



Estimation of Specific Energy and Evaluation of Roadheader Performance Using Rock Properties and Bond Work Index

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Abstract

Specific energy (SE) is defined as the amount of work required to cut a unit volume of rock and is used to estimate the performance of excavation machines. Generally, the SE value is produced from full-scale or small-scale rock cutting tests. However, these tests require expensive equipment and experienced personnel, and the testing procedure is time consuming and impractical. Therefore, for estimation of SE , this study aimed to find a solution to estimate SE using rock mechanics test results and Bond work index values (BW_i), which can be produced in a more practical, less time-consuming manner and with inexpensive test equipment. Small-scale rock cutting, rock mechanics and Bond work index tests were carried out on seven rock samples, which can be grouped into two different type of rocks: marble and travertine. In addition, the instantaneous cutting rates (ICR) of a selected roadheader were calculated using SE values. Rock mechanics tests performed in this study were uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), ultrasonic velocity (V_p), Schmidt rebound hardness (R_L), corrected point load index ($I_{s(50)}$) and density (ρ). The simple regression method was used to estimate SE from rock properties and BW_i . As a result of this simple regression, a significant and highest correlation was found between SE vs. UCS and $I_{s(50)}$. A good correlation was found between SE vs. BTS , R_L and BW_i values. A moderate correlation was found between SE vs. V_p and ρ .

Keywords Specific energy · Bond work index · Roadheaders · Instantaneous cutting rate

1 Introduction

Mechanized excavation is a method based on mechanically cutting/excavating and breaking rocks with the help of various excavation machines. In the mining sector, which requires a high level of investment due to technological developments, mechanized excavation is inevitable at every stage in order to achieve the optimum efficiency level and to reduce operating costs. Such stages include preparatory work and coal/ore production. In addition, mechanized excavation is the only way to

achieve high production capacity at low cost by carrying out rapid excavation operations. Mechanical excavators are commonly used for various purposes in mining and tunnelling operations. Metro excavations, water tunnels, railway tunnels, roadway tunnels and underground storage projects are primarily excavated using tunnel boring machines (TBM). There is an increase in the use of roadheaders in the preparatory work and production stages of coal, metallic and rock salt mines, mine roadway excavation or tunnelling projects.

The cutting tools used in these mechanical excavators are divided into two types, as drag and roller type cutters, according to the excavation principle. In general, chisel type and conical type cutters are used in roadheaders and disc cutters are used in TBMs. These cutting tools generally perform excavation by shredding and grinding the rock. Although the excavation principle of these two cutting tools appears to be the same, some differences exist. The drag cutters break rock mainly overcoming the shear strength of rock for a better energy efficiency, while the disc cutters by overcoming mainly the compressive strength. The drag type cutters break the piece in front of the rock and then continue to break the piece by penetrating the rock again. This cycle continues until the excavation is finished. The disc cutters penetrate the rock,

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crush the part beneath (grinding) and continue the excavation process.

Various experimental, numerical modelling, fracture mechanics and theoretical modelling techniques have been used in recent years to investigate the basis of the rock cutting mechanism. In these studies, prediction models have been developed by using important variables such as tool forces (cutting and normal), SE , cutting depth, cutting angle, cleaning angle, line spacing of cutting tools and various rock properties. In all of these studies, the aim was to explain the mechanism of cutting rock with picks.

There is a large number of previous studies correlating performance of chisel type tools (SE , normal and cutting forces) with the physical and mechanical properties of rocks. Generally, statistical analysis has been carried out to estimate SE values from rock properties. In previous studies, UCS , BTS , R_L , $I_{s(50)}$, V_p , ρ , Cerchar abrasivity index, Shore hardness, cone indenter hardness, Brittleness index, mineralogical and petrographic analyses were used to gain a better understanding of the effects of rock properties on SE . According to these previous studies, the best correlations and dominant rock properties affecting the SE were found to be the uniaxial compressive, BTS and the R_L values [1–27].

The comminution process is used in mineral processing applications to release minerals and determine the required grain size to obtain the required surface area. The comminution process constitutes the largest portion of the energy requirements of mineral processing. Crushing, the reduction of large particles to the required size for grinding, is the first stage of the comminution process. Grinding is the second stage of the comminution process, applied after crushing. The apparatus used in the crushing and grinding processes transfers its energy to the material as compression, impact, attrition and shear forces.

Energy consumption and resistance to grinding can be determined using the work index. The Bond method is commonly utilized in the planning of grinding circuits, grinding instrument choice, determination of power needed and efficiency assessment. Upon examination of the relations between BW_i and rock mechanics parameters [28–33], it can be seen that these are similar to the relations between SE and rock mechanics parameters.

