International Journal of Rock Mechanics & Mining Sciences 53 (2012) 38–44

Contents lists available at SciVerse ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Prediction of specific cutting energy for large diameter circular saws during natural stone cutting

Murat Yurdakul [a],*, Hürriyet Akdaş [b]

[a] Bilecik University, Department of Natural Building Stones Technologies, Bozuyuk MYO, 11300 Bozuyuk/Bilecik, Turkey
[b] Eskisehir Osmangazi University, Department of Mining Engineering, Eskisehir, Turkey

ARTICLE INFO

Article history:
Received 20 April 2011
Received in revised form
5 February 2012
Accepted 10 March 2012
Available online 6 May 2012

Keywords:
Stone sawing
Block cutter
Specific cutting energy
Carbonate rocks
Regression analyses

ABSTRACT

Statistical methods re-utilized for the prediction of specific cutting energy values (SE_{cut}) based on the operational variables of block cutters and rock properties. Performance measurements of seven different types of block cutters were applied to six different carbonate rocks and three stone processing plants. Energy consumption of large diameter circular diamond saw block cutters was measured and recorded for a number of sawblade diameters during the cutting process by means of a portable power analyzer. Additionally, rock samples were collected from stone processing plants for laboratory tests. Uniaxial compressive strength, bending strength, Brazilian tensile strength, point load strength, Shore hardness test, Schmidt hammer hardness test, seismic velocity, water absorption at atmospheric pressure, apparent density, open porosity, sawblade diameter, and depth of cut values were used as input parameters in the analysis for the prediction of SE_{cut}. The reliability of the developed model was tested with statistical methods. The SE_{cut} values for carbonate rocks in the stone cutting process can be predicted successfully for large diameter circular saws in natural stone processing by using the model developed here.

1. Introduction

The prediction of the sawability of natural stones is very important in cost analysis and production planning. Due to the increase in the use of natural stone and the increase in the competition among the manufacturers in the field, studies on the improvement of productivity and costs by optimizing various operational parameters in the process of cutting became more important. For this reason, the sawing parameters of the stones to be cut with block cutters are important in terms of monitoring the sawing performance. Determining the proper parameters for the physico-mechanical and mineralogical–petrographical characteristics of the rock to be cut plays an important role in cost analysis, production planning, product quality, and the selection of an appropriate machine-equipment for the stone to be cut.

There are a number of studies in the related literature focusing on the circular diamond saws in stone sawing process. The early studies of Büttner [1] and Konstanty [2] explained the sawing mechanism and structural properties of diamond impregnated circular saws and evaluated the factors influential on cutting. Jennings and Wright [3], in their study on optimum choice and use of diamond sawblades, stated the factors influential on sawblade performance. Accordingly, some of the factors that affect performance and therefore the service life of sawblade are cutting mode, peripheral speed, machine conditions, properties of cutting rock, and operator skills. Tönshoff et al. [4] emphasized that the natural stone sawing process is a complex system influenced by a variety of factors. The researchers listed the factors directly or indirectly influential on the stone cutting process as follows: physical material properties of the stone such as grain size and strength, forces between the diamonds and the material, stress distribution in the rock, and temperatures in the tool–workpiece interface. Luo and Liao [5] investigated the effects of the types and sizes of the diamond on the stone sawing performance of the sawblades in stone cutting process. The diamond sawblade used in their tests had a diameter of 205 mm and a steel core thickness of 5 mm. Several studies [6–8] investigating the characteristics of diamond sawblade wear in stone processing and the factors affecting the use of sawblade exist in the literature. Ersoy and Atıcı [9], in their laboratory scaled study, examined the effects of operating and rock parameters on the performance of the diamond saws. They described the relationships among the cutting variables. Their results indicated that the diamond circular saw performances were significantly affected by the cutting variables. They emphasized that the specific cutting energy was a very significant measure of cutting performance because it indicated the amount of energy required to cut the rock. Kahraman et al. [10] investigated the regression models for the prediction of slab production of carbonate rocks with large diameter circular saws. They recommended models which included Schmidt hammer value, point load strength, impact strength, and P-wave velocity for the rapid estimation of the sawability of carbonate rocks. Ersoy and Atici [11] presented a theoretical model for the explanation

---

* Corresponding author. Tel.: +90 228 214 1569.
E-mail addresses: murat.yurdakul@bilecik.edu.tr, muyurdakul@gmail.com (M. Yurdakul).

1365-1609/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ijrmms.2012.03.008

of the relationship between the SE_{cut} of the sawblade operating parameters and rock properties. For this purpose, laboratory tests were carried out on three groups of rocks with the help of three types of diamond disk saws with various feed rates and cutting depths at constant peripheral speed. Their model for the limestone and marble group of rocks included bending strength, Schmidt rebound hardness, and wear factor. Guney [12] investigated the regression models for the prediction of hourly slab production of five different marbles quarried in the Mugla Province of Turkey. He recommended models which included Shore hardness and crystal size may also be used for the prediction of sawability (hourly slab production) of carbonate rocks using large diameter circular saws.

