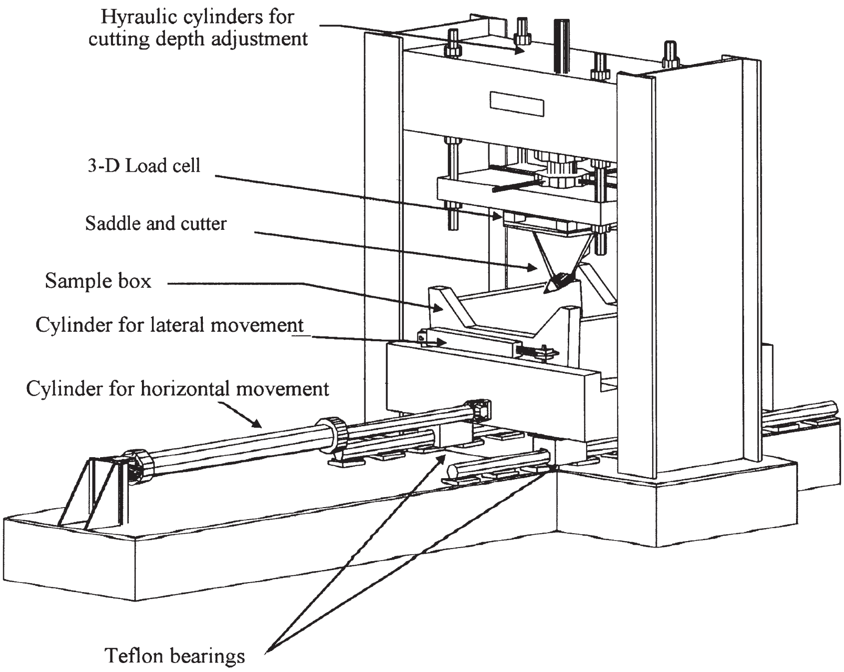

Figure 1—Schematic view of the full-scale rock cutting test

The linear cutting test variables consist of three independent variables: rock type, cut spacing and depth of cut. The only dependent variable is specific energy, which requires cutting force and cut volume (or debris weight) per unit cut length. The constant variables throughout the testing programme include cutting sequence (single-start), attack angle (55°), cutting speed (12.7 cm/s), skew angle (0°), tilt angle (0°) and a conical cutter (Sandvik-35/80H). Data sampling rate is set to 2 000 Hz. To eliminate the experimental error and control repeatability, at least three cuts are performed at each depth of cut and spacing values and the mean values are obtained.

The testing programme includes 23 rock, mineral and ore samples from different operating mines in Turkey. The samples include three different chromite ores, harsburgite, serpantinite, two different copper ores, trona, anhydrite, selestite, gypsum, three different sandstones, siltstone, claystone, limestone and six different tuffites.

All of the tests are carried out with a conical cutter of S-35/80H manufactured by Sandvik. It has a gage of 80 mm, flange diameter of 64 mm, shank diameter of 35 mm, tip diameter of 22 mm and primary tip angle of 80°.

Unrelieved and relieved modes of cutting are explained in Figure 2. There is no interaction between cutting grooves in the case of unrelieved cutting. There should be interaction between grooves in the case of relieved cutting. The initial linear cutting tests are carried out in unrelieved cutting mode to find out the variation of specific energy with the depth of cut. This helps to find out the optimum depth of cut value (d_{opt}) at which the relieved cutting tests are performed for determination of optimum specific energy and cut spacing at which the machine excavates the rock with the most energy efficient manner.

The effect of the spacing between the cuts and depth of cut on the cutting efficiency/specific energy is also explained in Figure 2. If the line spacing is too small (a), the cutting is