In this study, small-scale rock cutting tests, rock mechanics tests and Bond tests were carried out. The rock mechanics tests performed in this study are UCS , BTS , V_p , R_L , $I_{s(50)}$ and ρ . In the first part of the study, the correlation between SE and the above-mentioned rock mechanics parameters was investigated. Owing to the fact that SE and BW_i express the energy in the cutting and grinding processes, the relationship between SE and BW_i was investigated in this study, considering that there may be a similarity in cutting and grinding mechanisms. In the last part of the study, ICR value, the most commonly used method for the performance estimation of roadheaders,

was calculated by using the SE values and the excavation speed of a roadheader was determined.

2 Materials and Methods

Rock samples of marble and travertine, representing different strength values, were collected from seven different quarries of the Konya, Eskişehir, Yozgat and Karaman provinces in Turkey. The tests carried out in this study contained small-scale rock cutting tests, rock mechanics tests and Bond work index tests. In the rock mechanics context, UCS , BTS , V_p , R_L and $I_{s(50)}$ tests were carried out. R_L tests were conducted on the original block samples; 54-mm-diameter NX core samples were prepared from blocks by drilling perpendicular to lamination (Fig. 1a) for the other physico-mechanical properties of rocks. The mechanical and cuttability properties of rocks were determined with the ISRM standards [34]. The results of these tests are summarized in Table 1; 30x30x10-cm-sized blocks were prepared for rock cutting tests (Fig. 1b).

The rock cutting tests were carried out using a standard chisel pick having a rake angle of -5° , a clearance angle of 5° and tool width of 12.7 mm. The depth of cut was selected as 5 mm and data sampling rate was 1000 Hz. In this study, the data collection system included two load cells (cutting and

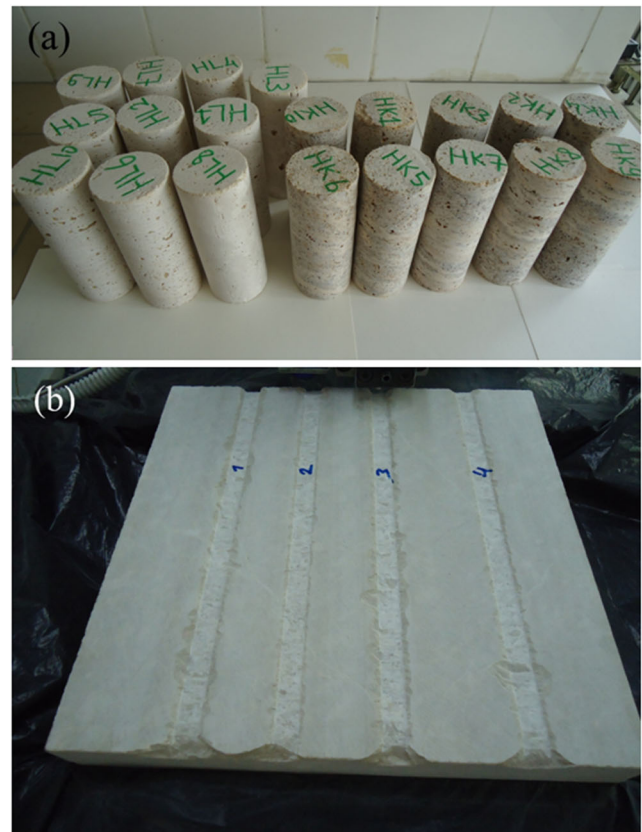


Fig. 1 Cylindrical core (a) and block (b) specimens used for rock mechanics and rock cutting tests

Table 1 Rock mechanics tests results

Location	Sample	Code	UCS (MPa)	BTS (MPa)	V_p (km/s)	$I_{S(50)}$ (MPa)	R_L	ρ (g/cm ³)
Eskişehir	White marble	WM	54.63	4.22	6.26	3.84	61.44	2.74
Konya	Beige marble	BM-1	71.98	6.51	6.58	5.69	70.14	2.71
Konya	Beige marble	BM-2	56.16	6.04	5.98	4.95	69.63	2.66
Konya	Beige marble	BM-3	80.73	4.43	6.54	5.73	65.49	2.70
Yozgat	Grey marble	GM	71.18	6.88	6.39	6.95	80.26	2.77
Karaman	Travertine	TR-1	32.23	3.74	5.22	3.94	61.67	2.40
Karaman	Travertine	TR-2	14.82	2.96	4.57	3.35	48.05	2.24

normal), a current and a voltage transducer, a power analyser, an AC power speed control system, a laser sensor, a data acquisition card and a computer. The rock cutting tests were performed in unrelieved (no interaction between grooves) cutting modes and using standard chisel pick during the rock cutting tests the tool forces in cutting directions were recorded by using a platform type load cell with a capacity of 750 kg, a data acquisition card and block diagrams in Matlab Simulink, as illustrated in Fig. 2. Three tests were carried out on each rock sample in which cutting forces were recorded. After each cutting test, the length of cut was measured and the rock cuttings for the cut were collected and weighed for determination of specific energy. The SE values are given in Table 2.