Previous studies were those performed under similar conditions in the laboratory. This study included in-situ measurement in stone processing plants from different regions in Turkey for the prediction of SE_{cut}. In practice, predicting the machine performance with simple equations is quite important for the stone cutting processes with large diameter circular saws. The SE_{cut} is an important factor for specifying the mechanical performance of a machine in a heading and its basic indicator of the cutting efficiency and performance, because it indicates the amount of energy required to cut the unit volume of rock. Cutting energy is often used as a parameter for monitoring the stone cutting process [11–15]. Many of the studies reported in literature are those carried out in fixed cutting depth. In the present study, industrial data obtained from different production conditions were used. The literature lacks industrial SE_{cut} values obtained from in-situ cutting conditions in natural stone cutting processes.

SE_{cut} in block cutters using diamond circular saws is one of the most important indicators of cutting performance and cutting efficiency. For that reason, a model is developed in order to predict SE_{cut} by measuring the cutting performance on carbonate natural stones with the use of least number of parameters.

Due to the lack of industrial data in the literature, for natural stone cutting processes, this study aims at investigating the relationship between the industrial SE_{cut} values and the relevant cutting parameters such as depth of cut, feed rate and rock properties. In this study, an equation was developed for the prediction of SE_{cut} based on the data obtained from different machines and at a range of feed rates, cutting depths, and from the block cutters with different characteristics. The validity of the equations developed was tested with statistical methods.

2. Block cutters and their performance parameters in stone processing

2.1. Block cutters

Block cutters are used in stone sawing process in order to obtain thick slices or plates from stone blocks. A block cutter consists of a large-size blade (diameter 1000–3000 mm) in the vertical plane and a relatively small size horizontal blade in the horizontal plane to release the slice from the block (Fig. 1). The blades move on an axial basis of the main body of the machine made of stainless steel or cast iron. The vertical blade releases the slice to be removed from the block on the vertical plane, while the horizontal blade cuts the same length as the plate thickness and releases the slice to be cut on the horizontal plane.

In general, there are two types of block cutters based on the number of the columns in the main carrier system namely two-column and four-column.

2.2. Performance parameters of block cutters

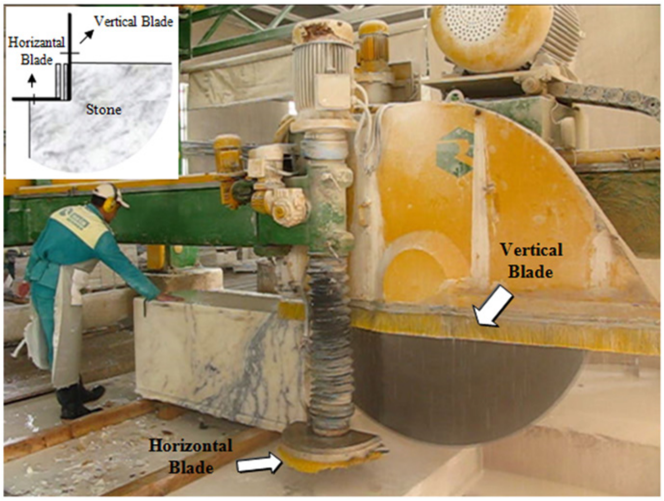

Fig. 1. Typical block cutter.

The sawability of various stones and its influence on the blade life of the sawing parameters are quite important in stone processing. In circular sawing, the blade turns in a stable direction, and the diamond particles and matrix wear in a certain direction with the blade–stone touch. As a result of the wear, the parameters that determine the relationships between the amount of the stone cut and segment consumption are generally those influencing the sawing performance.

It is quite important to optimize the sawing process and the life of the sawblade due to the quantity of the material cut. The life of the sawblade can be increased by optimizing the wear behavior of the sawblade and the process parameters. This way, the high cost of the sawblade can be reduced [16].

There are collateral factors affecting the performance of block cutters and the life of a sawblade regardless of the choice of diamond and the matrix.

There could be a general approach towards the sawing performance, which is a combination of a number of controllable and uncontrollable factors. In this respect, the diamond particle and the matrix structure are ignored as secondary factors; thus, the most important factors influencing the sawing performance and the life of the sawblade are as follows: cutting mode, cutting rate, blade design, cooling efficiency, workpiece properties, sawing conditions, machine conditions, and the operator's skills [2,3,17].

3. The data and sample collection phase

The present study was carried out on modeling the sawability of carbonate rocks merchandised in Turkey and in the World and cut by using large diameter circular saws on the block cutters as well as on seven different natural stones from five different locations in Turkey in three different stone processing plants. The technical features of the block cutters used in the study are presented in Table 1.

The data and sample collection phase of the study in the stone processing plants included five parts: the electrical data obtained from the electrical panel of the block cutters, the data obtained from the diamond segmented circular sawblade of the block cutters, the time measures and the data obtained from the block during and at the end of sawing, the Schmidt hammer rebound number data obtained from the cut block and sample preparation from sawing rocks.