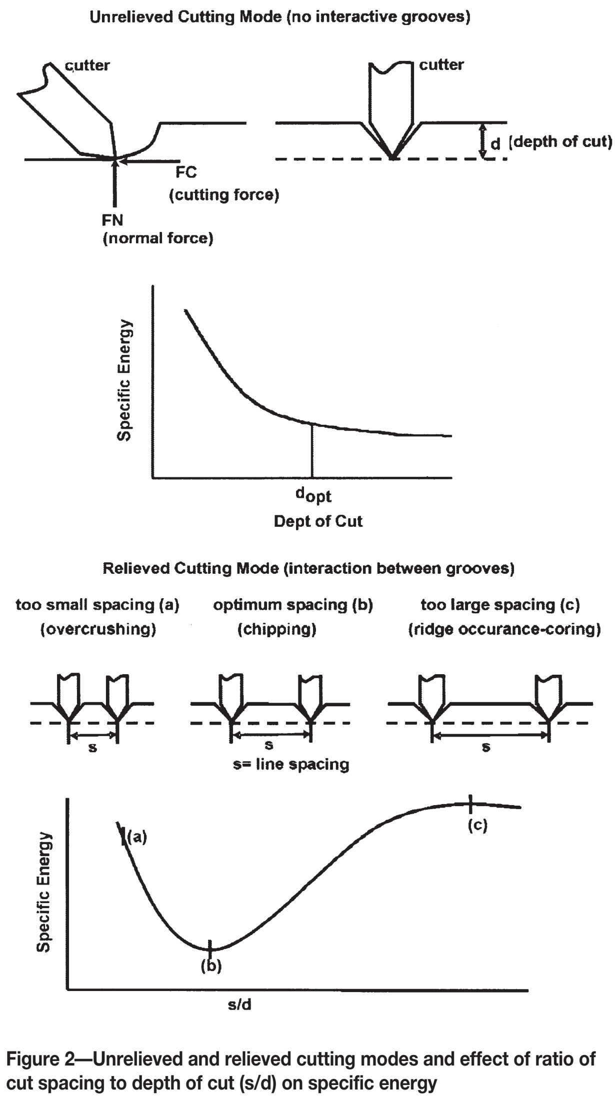

Figure 2—Unrelieved and relieved cutting modes and effect of ratio of cut spacing to depth of cut (s/d) on specific energy

not efficient due to over-crushing the rock. If the line spacing is too wide (c), the cutting is not efficient since the cuts cannot generate relieved cuts (tensile fractures from adjacent cuts cannot reach each other to form a chip), creating a groove-deepening situation or forming a bridge/rib between the cuts. The minimum specific energy is obtained with an optimum spacing to depth of cut ratio (b). The optimum ratio of cutter spacing to depth of cut varies generally between 1 and 5 for pick (drag) cutters. The specific energy (*SE*) is calculated as follows[25]:

$$SE = \frac{FC}{Q} \qquad [1]$$

where *SE* is the specific energy (MJ/m^3), FC is the cutting (drag) force (kN) and *Q* is the yield per unit length of cut (m^3/km). Cutting force and yield are functions of rock properties, bit type and cutting geometry. The instantaneous cutting rate of any mechanical miner is estimated as follows[26]:

$$ICR = k\frac{P}{SE_{opt}} \qquad [2]$$

where *ICR* is the instantaneous cutting rate in solid bank m^3/cutting hour, *P* is cutting power of the mechanical miner in kW, SE_{opt} is optimum specific energy in kWh/m^3 at which the formation is excavated in optimum cutting geometry, and *k* is a constant related to total system efficiency and usually assumed as 0.8 for roadheaders. Based on Equation [2], lower optimum specific energy means that a given machine will excavate more material or that a smaller/less expensive machine may be used to excavate the required amount of material.

Physical and mechanical properties of the rocks

Physical and mechanical property testing of the rock samples used for the linear cutting tests includes uniaxial compressive strength, indirect (Brazilian) tensile strength, static and dynamic elasticity moduli, Schmidt hammer rebound value, density, and Cerchar abrasivity index. Schmidth hammer tests are performed in the laboratory on the block samples by using an N-24 type hammer and applied using the procedures defined by Ayday and Bilgin *et al.*[27,28]. The other tests are performed based on the International Society for Rock Mechanics (ISRM) suggestions[29].

Results and discussion

The physical and mechanical properties of the rocks are summarized in Table I[14–16,30,31]. As seen, the range varies from soft to hard and nonabrasive to abrasive rocks, minerals and ores: uniaxial compressive strengths from 6 to 174 MPa, Brazilian tensile strengths from 0.2 to 11.6 MPa, Cerchar abrasivity indices up to 4.1, static elasticity modulus from 0.4 to 57 GPa, dynamic elasticity modulus from 2.8 to 76.4 GPa, Schmidth hammer values from 14 to 57 and densities from 1.49 to 4.13 g/cm^3.

