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DEVELOPMENT OF PREDICTIVE MODELS FOR SPECIFIC ENERGY OF DIAMOND SAWBLADES CONCERNING OPERATING VARIABLES

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Abstract:

This paper presents an experimental study on the sawing of granites by circular diamond sawblades. Depending on the operating variables, models were built for the estimation of specific energy that is one of the important performance indicators in sawing processes. The derived models were validated through the statistical tests such as the determination coefficient, t-test, F-test and residuals. The results revealed that the developed models have high potentials as a guidance for practical applications.

Keywords: Diamond Sawblades, Granite, Specific Energy, Statistical Analysis

Notation

F_h: The horizontal force (N)
F_v: The vertical force (N)
F_z: The axial force (N)
F_n: The normal force (N)
F_t: The tangential force (N)
F_c: The resultant cutting force (N)
D_s: The disc diameter (mm)
d: The cutting depth (mm)
V_c: The workpiece traverse speed (m/s)
V_p: The peripheral speed (m/s)
φ: The total included angle of the contact zone (degrees) and
kφ: The angle showing the location of the resultant force (degrees).
W: The width of the sawblade segments
F_c: Cutting force (N)
SE: Specific energy (Nm/mm^3)
CR: Contribution rate (%)
CNS: Constant
A: Peripheral Speed (m/s)
B: Traverse Speed (cm/min.)
C: Cutting Depth (cm)
D: Flow Rate of Cooling Fluid(ml/s)
IV: Independent Variable
CE: Coefficient
SEE: Standard Error of Estimate

1. Introduction

The use of granite due to its excellent features such as beautiful colors, splendid gloss, high durability and resistance to scratches, cracks, stains, spills, heat, cold, and moisture, has continually increased throughout the world (Hojamberdiev et al., 2011). As a result of this continual growing in recent years, there has been increasingly more attention for sustainability during the sawing of granite since the complex nature of granite

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has created difficulties in sawing processes. Circular diamond sawblades has extensive applications in sawing of granites. The performance of circular diamond sawblades depends on series of factors associated with the technology and the characteristics of the rock itself. The specific energy is one of the most important performance indicators in sawing processes with circular diamond sawblades. It is derived from the amount of energy required to remove a given volume of rock and has been successfully used for the performance evaluation of circular diamond sawblades in rock sawing. The lower value of specific energy indicates that the sawing is performed more efficiently (Atici and Ersoy, 2009).

As well known, it is very hard to build models for the performance prediction, valid for all rock types since the effect of process parameters on sawing performance varies from one rock type to another even in different samples of the same rock type. Therefore, the present study concentrated on a particular group of rocks (granites). The study aimed at developing models for the estimation of the specific energy as a function of operating variables.

2. Materials and Method

For the execution of experiments, three granite having different percentages of minerals and substantial market potential were selected from a stone processing plant and dimensioned according to the requirements of experimental studies. The selected rocks include Verde Giresun Vizon, Balaban Green and Bergama Gri. The samples have a length of 30 cm and 10 cm x 3 cm section.

Some physico-mechanical properties of the rocks are presented in Table 1. It may be important to note that in practice, there are serious difficulties of supplying enough samples having suitable dimensions, preparing and testing for their mechanical properties such as uniaxial compressive and bending strength. For these reasons, the uniaxial compressive and flexural strengths of the tested rocks were provided by the stone processing company where the tested rocks were supplied. Density (kN/m^3), water absorption by volume (%), porosity (%), ultrasonic velocity (m/s), Schmidt hammer hardness, Shore hardness were determined according to related ISRM (1981) suggested methods.