In this study, the KYORITSU 6300 Model digital powermeter is located on the power line that transfers electric to the block cutter vertical sawing disk in the block cutters' electrical panel. During the time the block cutter is cut along the block, the data

Table 1
Technical specifications of block cutters, origin information of the natural stones used and calculated SE_{cut} values.

Factory name	Trade name of rock	d (mm)	V_f (m/min)	SE_{cut} (J/mm^3)	Block cutter type	Motor power (kW)	Rotational speed of saw (rpm)	Saw diameter (mm)	Segment number
Ozsac	Altintas Stone	480	0.43	1.470	2 Column	132	510	1750	112
Ozsac	Altintas Stone	480	0.47	1.390					
Ozsac	Altintas Stone	480	0.51	1.400					
Ozsac	Ozsac White	350	1.01	1.018	2 Column	110	650	1600	104
Ozsac	Usak Stone	250	1.68	1.190	4 Column	132	994	1400	92
Ender	Mugla White	350	1.02	1.087	2 Column	110	698	1600	104
Ender	Mugla White	350	0.95	1.160					
Ender	Afyon Sugar	300	1.29	0.980	4 Column	110	780	1000	70
Ender	Afyon Sugar	300	1.40	0.910					
Ender	Afyon Sugar	300	1.58	0.790					
Ender	Afyon Sugar	650	0.47	1.165	2 Column	110	698	1600	104
Reis	Afyon White	650	0.58	0.913	4 Column	132	601	1750	112
Reis	Afyon White	650	0.59	0.900					

Table 2
Physico-mechanical properties of the rocks.

Rock name	σ_c (MPa)	BS (MPa)	PLI (MPa)	SH (MPa)	BTS (MPa)	N_R (MPa)	A_b (%)	ρ_b (g/mm^3)	ρ_o (%)
Afyon Sugar	61.91	22.65	6.66	46.50	4.46	60.5	0.07	2.71	0.19
Mugla Stone	54.74	14.67	6.04	33.25	3.08	59.5	0.05	2.70	0.14
Usak Stone	55.63	19.47	6.17	41.10	4.43	63.1	0.02	2.70	0.04
Altintas Stone	124.35	21.59	7.75	44.20	4.59	62.9	0.01	2.71	0.03
Ender White	63.21	9.44	6.60	31.75	3.66	62.1	0.05	2.71	0.14
Afyon White	75.62	13.15	6.54	32.95	3.26	60.8	0.01	2.71	0.03

were obtained in the course of the cutting with clamp sensors and voltage test leads during 3 or 4 cuts. Electrical parameters in the cutting process such as the power, current, and voltage that passed through each phase were recorded for analysis with computer by using the digital powermeter.

The sawblade diameter (D), number of segments, segment length, segment height, segment thickness, water channel width, and water channel height were measured on the vertical sawing disk on each block cutter. In addition, rotational speed was measured with an optic tachometer on the sawblade, during and before cutting. The obtained results are given in Table 1.

Cutting length, cutting depth, the cutting channel width (a total of 40 measurements were made at the beginning, the middle, and the end of the cutting process), and the time spent on each cut were measured and recorded in order to calculate the SE_{cut} value.

The Schmidt hammer hardness measures were recorded from each block with the help of an N-Type Schmidt hammer.

Twenty-five cubic samples with the dimensions of $70 \times 70 \times 70\,\text{mm}^3$ and ten samples with the dimensions of $25 \times 75 \times 150\,\text{mm}^3$ from each rock block were prepared following the overall measurements related to sawing, in order to determine the physico-mechanical and mineralogical–petrographical properties of the stone cut.

4. Laboratory studies

The samples prepared were transported to the laboratories, where the experiments would be conducted, and the physico-mechanical features and mineralogical–petrographical definitions were determined.

It is quite important to know the properties of a material cut for several reasons such as choosing an appropriate machine, equipment and sawblade. Therefore, it is necessary to define the properties of stones to be cut. A variety of sawblades can be used in practice for rock groups with different properties. The mineralogical–petrographical and physico-mechanical properties of the rock samples chosen for this purpose were determined through laboratory investigation and were intended to be associated with the sawability properties.

The mineralogical–petrographical definitions of the rocks, whose trade names are known among thin section samples prepared for each rock sample, were provided. As for the method of analysis, the model analysis method was applied, and the rocks were classified according to Folk's classification [18]. As a result of the analysis carried out, all the stones involved in the study were determined as "marble".

In this study, several physico-mechanical properties used in natural stone definition in literature were determined (see Table 2).