The optimum specific energy and the optimum cut spacing to depth of cut ratios at 5 and 9 mm depth of cut values obtained from the linear cutting tests are summarized in Table II[14–16,30,31]. The optimum specific energy and the optimum cut spacing to depth of cut ratios at 5 mm depth of cut values vary from 1.3 to 17.6 kWh/m^3 and 2 and 3, respectively. Same values at 9 mm depth of cut values vary from 1.3 to 15.4 kWh/m^3 and 2 and 5, respectively.

Table I

Summary of physical and mechanical properties of rocks[14,15,16,30,31]

Rock	γ (g/cm^3)	UCS (MPa)	BTS (MPa)	E_{sta} (GPa)	E_{dyn} (GPa)	SHRV	CAI
High-grade chromite (46 to 50% Cr_2O_3)	4.03	32	3.7	3.5	31.2	30	2.1
Medium-grade chromite (42 to 46% Cr_2O_3)	3.39	47	4.5	2.3	76.4	43	1.6
Low-grade chromite (20 to 25% Cr_2O_3)	2.88	46	3.7	2.9	35.2	42	2.4
Copper ore (yellow)	4.13	33	3.4	-	42.0	-	2.8
Copper ore (black)	4.07	41	5.7	-	49.6	-	3.0
Harsburgite	2.65	58	5.5	2.1	16.1	-	0.8
Serpantinite	2.49	38	5.7	2.3	13.9	52	1.0
Trona	2.13	30	2.2	3.4	3.7	39	
Anhydrite	2.90	82	5.5	-	-	-	-
Selestite	3.97	29	4.0	-	-	-	-
Gypsum	2.32	33	3.0	-	-	-	-
Claystone	2.76	58	5.6	-	-	-	-
Sandstone-1	2.65	114	6.6	17.0	36.5	53	4.1
Sandstone-2	2.67	174	11.6	28.0	62.2	57	2.4
Sandstone-3	2.67	87	8.3	33.3	55.0	52	1.6
Siltstone	2.65	58	5.3	30.0	48.8	48	2.9
Limestone	2.72	121	7.8	57.0	37.9	55	1.4
Tuffite 1 (acigol)	1.49	10	0.9	1.1	3.8	28	-
Tuffite 2 (gelveri)	1.70	11	1.2	1.4	5.2	42	-
Tuffite 3 (gostug)	1.80	27	2.6	2.4	7.5	31	-
Tuffite 4 (kizilkaya)	1.71	14	1.5	1.6	5.2	39	-
Tuffite 5 (kizilkaya pembe)	1.71	19	2.3	1.3	6.1	38	-
Tuffite 6 (selime)	1.49	6	0.2	0.4	2.8	14	-

γ: Density, UCS : Uniaxial Compressive Strength, BTS : Brazilian Tensile Strength,
E_{sta}: Static Elasticity Modulus, E_{dyn}: Dynamic Elasticity Modulus, SHVR: Schmidth Hammer Rebound Value (N Type Hammer), CAI: Cerchar Abrasivity Index

Table II

Optimum specific energy values obtained from full-scale linear rock cutting tests[14,15,16,30,31]

Rock Name	Depth of cut 5 mm		Depth of cut 9 mm	
	Optimum specific energy (kWh/m3)	Optimum s/d	Optimum specific energy (kWh/m3)	Optimum s/d
High-grade chromite (46 to 50% Cr_2O_3)	9.3	3	3.9	3
Medium-grade chromite (42 to 46% Cr_2O_3)	12.8	2	6.4	2
Low-grade chromite (20 to 25% Cr_2O_3)	10.4	3	5.0	3
Copper ore (yellow)	-	-	3.7	4
Copper ore (black)	-	-	9.2	4
Harsburgite	14.6	3	8.4	5
Serpantinite	7.0	2	6.2	3
Trona	6.0	2	2.7	3
Anhydrite	-	-	3.8	5
Selestite	-	-	3.0	3
Gypsum	-	-	3.4	3
Claystone	-	-	6.0	2
Sandstone-1	17.6	2	12.6	3
Sandstone-2	-	-	15.4	2
Sandstone-3	-	-	5.5	3
Siltstone	-	-	9.8	3
Limestone	-	-	11.9	5
Tuffite 1 (acigol)	2.3	3	1.8	3
Tuffite 2 (gelveri)	4.7	3	3.2	3
Tuffite 3 (gostug)	4.4	3	2.6	3
Tuffite 4 (kizilkaya)	4.3	3	2.7	3
Tuffite 5 (kizilkaya pembe)	4.5	3	2.9	3
Tuffite 6 (selime)	1.3	3	1.3	3