Table 1. Mechanical and intact properties of rocks used in the sawing tests

Rock Properties	***Verde Butterfly***	***Balaban Green***	***Bergama Gri***
Uniaxial strength (MPa)	191.18	145.00	92.65
Density (kN/m^3)	27.60	26.6	26.09
Bending strength (MPa)	13.14	15.20	14.90
Water absorption by volume (%)	0.20	0.19	0.30
Porosity (%)	1.50	2.20	1.80
Ultrasonic Velocity (m/s)	4130	4849	4836
Cerchar abrasion Index	4.348	4.356	4.622
Schmidt hammer hardness	47	55	54
Microhardness (HV)	502.04	559.03	537.93
Shore hardness	72.65	75.15	71.35
Mohs hardness	6.1	6.0	6.3

The microhardnesses of samples were measured by a Vickers microhardness meter, which is an average of 3-5 points for a mineral. In the experiment, it is difficult to identify indention diagonal of various hardbrittle minerals due to the fracture around the indention, thus measure load of 100 g was chosen (Xie and Tamaki, 2007). Microhardness stands for a weighed average value of granite microhardness in a whole, concerning mineral microhardness and its weight in granite. Similar procedure was applied for the determination of Mohs hardness of each rock sample.

For Cerchar abrasiveness index testing, a pointed steel pin which has 610±5 Vickers hardness, 200 kg/mm^2 tensile strength, and a cone angle of 90° was applied to the surface of a rock samples for approximately one second under a static load of 68.646 N to scratch a 10 mm long groove. This procedure was repeated five times in various directions using a fresh pin for each repetition. The abrasiveness of the rock was determined by the resultant wear flat generated at the point of the stylus, which was measured in 0.1 mm units under a microscope. The unit of abrasiveness was defined as a wear flat of 0.1 mm which is equal to 1 Cerchar abrasivity index, ranging from 0 to 6 (Yarali and Kahraman, 2011; Valantin, 1974).

Petrographic studies conducted in the study include the determination of mineral composition. For this purpose, thin sections for each rock were prepared and examined under the polarizing microscope. Polished hand specimens were also examined for the grain size characterization for the coarse-grained rock samples. Petrographic descriptions and mineralogical compositions of the studied rocks are given in Table 2. As can be followed from the Table, quartz, K-feldspar, plagioclase and biotite were the main rock-forming minerals in all samples, varying in their percentage contents.

Table 2. Mineralogical properties of the rocks

Rock Type	*Mineral*	*Prop. (%)*	*Summary of petrographic description (texture, grain size)*
Verde Butterfly	Alkali feldspar (orthoclase) Plagioclase Quartz Pyroxene Biotite Garnet Opaque	41 29 11 9 6 2 2	Allotriomorphic, very coarse-grained, grains between 0.08 and 20.0 mm
Balaban Green	Alkali feldspar (orthoclase, mikroklin) Quartz Plagioclase Amphibole Epidot Biotite Other and secondary components (mica, titanit, zircon, opaque)	38 25 14 10 6 4 3	Hypidiomorphic, coarse-grained, grains between 0.08 and 6.80 mm
Bergama Gri	Plagioclase Alkali feldspar (orthoclase) Quartz Biotite Amphibole Other and secondary components (titanit, apatite, opaque)	43 20 19 10 6 2	Hypidiomorphic, fine-grained, grains between 0.24 mm and 3.85 mm

The cutting tests were performed on a high precision experimental cutting machine (Fig.1). The diamond sawblade used in the tests was of 40 cm diameter, having 28 impregnated diamond segments (circumferential length 40 mm, width 3.5 mm and height 10 mm). The diamonds were sized at 40/50 US mesh with a concentration of 30 which is recommended for the sawing of hard materials. Sawblade movements, forward–backward in the horizontal plane and up–down in the vertical plane, were driven with two 0.75 kW AC motors, while the turn of the disc were driven with 4 kW AC motor. Moreover, 0.75 kW AC motor was used to move the wagon through the cutting line.

Figure 1. Experimental set-up

In order to determine the levels of the operating variables for the study, preliminary cutting tests were conducted by considering instructions of diamond disc manufacturers and related studies. Consequently, valid for the type of tested rocks, the operating variables were varied at five levels (Table 3) and the experiment layout is given in Table 4. Each experiment was repeated five times to increase the accuracy of the results obtained.