- Uniaxial compression tests were performed on cubic samples, which had a dimension of 70 mm at a 0.6 MPa/s constant loading rate. Tests were carried out according to Turkish standard TS EN 1936 [19].
- 50 kN maximum load capacity of mechanical testing device was used for the determination of the Brazilian tensile strength tests. Core samples had a diameter ratio of 0.5. The tests were carried out according to TS 699 Standards with the 0.20 MPa/s loading rate [20].
- The point load strength test is intended as an index test for the strength classification of rock materials. Specimens used for point load strength are NX size drill core samples in 1:2 length/diameter ratios. The tests were carried out according to ISRM [21].
- Bending strength tests were carried out according to the TS EN 12372 Turkish Standard [22]. 10 specimens were prepared with the dimensions of $25 \times 75 \times 150\,\text{mm}^3$. The loading rate applied was 0.25 MPa/s.
- The C-2 model Shore hardness test device was used in order to determine Shore hardness values of rock samples. The tests were carried out according to the ISRM [23] standard. The hardness value was recorded thirty times in a way to have at

least 5 mm between the measurement points, and the mean of the hardness values was calculated for each sample.

- Schmidt hammer rebound tests were applied on the rock blocks having different dimensions varying between 2–6 m^3. The tests were performed with an N-type hammer with impact energy of 2.207 J. The ISRM [24] recommendations were applied for each rock type. ISRM suggested that 20 rebound values from single impact separated by at least a plunger diameter should be recorded, and the mean of the highest ten values were recorded as the Schmidt hammer hardness value (N_R).
- The mean values of the P-wave velocity were obtained by averaging three measurements of the transit time recorded during the test. After measuring the sample length, the values of the velocity were calculated. The mean values of the ultrasonic pulse velocity of the cubic specimens with the dimensions of $70 \times 70 \times 70$ mm^3 were measured. Controls UPV E48 portable and non-destructive test device was used to conduct the tests. This device has one transmitter and one receiver, which are 50 mm diameter and a maximum resonant frequency of 54 kHz. P-wave velocity values were calculated by [25].

$$V_p = L_p/T_p \tag{1}$$

where V_p is the seismic velocity (m/s), L_p is the pulse travel distance (m), and t is the effective pulse travel time (s).

- The water absorption at atmospheric pressure (A_b) tests was determined following TS EN 13755 recommendations [26], and the tests were carried out on cube shaped samples having a side length of 70 mm prepared by sawing from large blocks.
- Apparent density (ρ_b) and open porosity (ρ_o) of the rocks were determined according to the specifications outlined by the TS EN 1926 [27].

5. Calculation of specific cutting energy

Specific energy is defined as the energy required for the excavation of the unit volume of rock. Generally, mechanical efficiency is at a maximum when specific energy is at a minimum [28]. SE_{cut} is a function of the machine working parameters, the properties of the blade used, and the mineralogical–petrographical and physico-mechanical properties of the rock cut.

With the help of the data obtained, the SE_{cut} was calculated by

$$SE_{cut} = E_t/Q \tag{2}$$

where SE_{cut} is specific cutting energy (J/mm^3), E_t is the total energy consumed during cutting (J), and Q is the volume of the channel cut in the stone by the saw during cutting (mm^3).

The power values at the moment the sawblade is entirely in the stone are used for calculation (Fig. 2, position 2, 3, and 4) in the calculation of the SE_{cut}.

The energy consumption from the moment the sawblade makes contact to the stone to the moment the sawblade is entirely in the stone relatively increases (Fig. 2, position 1), while the energy consumption from the moment the sawblade starts moving away from the stone to the moment the cut ends and the sawblade turns back (Fig. 2, position 5) relatively decreases.

The cutting time–power consumption chart is prepared via the records of the power analyzer that includes the cutting energy data (Fig. 3) while calculating the SE_{cut}. The points where the diamond circular saw enters and leaves the stone can be determined with the help of the changes in the energy consumption found in this chart. This chart and the data recorded in the power analyzer help to determine the duration of the time during which the diamond circular saw enters the stone as a whole and help determine the mean of the amount of energy the sawblade consumes during this time. The multiplication of the amount of the power and time spent reveals the amount of the energy consumed during cutting (E_t). The SE_{cut} value for each cutting can be calculated as the amount of the energy found divided by the volume of the channel cut by the sawblade on the stone:

$$SE_{cut} = (P \times t)/(V_f \times t \times d \times w) \tag{3}$$

where P is the average power consumption during cutting (W), t is the cutting time (s), V_f is the feed rate (m/min), d is depth of the cut (mm), and w is the average width of the cutting zone (mm).

The SE_{cut} values calculated via the cutting depths and the feed rates measured are given in Table 1.