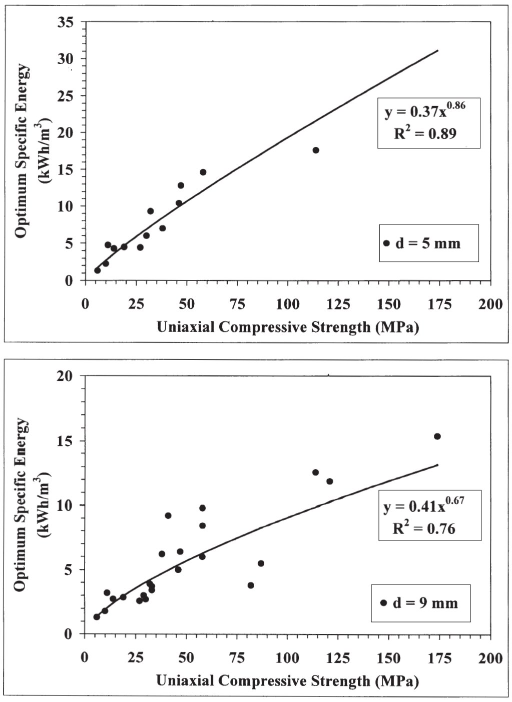

Figure 3—Relationships between optimum specific energy and uniaxial compressive strength at 5 and 9 mm depth of cut values

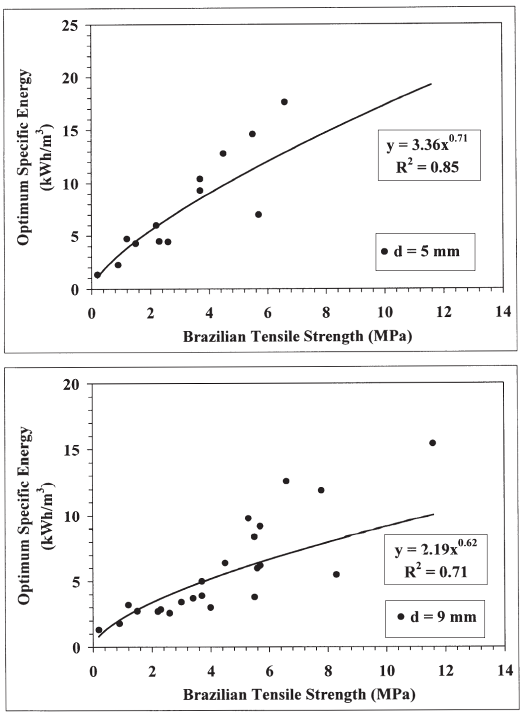

Figure 4—Relationships between optimum specific energy and Brazilian tensile strength at 5 and 9 mm depth of cut values

The statistical relationships between the optimum specific energy and uniaxial compressive strength, Brazilian tensile strength, Schmidth hammer rebound values, static and dynamic elasticity moduli are investigated by using regression analysis based on the method of least-squares[32,33]. Equations of the best fit curves with 95% confidence limit, observed t- and F-test values, standard error and coefficient of correlation (R^2) values are determined for each regression. Microsoft Excel™ is used for the statistical analysis. The best fit curves are presented in Figures 3, 4, 5, 6 and 7. The regression equations with related statistical analysis results are presented in Table III.

The best-fitted relationships are found to be best represented by power and/or exponential functions. The correlation coefficients for the uniaxial compressive strength at 5 and 9 mm depth of cut values are found to be 0.89 and