The BW_i values of the rock samples were determined in accordance with the standard Bond grindability test [35]. This test is a closed-cycle dry grinding and sieving process and continued until obtaining steady-state conditions. For standard Bond ball mill tests (Fig. 3), a feed of -3.35 mm compressed to 700 cm^3 of each rock sample was used. For the first grinding cycle, the number of mill revolutions was selected as 100. At the end of each cycle, the entire material was discharged from the mill and sieved by a test sieve. The fresh feed material was added to the oversize fraction to obtain the weight corresponding to 700 cm^3 . This charge was returned to the mill for the second cycle. Then grindability (G , g/rev) of the cycle was calculated and used to determine the number of the mill revolutions required for the second

cycle producing the 250% circulating load. This procedure was continued until a constant grindability at the equilibrium conditions was obtained. At the end of this process, the G values of the last three cycles were averaged and accepted as the standard Bond grindability. After determining the G value of each rock sample, BW_i values were calculated. The BW_i values of each sample are provided in Table 3.

3 Results and Discussion

The aim of this study was to estimate SE values using various rock mechanics parameters and BW_i values. For this purpose, small-scale linear rock cutting tests, rock mechanics tests and standard Bond tests were applied on seven rock samples in the laboratory and the results were statistically analysed by using the simple regression method.

SE , the key parameter for mechanical rock excavations, is commonly determined by small-scale or full-scale linear rock cutting tests. However, because the setup of these test sets is expensive and the testing procedure time consuming and impractical, it is important to develop alternative methods for estimating the SE value more easily, economically and practically. To this end, in various studies the correlations between SE and various physical and mechanical rock properties have been investigated and various empirical equations have been suggested [8, 10–13, 15–17, 22, 23, 27]. The results obtained in this study are similar

Fig. 2 Block diagrams in Simulink for cutting forces

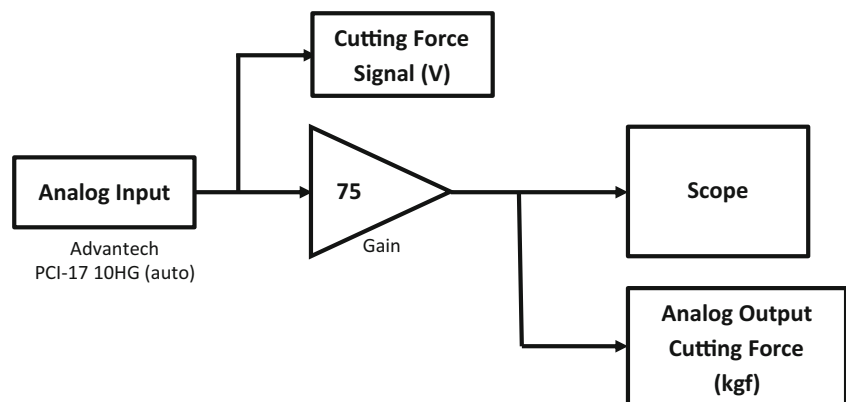


Table 2 Small-scale rock cutting test results

Location	Sample	Code	SE (kWh/m ³)
Eskişehir	White marble	WM	11.71
Konya	Beige marble	BM-1	17.63
Konya	Beige marble	BM-2	17.41
Konya	Beige marble	BM-3	17.28
Yozgat	Grey marble	GM	16.69
Karaman	Travertine	TR-1	12.19
Karaman	Travertine	TR-2	9.01

Table 3 BW_i values of rock samples

Location	Sample	Code	BW_i (kWh/m ³)
Eskişehir	White marble	WM	17.02
Konya	Beige marble	BM-1	29.95
Konya	Beige marble	BM-2	23.33
Konya	Beige marble	BM-3	37.72
Yozgat	Grey marble	GM	39.44
Karaman	Travertine	TR-1	21.94
Karaman	Travertine	TR-2	13.62

to many previously published research studies. In addition, this study attempted to estimate the SE value by using the BW_i value, which was not used in the previous studies. This is one of the research activities which differentiates this study from similar previous studies.

The samples used in this study were selected from rocks with similar structural properties (fissure, crack) in terms of size and homogeneity. The mineralogical and petrographic contents of the rock samples were determined by thin section method. The petrography studies (thin sections) indicated that the samples contain micrite, which is a fine-grained matrix (Fig. 4a). Therefore, the BW_i value of this sample is considered to be the highest compared to other samples. It is thought that the BW_i values of the BM-1, BM-2 and BM-3 samples (Fig. 4b–d) are lower than the GM sample because they contain sparite, which is a relatively coarse-grained cement to micrite. The WM sample (Fig. 4e) is crystallized limestone with a granoblastic texture and high content of calcite. The rock consists of medium sized grains. Breakage rate of coarse grains is higher than fine grains. Therefore, it is thought that the BW_i value of the WM sample will be lower than the other samples. TR-1 and TR-2 travertine samples (Fig. 4f, g) were found to contain sparite. In general, the low BW_i values of these samples compared to the other samples are thought to be due to the high porosity of these samples.