The data obtained in this study were evaluated with the multiple regression analysis, a classic statistical method. The method that mathematically presents the cause and effect relationship between the variables used to solve a problem or explain

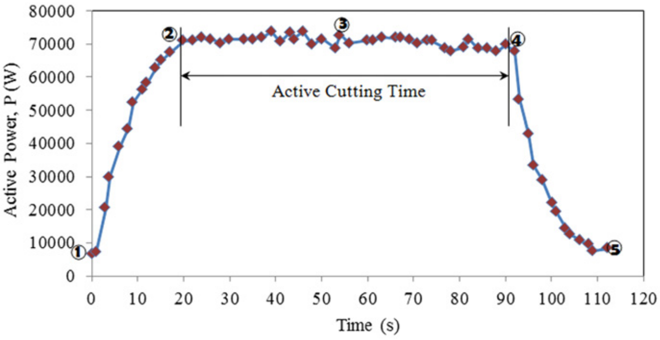

Fig. 3. Active power data as a function of time.

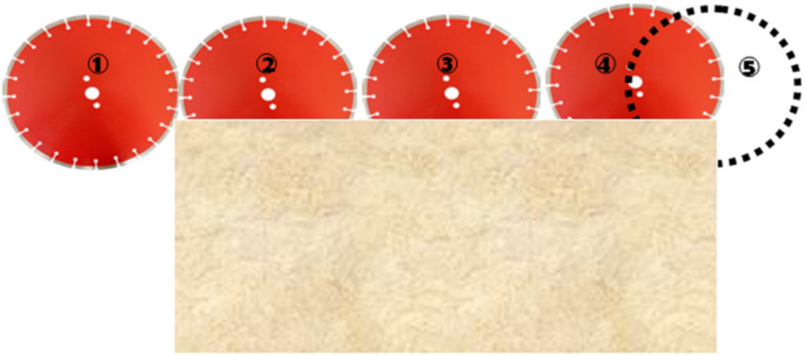

Fig. 2. Positions of sawblade during cutting.

a situation is called “regression analysis”. The variable that the researcher tries to explain or attempts to establish relationships is called “dependent variable”, and the variable used to solve the problem is called “independent variable”. The method that determines the degree and strength of the relationship between the dependent variable and the independent variable is called “correlation analysis” [29]. The method that tries to explain the relationship between one dependent variable and two or more independent variables is referred to as “multiple linear regression” [30].

In multiple linear regression analyses, coefficient of determination (R^2) determines the extent of the model obtained that explains the variance of the dependent variable [31]. For a good predictive model, the value of R^2 is expected to be close to 1. However, in regression analysis, the fact that value of R^2 is 1 or close to 1 is not enough for the validity of the model developed. In regression analysis, in general, two different tests are applied for the validity of the model developed. One of these tests is the one applied for the significance of each regression parameter (*t* or *Z* test), and the other is the “*F test*” for the significance of the regression parameters as a whole. In “*t test*”, which is conducted for the significance of each of the regression parameters, the value of a hypothesis put forward regarding the main parameter is tested in terms of whether it is close to the value expected regarding the sample. If the model is valid, it is concluded that the related independent variable is an important variable influencing the dependent variable and that it should be included in the model [32]. In regression analysis, “*F test*” is applied to determine the significance of all parameters, except for the regression constant [33,34]. In the analysis phase of the multiple linear regression model, it is important to determine the most independent variables explaining the dependent variable and to establish the best regression model. Among numerous variables found in the initial model, a number of tests may have to be conducted for determining the best model to explain the change in the dependent variable best [31]. Therefore, the stepwise regression method was developed to create a reliable and appropriate model via which appropriate tests are conducted by a program. Stepwise regression minimizes the number of variables in cases of a number of independent variables and is a method of maximizing R^2 and thus leading to the best regression model [34].

The stepwise method feature of SPSS 11.0 was used for the multiple linear regression analysis in order to determine the relationship between the dependent variable, SE_{cut} and the independent variables; cutting depth values, uniaxial compressive strength, bending strength, Brazilian tensile strength, point load strength, Shore hardness, Schmidt hammer hardness, seismic velocity, water absorption at atmospheric pressure, apparent density, and open porosity. The stepwise regression method chooses the dependent variable and one of the independent variables giving the best correlation in the first phase. Following that, it chooses the independent variable giving the second best correlation. This procedure is repeated until the best and most significant coefficient of determination is obtained within the level of confidence selected.

The predictive performances of the models were compared in order to determine the applicability of the models obtained. RMSE (Root Mean Square Error) (Eq. (4)), coefficient of determination (Eq. (5)) and adjusted coefficient of determination (Eq. (6)) and performance indices were used for the purpose of measuring the predictive performances of the models.

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i-\widehat{y})^2} \tag{4}$$

$$R^2=1-\sum\frac{(y_i-\widehat{y})^2}{\sum(y_i-\overline{y})^2} \tag{5}$$

$$\overline{R}^2=1-(1-R^2)\frac{N-1}{N-k} \tag{6}$$

where y_i is the measured value, $\widehat{y}$ is the predicted value, k is the number of parameters, and N is the number of samples.

The performance indices above can be interpreted as follows: if the RMSE is low, then the model performs better also for a good predictive model, the value of R^2 and $\overline{R}^2$ are expected to be close to 1 [35].

6. Results

Results of the basic descriptive statistical analysis performed on input parameters are given in Table 3.