Table 3. Levels of operating variables

Operating Variables	*Level*				
A	25	30	35	40	45
B	40	50	60	70	80
C	0.5	1.0	1.5	2.0	2.5
D	50	100	150	200	250

Table 4. Experimental Layout

Number of Experiment	*A*	*B*	*C*	*D*
1	**25**	60	2.0	150
2	**30**	60	2.0	150
3	**35**	60	2.0	150
4	**40**	60	2.0	150
5	**45**	60	2.0	150
6	35	**40**	2.0	150
7	35	**50**	2.0	150
8	35	**60**	2.0	150
9	35	**70**	2.0	150
10	35	**80**	2.0	150
11	35	60	**0.5**	150
12	35	60	**1.0**	150
13	35	60	**1.5**	150
14	35	60	**2.0**	150
15	35	60	**2.5**	150
16	35	60	2.0	**50**
17	35	60	2.0	**100**
18	35	60	2.0	**150**
19	35	60	2.0	**200**
20	35	60	2.0	**250**

Additionally, the diamond sawblade was dressed by cutting a siliceous sedimentary tuff block before the cutting tests. The cutting experiments were then conducted in the down-cutting mode. The horizontal and vertical force components acting on the disk were measured using load cells. Cutting force and specific energy were derived from the equations (1-12) considering the geometrical relations presented in Fig. 2.

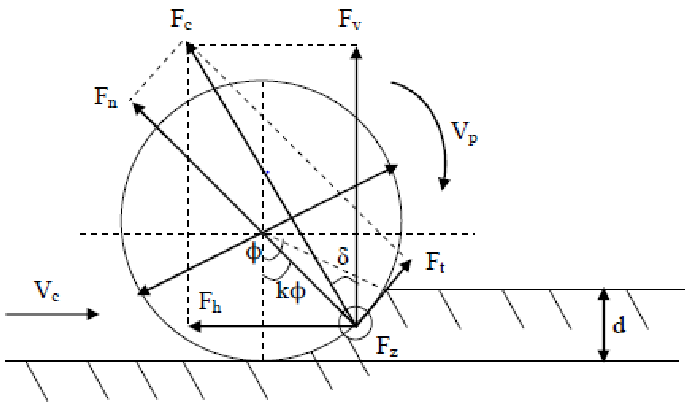

Figure 2. The kinematics of cutting process for the down-cutting model (Konstanty, 2002)

$$\mathrm{Cos}\,\delta = \frac{F_v}{F_c} \tag{1}$$

$$\mathrm{Sin}\ \delta = \frac{F_h}{F_c} \tag{2}$$

$$F_n = F_c\,\mathrm{Cos}[(k\phi) - \delta] \tag{3}$$

$$F_n = F_c\,(\mathrm{Cos}(k\phi)\frac{F_v}{F_c} + \mathrm{Sin}\ (k\phi)\frac{F_h}{F_c}) \tag{4}$$

$$F_n = F_v\,\mathrm{Cos}(k\phi) + F_h\ \mathrm{Sin}\ (k\phi) \tag{5}$$

$$F_t = F_c\ \mathrm{Sin}\,[(k\phi) - \delta] \tag{6}$$

$$Ft = F_c\,(\mathrm{Sin}\ (k\phi)\frac{F_v}{F_c} - \mathrm{Cos}(k\phi)\frac{F_h}{F_c}) \tag{7}$$

$$F_t = F_v\ \mathrm{Sin}\ (k\varphi) - F_h\ \mathrm{Cos}\ (k\varphi) \tag{8}$$

$$F_c = \sqrt{F_n{}^2 + F_t{}^2} \tag{9}$$

The total included angle of the contact zone (φ) and the angle (kφ) indicating the location of the resultant force can be calculated by the following formulas:

$$\phi = \mathrm{Cos}^{-1}(1 - \frac{2d}{D_s}) \tag{10}$$

$$k\phi = 0.7\,\phi \tag{11}$$

Specific energy (SE) was calculated as:

$$SE = \frac{F_t\ V_p}{d\,W\,V_c} \tag{12}$$

3. Results and Discussion

A computing package program (SPSS 11.5) was used for the statistical analysis. Multi-variable linear regression analysis was carried out to predict the specific energy. A number of statistical parameters or terms are associated with multi-variable linear regression analysis. Some of the most important include the coefficient of multiple determination, the confidence level, standard error, model error, the significance level, the t-distribution, the F-distribution and the residual. Detailed explanation of these parameters or terms can be found from the related sources (Field, 2009; Sekercioglu et al., 2010; Akbulut, 2011). The best model (13-15) developed for the estimation of specific energy from operating variables for each rock is given below together with the contribution rates (CR) of each operating variable to specific energy.

SE_{VB}= 2.7855 + 0.0778 A – 0.0222 B – 0.5190 C – 0.0027 D (13)
CR (%): A: 37.27, B: 21.27, C: 28.92, D: 12.74

SE_{BG}= 3.3563 + 0.0826 A – 0.0274 B – 0.5305 C – 0.0033 D (14)
CR (%): A: 35.64, B: 23.65, C: 26.63, D: 14.15

SE_{BERG}= 2.5702 + 0.0746 A – 0.022 B – 0.4363 C – 0.0023 D (15)
CR (%): A: 38.77, B: 22.87, C: 26.38, D: 11.95

CR was used to determine the significant process factors in percentage. It is a tool to see which process factor has a significant effect on the process. Higher CRs indicates that there is a considerable change on the performance characteristic due to the variation of the related operating variables. Unlike the general expectations, the most significant operating variable affecting the specific energy was determined as peripheral speed instead of cutting depth. This result could be caused by selecting low cutting depths for the tests due to available power limits of the cutting machine. The peripheral speed was followed by the cutting depth, traverse speed (the order of cutting depth and traverse speed changes for some rocks) and flow rate of cooling fluid according to the order of importance in terms of specific energy.

The predictive models derived from operating variables were verified by considering the following criteria: the behavior of determination coefficients (R^2), and, the t-test, the F-test and the residual analysis (see Table 5). R^2 values for all models built from operating variables are around 0.90, indicating a high degree of relationship between the predicted and observed specific energy. As can be seen from Table 5, at the 95 % confidence level, the computed t-values and computed F-values are greater than the tabulated t-values and tabulated F-values, suggesting that the models built are statistically valid. A regression analysis is not completed by fitting a model on the basis of coefficients of determination, by providing confidence intervals or by testing. These steps tell only half the story and give only the statistical inferences. A better test is to make a more direct comparison of model and real data in the form of residuals (Ersoy et al., 2005; Aydın et al., 2012). The plots of the residuals against the predicted specific energy for the model case were shown in Fig. 3. The Figure indicates that the residuals appear to be randomly scattered about the line, confirming the accuracy of the models.