Some studies have previously been conducted in order to investigate the correlation between the mechanical strength of materials and their resistance to grinding, for example, Deniz and Özdağ [28] performed ultrasonic wave velocity and BW_i

experiments using sedimentary and volcanic rock samples. Dynamic elastic properties of the samples were determined by an ultrasonic wave velocity test and they determined that when the dynamic elastic properties increased, the BW_i increased. Özkahraman [29] determined the friability and BW_i values of certain rocks and stated that the increase of friability values decreased the BW_i . Furthermore, Özer and Çabuk [30] investigated the relationship between BW_i and rock parameters. For this purpose, they determined the BW_i values and mechanical strength values of the samples. According to their results, V_p , $I_{s(50)}$, UCS and Shore hardness values have the highest correlation with BW_i . Aras et al. [32] specified that the BW_i values increased with the increase of $I_{s(50)}$. Chandar et al. [33] described a strong relationship between BW_i and several rock properties, in particular R_L and ρ . Hafez [31] obtained a strong relationship with UCS values.

In this study, using the simple regression method, the relationships between SE value vs. rock mechanics parameters and BW_i value were examined. The rock mechanics parameters used in the investigations are UCS , BTS , R_L , V_p , $I_{s(50)}$ and ρ . The equations obtained in the analyses are power and logarithmic. The highest correlation values were achieved in UCS and $I_{s(50)}$. When the graphs are examined, SE values increased with the increase of UCS and $I_{s(50)}$ values (Figs. 5 and 6). This relationship is given in Eqs. 1 and 2.

$$SE = 3.0704(UCS)^{0.3943} \quad R^2 : 0.80 \quad (1)$$

$$SE = 11.965 \ln(I_{s(50)}) - 4.1533 \quad R^2 : 0.80 \quad (2)$$

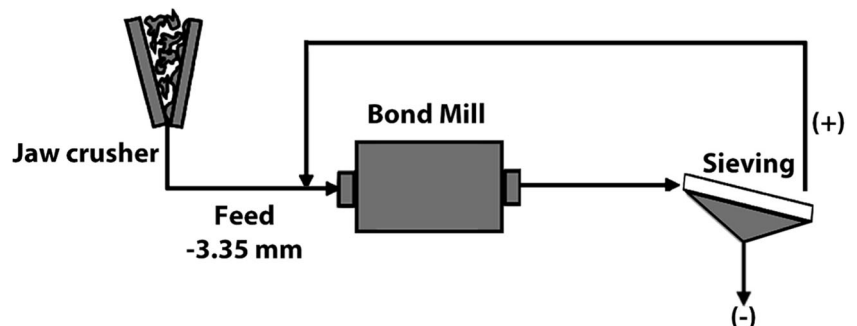
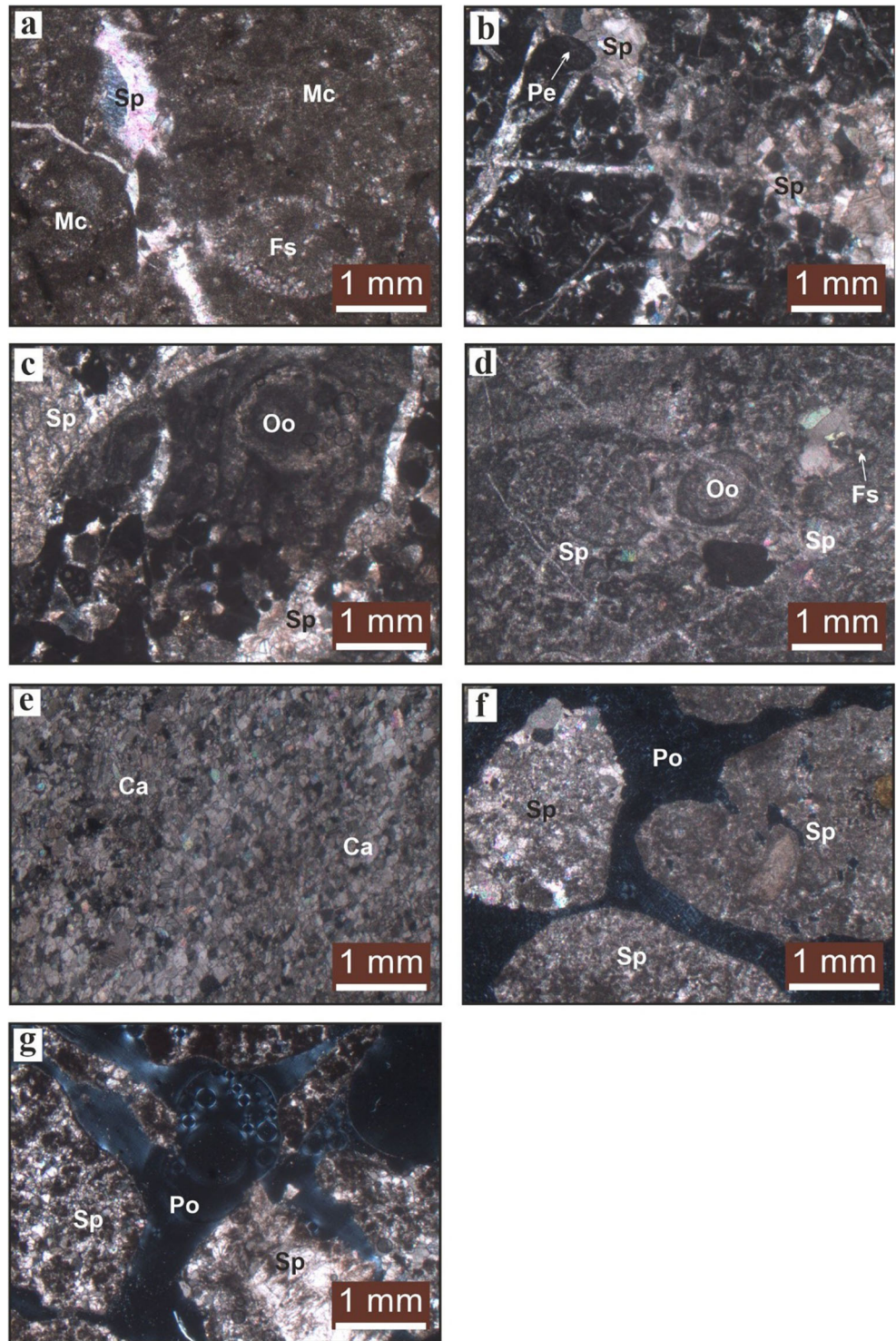
Fig. 3 Flowchart of standard Bond test