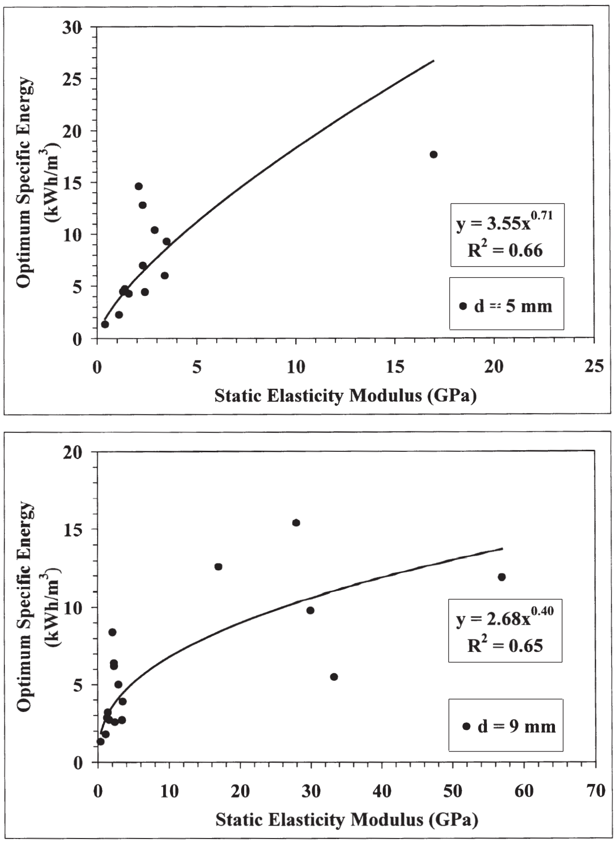

Figure 5—Relationships between optimum specific energy and static elasticity modulus at 5 and 9 mm depth of cut values

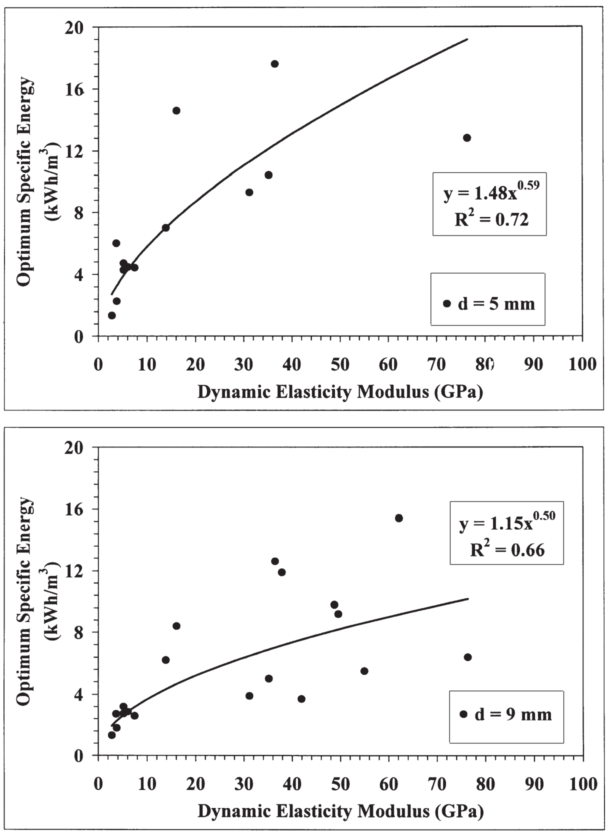

Figure 6.—Relationships between optimum specific energy and dynamic elasticity modulus at 5 and 9 mm depth of cut values

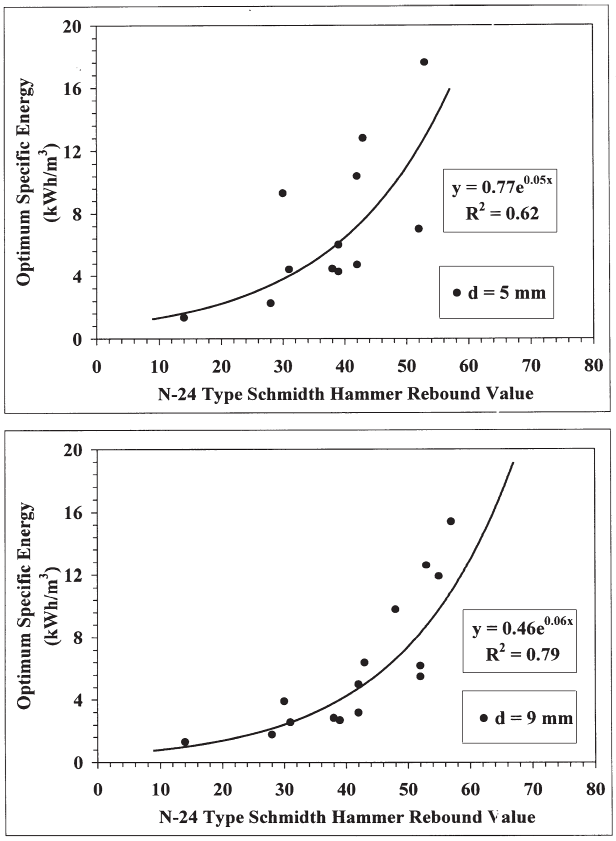

Figure 7—Relationships between optimum specific energy and Schmidth hammer rebound value at 5 and 9 mm depth of cut values

0.76, respectively. The correlation coefficients for the tensile strength at 5 and 9 mm depth of cut values are found to be 0.85 and 0.71, respectively. The correlation coefficients for the static and dynamic elasticity moduli at 5 and 9 mm depth of cut values are found to be 0.66 and 0.65, 0.72 and 0.66, respectively. The correlation coefficients for the Schmidt hammer rebound values at 5 and 9 mm depth of cut values are found to be 0.62 and 0.79, respectively.