First, the correlation matrix was constructed for all the data (Table 4) in order to reveal the relationships among the variables.

According to the correlation matrix for all the data, certain input parameters had the highest correlation coefficient ($r>0.70$) (Table 4). The value of SE_{cut} is well correlated with rock properties σ_c, *PLI*, N_R, and *r* values are 0.76, 0.73, 0.79, respectively.

The SE_{cut} values were analyzed with regression analysis techniques depending on rock characteristics and block cutter working parameters. The models developed for the SE_{cut} estimation are given in Eqs. (7)–(9).

$$\text{Model 1}: SE=0.138N_R-7.404 \tag{7}$$

$$\text{Model 2}: SE=0.125N_R-0.182V_f-6.395 \tag{8}$$

$$\text{Model 3}: SE=0.095N_R-0.469V_f-0.0009d-3.861 \tag{9}$$

In these models, the maximum coefficient of determination ($R^2=0.87$) was obtained in model 3, which selected N_R, V_f, and *d*, as input variables. In this model which revealed the regression equation, the regression parameters were all significant ($p=0.027$). A summary of the models generated for stepwise regression analysis is given in Table 5. A plot of the estimated SE_{cut} values versus observed SE_{cut} values for the model 3 is shown in Fig. 4.

The R^2 and *RMSE* values were found in order to check the level of confidence of the equations obtained as a result of the statistical model and to compare the level of confidence of the models. The results are presented in Table 5.

According to the results obtained, the model predicting the SE_{cut} value best was the model 3. The correlation coefficient value of the model presented in Eq. (9) was found to be 0.87.

According to Table 5, the regression parameters explaining the dependent variable in other words, all the independent variables were significant ($p=0.027$).

The high level of coefficient of determination demonstrates that the SE_{cut} is a function of the feed rate and depth. Besides the feed rate and depth, the physico-mechanical feature found in the

Table 3
Basic descriptive statistics of the input parameters.

	Minimum	Maximum	Mean	Std. deviation
d (mm)	250	650	430	145.78
D (mm)	1000	1750	1503	304.45
V_f (m/min)	0.43	1.68	0.92	0.45
σ_c (MPa)	54.74	124.35	77.59	27.33
BS (MPa)	9.44	22.65	18.05	5.26
PLI (MPa)	6.04	7.75	6.80	0.58
SH (MPa)	31.75	46.50	40.18	6.48
BTS (MPa)	3.08	4.59	4.07	0.59
N_R	59.50	63.10	61.47	1.23
V_P (m/s)	40.82	72.87	55.25	10.10
A_b (%)	0.01	0.07	0.04	0.03
ρ_b (g/mm^3)	2.70	2.71	2.71	0.003
ρ_o (%)	0.03	0.19	0.11	0.07

Table 4
Statistical correlation matrix of the input parameters and output parameter.

	d	D	V_f	σ_c	BS	PLI	SH	BTS	N_R	V_P	A_b	ρ_b	ρ_o	SE_{cut}
d	1	0.67	−0.84	0.35	−0.11	0.26	−0.17	−0.26	−0.07	−0.03	−0.46	0.40	−0.43	0.12
D	0.67	1	−0.83	0.53	−0.44	0.35	−0.50	−0.36	0.42	0.40	−0.75	0.01	−0.73	0.57
V_f	−0.84	−0.83	1	−0.67	0.11	−0.59	0.15	0.12	−0.21	−0.06	0.54	−0.42	0.50	−0.53
σ_c	0.35	0.53	−0.67	1	0.30	0.95	0.27	0.40	0.63	0.43	−0.68	0.36	−0.66	0.76
BS	−0.11	−0.44	0.11	0.30	1	0.42	0.98	0.85	0.03	0.14	0.17	0.08	0.15	0.20
PLI	0.26	0.35	−0.59	0.95	0.42	1	0.44	0.58	0.61	0.24	−0.46	0.54	−0.44	0.73
SH	−0.17	−0.50	0.15	0.27	0.98	0.44	1	0.91	0.07	0.04	0.27	0.21	0.25	0.20
BTS	−0.26	−0.36	0.12	0.40	0.85	0.58	0.91	1	0.44	0.21	0.12	0.24	0.10	0.45
N_R	−0.07	0.42	−0.21	0.63	0.03	0.61	0.07	0.44	1	0.69	−0.61	0.06	−0.63	0.79
V_P	−0.03	0.40	−0.06	0.43	0.14	0.24	0.04	0.21	0.69	1	−0.75	−0.53	−0.78	0.57
A_b	−0.46	−0.75	0.54	−0.68	0.17	−0.46	0.27	0.12	−0.61	−0.75	1	0.06	1	−0.51
ρ_b	0.40	0.01	−0.42	0.36	0.08	0.54	0.21	0.24	0.06	−0.53	0.06	1	0.09	0.00
ρ_o	−0.43	−0.73	0.50	−0.66	0.15	−0.44	0.25	0.10	−0.63	−0.78	1	0.09	1	−0.51
SE_{cut}	0.12	0.57	−0.53	0.76	0.20	0.73	0.20	0.45	0.79	0.57	−0.51	0.00	−0.51	1

Table 5
Summary of the generated models for stepwise regression analysis.