Fig. 4 Petrographic studies (thin sections) of rock samples (a) GM (b) BM-1 (c) BM-2 (d) BM-3 (e) WM (f) TR-1 (g) TR-2 (Sp, Sparite, Oo, Ooids, Fs, Fossil shell, Mc, Micrite, Pe, Pellet, Ca, Calcite, Po, Porosity, // Nicol)



When the correlation between R_L , BTS and BW_i vs. SE was investigated, high correlation values were obtained which can be defined as ‘good’. A power relation was detected in all three functions. Similar to the previous functions, when the graphs are examined, SE values increased with the increase of BTS , R_L and BW_i values (Figs. 7, 8 and 9). The equations of these parameters are Eqs. (3, 4 and 5).

$$SE = 4.4756(BTS)^{0.7372} \quad R^2 : \cdot 0.77 \quad (3)$$

$$SE = 0.0319(R_L)^{1.4624} \quad R^2 : \cdot 0.77 \quad (4)$$

$$SE = 2.2077BW_i^{0.581} \quad R^2 : \cdot 0.76 \quad (5)$$

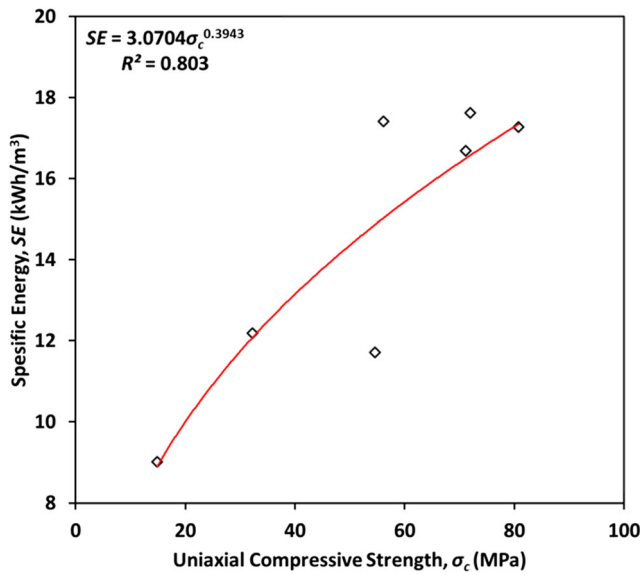


Fig. 5 The correlation between SE and UCS

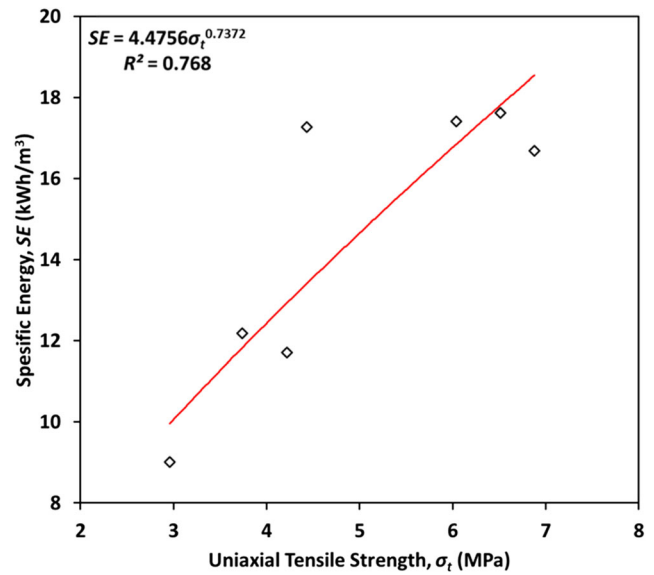


Fig. 7 The correlation between SE and BTS