F-statistics is used to test the significance of the correlation coefficients—whether these results with such high R^2 values occur by chance. If the observed F-value is greater than the critical F-value obtained from commonly known statistical tables, the null hypothesis is rejected, which means that the correlation coefficients of the relationships between the optimum specific energy and the rock properties are statistically significant. Confidence limit and alpha are chosen as 95% and 0.025, respectively, for the F-test in this study. As is seen in Table III, all the observed absolute F-values are greater than the critical F-values.

Accuracy of constants in each equation is determined by t-statistics, assuming that both variables are normally distributed and the observations are chosen randomly. The test compares the observed t-value with the critical t-value using the null hypothesis. If the observed t-value is greater than the critical t-value obtained from commonly known statistical tables, the null hypothesis is rejected, which means that the equation constants are statistically significant. Confidence limit and alpha are chosen as 95% and 0.025 with the right tail probabilities, respectively, for the t-test in this study. Asis seen in Table III, all the observed absolute t-values are greater than the critical t-values.

Table III

Regression equations and related statistical analysis

Equation	R^2	df.	F-value (observed)	F-value (critical)	t-value (observed)	t-value (critical)	S.error
Depth of cut, d = 5 mm							
$SE_{opt} = 0.37\ UCS^{0.86}$	0.89	11	87.03	6.72	9.33	2.20	0.092
$SE_{opt} = 3.36\ BTS^{0.72}$	0.85	11	64.35	6.72	8.02	2.20	0.089
$SE_{opt} = 3.55\ E_{sta}^{0.71}$	0.66	11	21.73	6.72	4.66	2.20	0.815
$SE_{opt} = 1.48\ E_{dyn}^{0.59}$	0.72	11	27.91	6.72	5.28	2.20	0.112
$SE_{opt} = 0.77\ e^{0.05\ (SHRV)}$	0.62	10	16.37	6.94	4.04	2.23	0.013
$SE_{opt}=1.16(UCSxBTS)^{0.40}$	0.90	11	104.42	6.72	10.22	2.20	0.039
Depth of cut, d = 9 mm							
$SE_{opt} = 0.41\ UCS^{0.67}$	0.76	21	64.92	5.83	8.06	2.08	0.084
$SE_{opt} = 2.19\ BTS^{0.62}$	0.71	21	51.91	5.83	7.21	2.08	0.086
$SE_{opt} = 2.68\ E_{sta}^{0.40}$	0.65	15	28.16	6.20	5.31	2.13	0.076
$SE_{opt} = 1.15\ E_{dyn}^{0.50}$	0.66	17	32.57	6.04	5.71	2.11	0.088
$SE_{opt} = 0.46\ e^{0.06\ (SHRV)}$	0.79	14	54.29	6.30	7.37	2.14	0.008
$SE_{opt}=0.92(UCSxBTS)^{0.34}$	0.76	21	66.87	5.83	8.18	2.08	0.041

Table IV

Empirical performance prediction models previously developed for roadheaders

References	ICR prediction equations	Explanations
Bilgin *et al.*[6,7]	$ICR = 0.28 \times P \times (0.974)^{RMCI}$ $RMCI = UCS \times (RQD/100)^{2/3}$	It was basically developed for axial type roadheaders and based on the *in situ* observation of many tunnelling and mining projects.
Gehring)[8]	$ICR = \frac{719}{UCS^{0.78}}$ transverse type $ICR = \frac{1739}{UCS^{1.13}}$ axial type	It was based on the performance of a roadheader with a 230 kW axial type cutterhead and an Alpine Miner AM 100 with a 250 kW transverse type cutterhead.
Thuro[9]	ICR = 75.7 - 14.3 x ln(UCS)	It was based on the performance of a Atlas Copco Eickhoff ET 120 (132 kW) transverse roadheader.