Model	Predictors	RMSE	R	R^2	$\overline{R}^2$	Std. error of the estimate	p value
1	N_R	0.045	0.791	0.626	0.592	0.1375	0.001
2	N_R, V_f	0.035	0.874	0.764	0.717	0.1144	0.036
3	N_R, V_f, d	0.026	0.931	0.867	0.823	0.0906	0.027

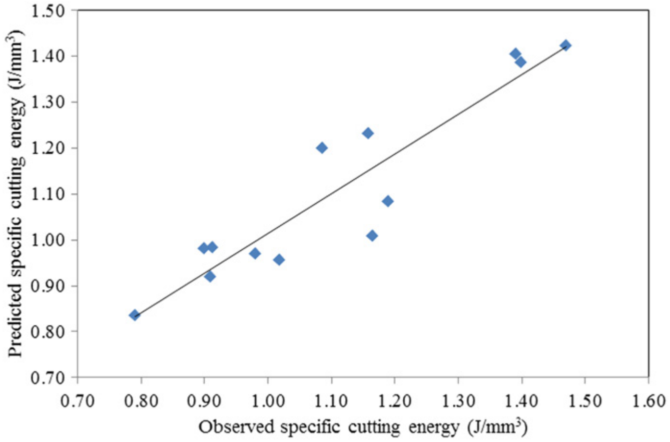

Fig. 4. Measured versus predicted SE_{cut} values for the stepwise regression model.

regression model is a function of the mineralogical–petrographic structure of the rock.

7. Discussion

The best model obtained as a result of the stepwise analysis includes the feed rate and cutting depth among the working parameters of the machine and includes the Schmidt hammer hardness value which is one of the physico-mechanical properties of the rock. The results are consistent with the practice. The models including only one of the feed rate or cutting depth values are not valid because the SE_{cut} value is influenced individually by feed rate and cutting depth values. The cutting depth in natural stone processing with block cutters is determined based on the order demands of the market and product properties. Since the cutting depth is determined according to the request of customers, the practitioner can only change the feed rate. That is, the physico-mechanical features of the rock depend on its petrographic features. The best model obtained by stepwise regression includes only the Schmidt hammer impact hardness among all other rock properties. Schmidt hammer test is a very simple and inexpensive test to conduct, and the rebound value is a good indicator of mechanical properties of rock material [36]. Schmidt hardness value is widely used in determining the performance of tunnel boring machines, impact hammers, roadheaders, and it is generally very successful in rock cutting applications for predicting the performance of the cutting process [36–41]. For the practitioner, each experiment means high cost and time consumption. Therefore, in practice, it is quite important to develop a model that best predicts with the fewest parameters.

8. Conclusions

In block cutters used in natural stone processing plants, production is directly related to the performance of block cutters to a great extent. The first phase of all cutting processes generally starts with usage of block cutters. Therefore, in a natural stone processing plant, it is quite important to determine the performance of a block cutter in advance and to determine the cost of the process in terms of the planning of production.

In the related literature, lack of studies on determining the SE_{cut} value of a block cutter via industrial data is important for supporting the need for experimental studies.

It should be noted that the data obtained in the present study and the predictive models obtained are used to generalize different cutting conditions and that they reflect only the conditions in the market of natural stone cutting with respect to a number of different parameters.

Acknowledgment

This study was supported by the Scientific and Research Council of Turkey (TUBITAK)—no. BIDEB 2219 and partially by the Anadolu University Research Project (Project no. 161835).

References

[1] Büttner A. Diamond tools and stone. Ind Diamond Rev 1974;34:89–93.
[2] Konstanty J. Theoretical analysis of stone sawing with diamonds. J Mater Process Technol 2002;123:146–54.
[3] Jennings M, Wright D. Guidelines for stone sawing. Ind Diamond Rev 1989;2:70–4.
[4] Tönshoff HK, Hillmann-Apmann H, Asche J. Diamond tools in stone and civil engineering industry: cutting principles, wear and applications. Diamond Relat Mater 2002;11:736–41.

[5] Luo SY, Liao YS. Study of the behavior of diamond saw-blades in stone processing. J Mater Process Technol 1995;51:296–308.

[6] Wright DN, Wapler H, Tönshoff HK. Investigations and prediction of diamond wear when sawing. CIRP Ann: Manuf Technol 1986;35:239–44.

[7] Ertingshausen W. Wear processes in sawing hard stone. Ind Diamond Rev 1985;45:254–8.

[8] Liao YS, Luo SY. Wear characteristics of sintered diamond composite during circular sawing. Wear 1992;157:325–37.

[9] Ersoy A, Atıcı U. Performance characteristics of circular diamond saws in cutting different types of rocks. Diamond Relat Mater 2004;13:22–37.