When the relations between V_p and ρ vs. SE values are examined, it can be called moderate. A power function was detected in both relations. Similar to the previous functions, when the graphs are examined, SE values have increased with the increase of V_p and ρ values (Figs. 10 and 11). The equations of these parameters are given in Eqs. (6) and (7).

$$SE = 0.7984(V_p)^{1.6216} \quad R^2 : \cdot 0.7056 \quad (6)$$

$$SE = 1.1951(\rho)^{2.5913} \quad R^2 : \cdot 0.6234 \quad (7)$$

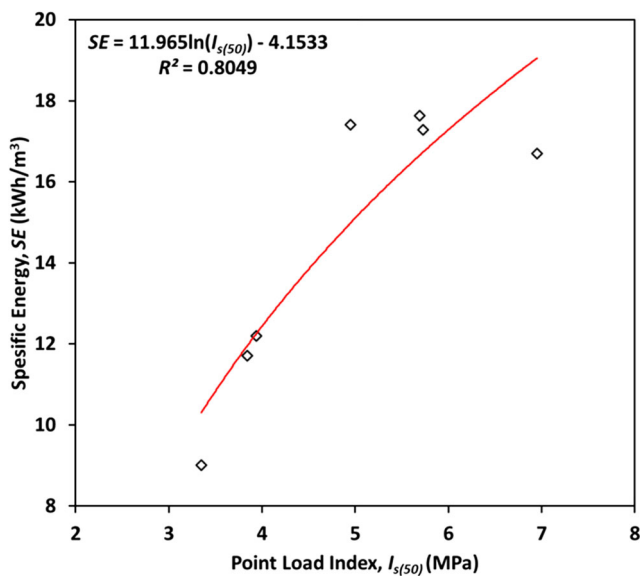


Fig. 6 The correlation between SE and $I_{s(50)}$

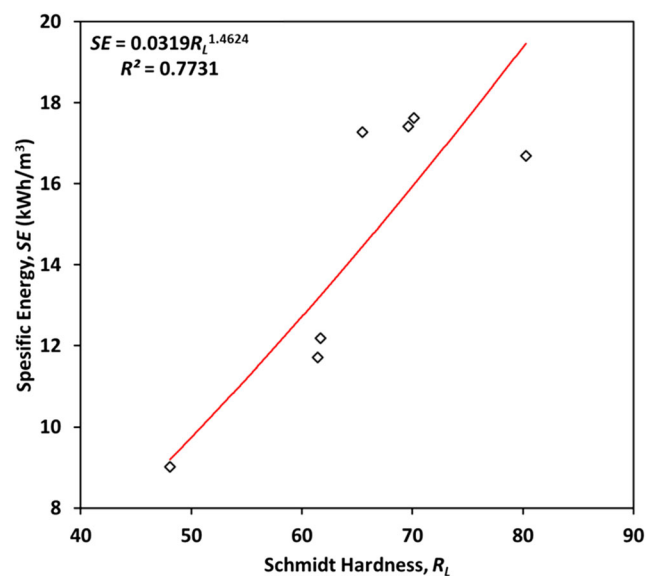


Fig. 8 The correlation between SE and R_L

3.1 Performance Prediction of Roadheaders Based on ICR

Roadheaders have commonly been used for production or preparatory activities such as coal, soft rocks, evaporitic minerals (trona, salt, potash, etc.), metallic ores and other industrial minerals in the underground mining industry. In addition, these machines are used in secondary excavation activities for the widening and excavation of tunnels such as for metro, railway, roadway, sewer, water tunnels, etc., in the civil industry [24].