ICR: Instantaneous Cutting Rate in solid bank m^3/h, P: Installed Cutterhead Power in HP, RMCI: Rock Mass Cuttability Index, UCS: Uniaxial Compressive Strength in MPa, RQD: Rock Quality Designation in %

The statistical analyses indicate that the relationships between the optimum specific energy and the mechanical rock properties are reliable. Therefore, Equation [2] can be rewritten, for example, as follows:

$$For\ d = 5\ mm,\ ICR = 0.8 \times \frac{P}{0.37 \times UCS^{0.86}} \quad [3]$$

$$For\ d = 9\ mm,\ ICR = 0.8 \times \frac{P}{0.41 \times UCS^{0.67}} \quad [4]$$

Some of the most widely used empirical performance prediction models used for roadheaders are summarized in Table IV. In order to make a comparison, the instantaneous cutting rates are estimated using the equations developed by other researchers[6–9] given in Table IV and Equations [3] and [4] developed in this study. For these estimations, the uniaxial compressive strength (*UCS*) values are varied to be between 10 to 100 MPa, rock quality designation (*RQD*) and cutterhead power (*P*) are assumed to be 100% and 100 kW, respectively. Assuming the cutterhead power is directly proportional to the instantaneous cutting rate, all the equations given in Table IV are normalized for a cutterhead power of 100 kW to make a reasonable comparison. For example, the instantaneous cutting rate found in the model developed by Thuro[9] is divided by 1.32, since that model was developed for a roadheader with 132 kW cutterhead power. The graphical representation of the comparison is shown in Figure 8.

The comparison includes both axial and transverse type roadheaders. The result of this study at 9 mm of depth of cut value is very close to the results of the models developed by Gehring[8] and Thuro[9] for transverse type roadheaders. On the other hand, the result of this study at 5 mm of depth of cut value is very close to the results of the models developed by Bilgin[6,7] and Gehring[8] for axial type roadheaders.

The results of a previous study[16] analysed the relationship between the optimum specific energy and multiplication of uniaxial compressive strength × Brazilian tensile strength in ten samples at 9 mm of depth of cut. The same relationship is also analysed in this study in eleven and twenty-one samples at 5 and 9 mm of depth of cut values, respectively. The results are presented in Figure 9 and Table III. As is seen, similar trends are observed with more data in this study. However, the relationship between the optimum specific energy and uniaxial compressive strength, as seen Figure 3, is not improved too much. Therefore, using only the uniaxial compressive strength or Brazilian tensile strength is good enough to make a reasonable estimation of the optimum specific energy.

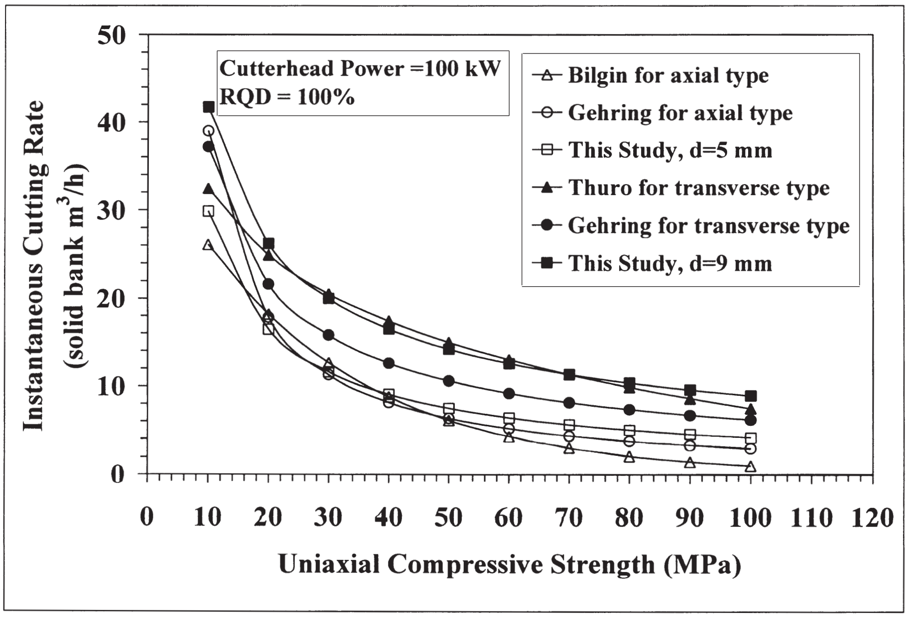

Figure 8—Comparison of different empirical methods with the results of this study