[10] Kahraman S, Fener M, Gunaydin O. Predicting the sawability of carbonate rocks using multiple curvilinear regression analysis. Int J Rock Mech Min Sci 2004;41:1123–31.

[11] Ersoy A, Atici U. Specific energy prediction for circular diamond saw in cutting different types of rocks using multivariable linear regression analysis. J Min Sci 2005;41:240–60.

[12] Guney A. Performance prediction of large-diameter circular saws based on surface hardness tests for Mugla (Turkey) marbles. Rock Mech Rock Eng 2011;44:357–66.

[13] Buyuksagis IS. Effect of cutting mode on the sawability of granites using segmented circular diamond sawblade. J Mater Process Technol 2007;183:399–406.

[14] Polini W, Turchetta S. Force and specific energy in stone cutting by diamond mill. Int J Mach Tools Manuf 2004;44:1189–96.

[15] Hughes HM. Some aspects of rock machining. Int J Rock Mech Min Sci 1972;9:205–11.

[16] Tönshoff HK, Asche J. Wear of metal-bond diamond tools in the machining of stone. Ind Diamond Rev 1997;1:7–13.

[17] Konstanty J. The materials science of stone sawing. Ind Diamond Rev 1991;1:27–31.

[18] Folk RL, Spectral subdivision of limestone types. In: Ham WE, editor. Classification of Carbonate Rocks-A Symposium: American Association of Petroleum Geologists Memoir; 1962. p. 62–84.

[19] Türk Standartları Enstitüsü, TS EN 1936 Doğal Taşlar-Deney Metodları-Basınç Dayanımı Tayini; 2000. s. 10.

[20] Türk Standartları Enstitüsü, TS 699 Yarmada Çekme Mukavemeti Deneyi; 1987. s. 30–32.

[21] Franklin JA. Suggested method for determining point load strength. Int J Rock Mech Min Sci 1985;22:51–60.

[22] Türk Standartları Enstitüsü, TS EN 12372 Tek Eksenli Yük Altında Eğilme Dayanımı Tayini; 2001. s. 7.

[23] ISRM (International Society for Rock Mechanics). Commission on standardization laboratory and field results, suggested methods for determining hardness and abrasiveness of rocks. Int J Rock Mech Min Sci 1978;15:89–97.

[24] Brown ET. In: Brown ET, editor. Rock characterization, testing & monitoring: ISRM suggested methods. Oxford: Pergamon; 1981.

[25] ASTM D2845—08 Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock.

[26] Türk Standartları Enstitüsü, TS EN 13755 Doğal Taşlar-Deney Metotları-Atmosfer Basıncında Su Emme Tayini; 2003. s. 2.

[27] Türk Standartları Enstitüsü, TS EN 1926 Doğal Taşlar-Deney Metotları-Gerçek Yoğunluk, Görünür Yoğunluk, Toplam ve Açık Gözeneklilik Tayini; 2001. s. 5.

[28] Teale R. The concept of specific energy in rock drilling. Int J Rock Mech Min Sci 1965;1:57–73.

[29] Özdamar K. Paket Programlar ile İstatistiksel Veri Analizi 1. 5. baskı. Eskisehir: Kaan Kitabevi; 2004.

[30] Field A. Discovering statistics using SPSS (introducing statistical methods). London: Sage Publications; 2005.

[31] Rogerson P. Statistical methods for geography. London: Sage Publications; 2001.

[32] Tarı R. Ekonometri. Kocaeli: Kocaeli Üniversitesi Yayınları; 1996.

[33] Gujarati DN. Basic Econometrics. New York: McGraw Hill; 1995.

[34] Clark WAV, Hosking PL. Statistical methods for geographers. New Jersey: Wiley; 1986.

[35] Alvarez Grimaa M, Babuska R. Fuzzy model for the prediction of unconfined compressive strength of rock samples. Int J Rock Mech Min Sci 1999;36:339–49.

[36] Bilgin N, Dincer T, Copur H. The performance prediction of impact hammers from Schmidt hammer rebound values in Istanbul metro tunnel drivages. Tunneling Underground Space Technol 2002;17:237–47.

[37] Aydin A, Basu A. The Schmidt hammer in rock material characterization. Eng Geol 2005;81:1–14.

[38] Bilgin N, Seyrek T, Shahriar K. Roadheaders glean valuable tips for Istanbul metro. Tunnels Tunnelling 1990:29–32.

[39] Howarth DF, Adamson WR, Berndt JR. Correlation of model tunnel boring and drilling machine performances with rock properties. Int J Rock Mech Min Sci 1986;23:171–5.

[40] Poole RW, Farmer IW. Geotechnical factors affecting tunneling machine performance in coal measures rock. Tunnels Tunnelling 1978:27–30.

[41] Tuncdemir H. Impact hammer applications in Istanbul metro tunnels. Tunnelling Underground Space Technol 2008;23:264–72.