Roadheaders are restricted to the excavation of rocks which have 100–120 MPa of UCS values, based on certain

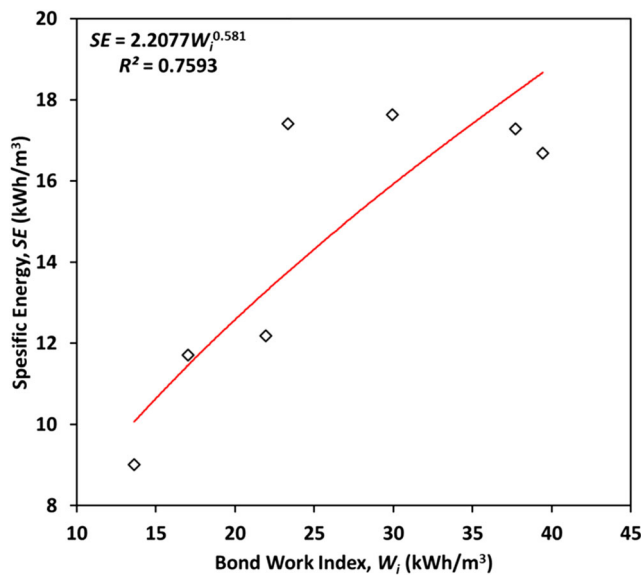


Fig. 9 The correlation between *SE* and *BW_i*

geological and geotechnical properties of rock mass and some specifications of the machine, such as cutterhead power and the weight of the machine [36, 37]. In order for the machine to excavate a rock mass of up to 160 MPa of *UCS*, the rock mass must be easy to excavate and must have a highly fractured and jointed characteristics. For cutting rock with roadheaders, drag type picks are commonly used [24].

ICR is generally used for the performance prediction of excavation machines in the mining industry for excavation of rock mass, which depends on particular rock parameters (geological and geotechnical) and machine characteristics [24].

Many researchers have developed various performance prediction models for roadheaders based on *ICR*. These models are empirical models based on various rock properties (*SE*, *UCS*, *BTS*, rock quality designation (*RQD*), Shore

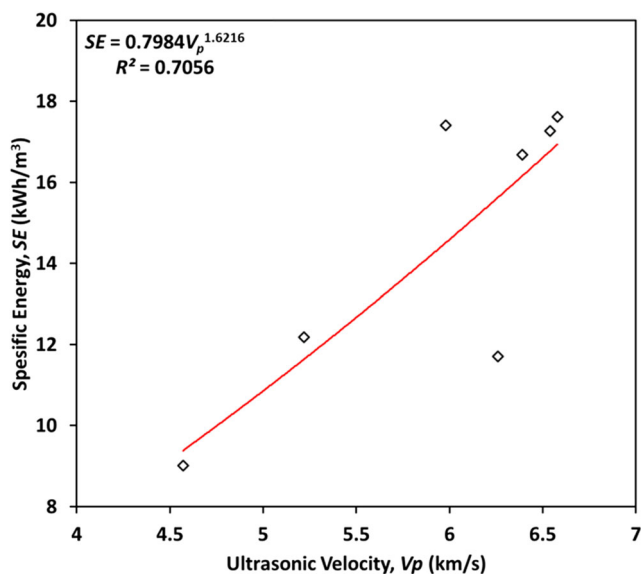


Fig. 10 The correlation between *SE* and *V_p*

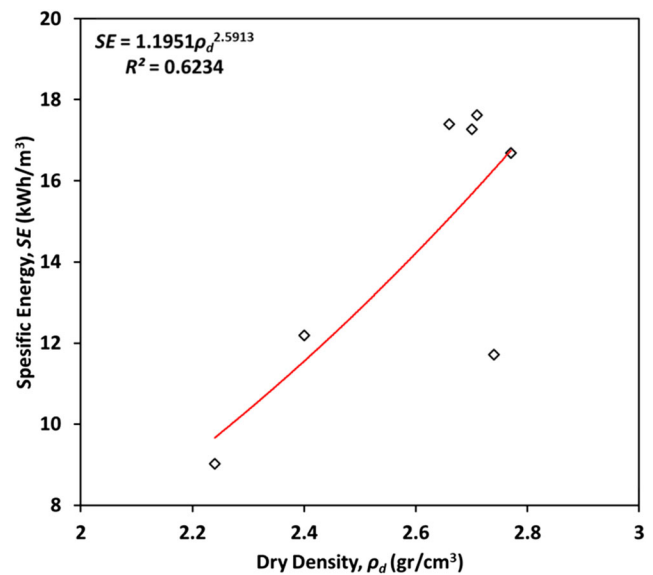


Fig. 11 The correlation between *SE* and ρ_d

hardness, $I_{s(50)}$, water absorption) and some machine specifications (cutterhead power and weight of the roadheader) [4–7, 12, 18, 23, 36–45]. On the other hand, the *UCS* value of rocks is the most used mechanical rock property for predicting *ICR*.

Rostami et al. [4] developed an *ICR* model for roadheaders which is based on full-scale linear cutting tests and is the most important and most preferred model given in Eq. (8).

$$ICR = k*(P/SE_{opt}) \tag{8}$$

where

- ICR* instantaneous (net) cutting rate (m³/h);
- k* energy transfer coefficient, which is suggested as being between 0.45 and 0.55 for roadheaders;
- P* installed cutterhead power of the mechanical miner (kW);
- SE_{opt}* optimum specific energy obtained from full-scale linear cutting tests (kWh/m³).