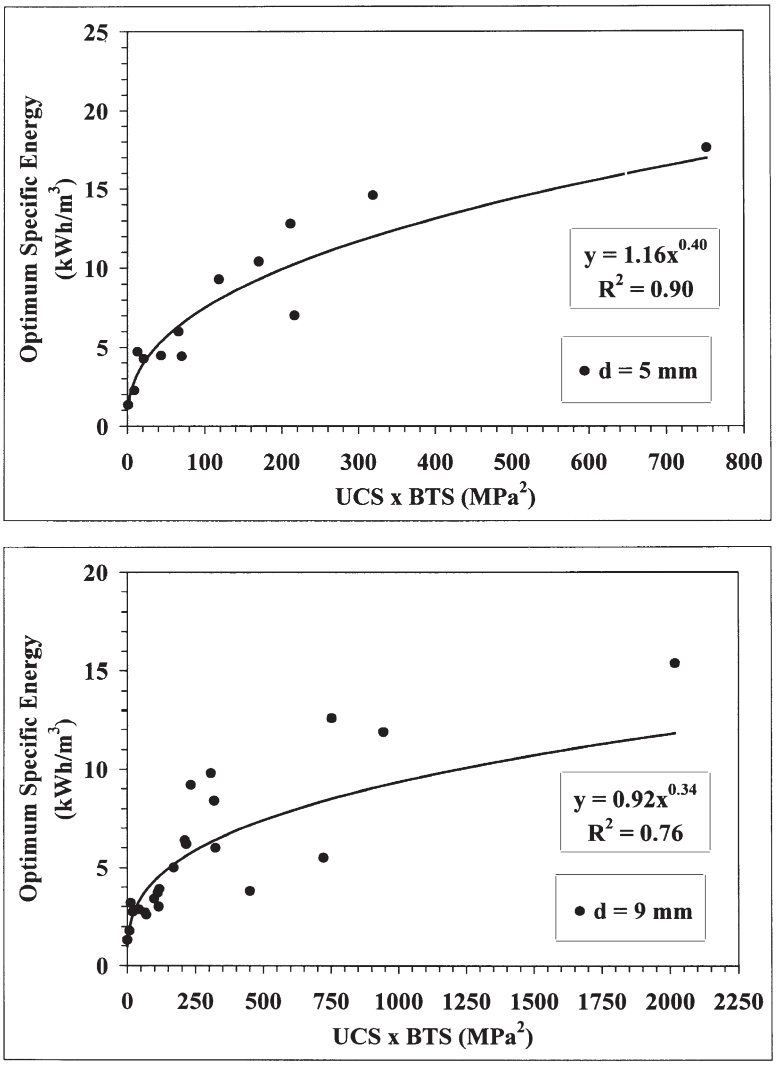

Figure 9—Relationships between optimum specific energy and (uniaxial compressive strength x Brazilian tensile strength) at 5 and 9 mm depth of cut values

These results indicate that the models developed in this study are in good agreement with the most widely used empirical performance prediction models. It should be kept in mind that the experimental studies and analysis performed in this study do not include the effect of discontinuities found in rock masses such as joints, bedding and foliation, even though it is known to have some influence on the performance of mechanical miners. Total system efficiency (machine utilization time, excluding the stoppages) should also be considered when planning a mechanized mining system. The results of this study can also be applied to other mechanical miners such as continuous miners, shearers and surface miners. Some rules might be adapted to the tunnel boring machines provided that a database with disc cutting is available.

Conclusions

The results of the experimental and statistical analyses indicate that the optimum specific energy obtained in the laboratory from the full-scale rock cutting tests can be predicted reliably from the uniaxial compressive strength, tensile strength, static and dynamic elasticity moduli and Schmidt hammer rebound values of the rocks. The correlation coefficients of the relationships between the optimum specific energy and rock properties can be considered as quite high for especially uniaxial compressive strength and Brazilian tensile strength at both 5 and 9 mm depth of cut values. This is supported by the empirical models previously developed for prediction of roadheader performance by some other researchers. The model developed based on the results of this study at 9 mm depth of cut (Equation [3]) yields reliable instantaneous cutting rates for transverse type roadheaders, whereas at 5 mm depth of cut (Equation [4]) for axial type roadheaders.

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