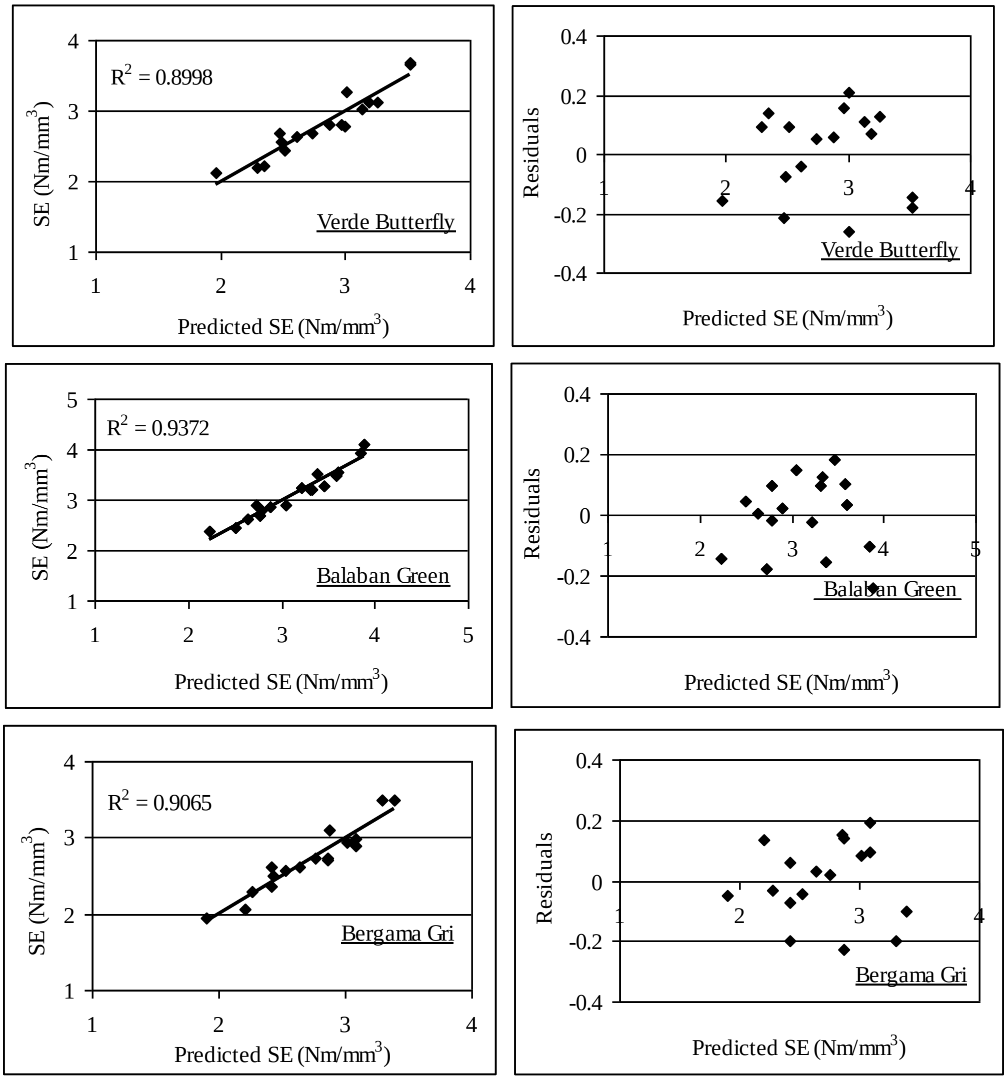

Figure 3. SE against the predicted SE and residuals

Table 5. Statistical results of the multiple linear regression analysis

Rock	***IV***	***CE***	***SE***	***SEE***	***t***	t_t	***F***	F_t	R^2
Verde Butterfly	CNS	2.7855	0.548	0.169	5.081	1.729	26.954	3.13	0.8998
	A	0.0778	0.011		7.262				
	B	- 0.0222	0.005		-4.144				
	C	- 0.5190	0.092		-5.634				
	D	- 0.0027	0.001		-2.483				
Balaban Green	CNS	3.3563	0.463	0.143	7.248	1.729	44.908	3.13	0.9372
	A	0.0826	0.009		9.128				
	B	- 0.0274	0.005		-6.056				
	C	- 0.5305	0.078		-6.819				
	D	- 0.0033	0.001		-3.625				
Bergama Gri	CNS	2.5702	0.485	0.150	5.295	1.729	29.465	3.13	0.9065
	A	0.0746	0.009		7.864				
	B	- 0.022	0.005		-4.638				
	C	- 0.4363	0.082		-5.350				
	D	- 0.0023	0.001		-2.425				

4. Conclusions

An experimental study on the specific energy in sawing of granites rocks was presented. The results showed that the most significant operating variable affecting the specific energy was the peripheral speed. The peripheral speed was followed by the cutting depth, traverse speed and flow rate of cooling fluid according to their significance on the specific energy. Further, the results disclosed that the models derived from the operating variables for the estimation of the specific energy have high potential as a guidance for practical applications.

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