In terms of how other researchers have developed models predicting *ICR* based on *UCS*, Gehring [40] developed models for *ICR* predictions based on *UCS* values of rocks for roadheaders having cutterhead powers of 230 kW (axial) and 250 kW (transverse) and Thuro and Plinninger [41] improved an estimation model for *ICR* of transverse type roadheaders (132 kW) based on *UCS*. Furthermore, Bilgin et al. [5–7, 38, 39] developed an *ICR* prediction model based on *UCS* and *RQD*, Copur et al. [36, 37] used *UCS*, cutterhead power and weight of roadheader for prediction of *ICR* and Balci et al. [12] developed two models for *ICR* prediction using *SE* and *UCS* values of rocks. Tumac et al. [18] used *UCS* and Shore hardness for prediction of *ICR* for roadheaders, whereas Ebrahimabadi et al. [43] used rock mass brittleness index (*RMBI*) for prediction of *ICR* based on *UCS*,

Table 4 The calculated *ICR* values of rock samples

Sample	Code	SE_{opt} (kWh/m ³)	<i>ICR</i> (m ³ /h) (calculated using Eq.8)
White marble	WM	7.71	11.68
Beige marble	BM-1	11.26	7.99
Beige marble	BM-2	11.13	8.09
Beige marble	BM-3	11.05	8.15
Grey marble	GM	10.69	8.42
Travertine	TR-1	7.99	11.26
Travertine	TR-2	6.09	14.79

BTS and *RQD*. Kahraman and Kahraman [44] used point load strength and water absorption by weight for prediction of *ICR*. Comakli [45] used *UCS*, *BTS*, $I_{s(50)}$ and Cerchar abrasivity index values of rocks for prediction of *ICR* and he developed a model using *UCS* for estimation of *ICR* based on field performance of roadheaders in the Cappadocia region of Turkey for excavation of cold storage caverns in tuff.

According to *UCS* values, the rocks used in this study have low and medium strength with *UCS* values ranging from 14.82 to 80.73 MPa. Thus, the rocks tested in this study can be excavated with an axial type roadheader with a power of 200 kW [24]. The excavation efficiency of a roadheader with a power of 200 kW was calculated for the tested rocks using Eq. (8). In this study, the *SE* values of rocks have been obtained by small-scale rock cutting tests. However, the optimum *SE* values obtained by full-scale linear rock cutting tests were used for calculating the performance of roadheaders using Eq. (8). Alternatively, the optimum *SE* can be predicted by Eq. (9), suggested by Balci and Bilgin [17], given below.

$$SE_{opt} = 0.60SE + 0.68 \quad (9)$$

In this study, *ICR* values were calculated for selected roadheaders with 200 kW cutterhead power using the model suggested by Rostami et al. [4]. However, Rostami et al. [4] calculated the *ICR* of roadheaders with 132 kW cutterhead power. Therefore, the results in this study were normalized by dividing to 200 kW. The results of the *ICR* that were calculated are given in Table 4.

Table 4 The calculated *ICR* values of rock samples.

4 Conclusions

In this study, small-scale linear cutting, rock mechanics and standard Bond tests were applied on seven natural stone block samples obtained in various locations of the Central Anatolia region. *SE* values were obtained by small-scale linear cutting tests, *UCS*, *BTS*, R_L , V_p , $I_{s(50)}$ and ρ values by rock mechanics tests and BW_i value by standard Bond test.

The correlation between *SE* vs. rock properties and BW_i was studied to obtain some empirical equations for the estimation of *SE*. While calculating these relationships, the simple regression method was used. As a result of the statistical analysis between *SE* and other rock mechanics parameters, power and logarithmic type relations were found. The highest R^2 value was reached in the function between *SE* vs. *UCS* and $I_{s(50)}$ parameters. The R^2 value was found to be 0.80 in both relationships. Good correlation was found between *SE* vs. R_L , *BTS* and BW_i . The R^2 values varied from 0.75 to 0.77. *SE* and BW_i values both express the energy in cutting and grinding processes; therefore, a consideration of there being a probable similarity in the cutting and grinding mechanisms of rocks is the main idea of this study. Based on this idea, the relationship between *SE* and BW_i was first investigated in this study.

Because *SE* and BW_i express the energy, there being a good correlation between them is an important result. As a result of the analysis between BW_i and rock mechanics parameters, equations with high correlation were achieved similar to *SE*. Parameters having moderate correlation with *SE* are V_p and ρ . The R^2 values varied from 0.62 to 0.70.

ICR depends on mechanical, geological, geotechnical and operational parameters. *ICR* values were also calculated in this study. To calculate the *ICR* values, *SE* values obtained from the small-scale rock cutting test were converted to SE_{opt} values using Eq. (26), which were provided from full-scale rock cutting tests by Balci and Bilgin [17]. It was determined that the *ICR* values calculated from Eq. (8) ranged between 4.79–8.09 m³/h. It was determined that *UCS* and *ICR* are inversely proportional; thus, when the strength increases, the cutting speed decreases.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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