Chapter

Force and Specific Energy in Natural Rocks Cutting by Four-Axis Machine

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Abstract

This study used a four-axis computer controlled machine to determine the cutting forces (C_f), specific cutting energy (S_c) and specific energy (S_e) affecting the processability of natural rocks. A total of 17 types of natural rocks were categorized according to their geological formations. This study consisted of three parts: (1) experimental measurement of the C_f resulting from processing natural rocks using a 6.0-mm diameter end mill cutting tool and a four-axis machine; (2) calculation of C_f, S_c and S_e values; and (3) statistical analysis of the parameters. In terms of C_f, S_c and S_e values, a statistically significant difference ($P < 0.001$) was observed among a depth of cut (d_p) and feed speed (V_a). It was found that the parameters that affected the processability of natural rocks were d_p and V_a. Accordingly, the processability of natural rocks processing type, d_p and V_a was found that affected. Simple linear regression was performed to examine the relationship between physicomechanical properties, and between C_f, S_e and S_c values. As a result, regression equations were developed in consideration of the physicomechanical properties of natural rocks and the C_f, S_c and S_e equation for the prediction of the efficiency of computer numerical control (CNC) machines.

Keywords: natural rock, CNC machine, efficiency, C_f, S_c, S_e

1. Introduction

Natural stone industry is one of the most effective actors of the Turkish mining industry economy. With its 4000-year history of natural stone production, Turkey is one of the oldest natural stone producers in the world. Natural stones are classified as metamorphic, sedimentary and magmatic according to their formations [1]. Marble is a metamorphic rock formed by recrystallization of limestone. Marble is a metamorphic stone composed of calcite ($CaCO_3$) and formed as a result of the recrystallization of the limestone under excessive pressure and heat [2–6]. CNC machines are electromechanical systems that process the materials according to the logical operation unit of numerical control (NC) codes defined by numbers, letters, and symbols of a product designed using a computer-aided design and manufacturing (CAD/CAM) program. Nowadays, 3D design in the natural stone industry can be processed with high accuracy, precision series and quality the use of CNC machine [7, 8]. Various processing technologies are used at natural stone quarries and factories to manufacture as building materials. In quarries, in the production of natural stone blocks, diamond wire cutting and chain arm cutting machines are widely used in factories, plates and panels manufacturing in the production of block cutter ST and gangsaw machines [9–18].

CNC machine is used to process natural stone blocks and wastes in 3D design products to be used in buildings. Many studies have been found on the C_f in circular saws depending on the physicomechanical properties of natural rocks, modeling of the S_e and socket [19–23], the definition of the theoretical chip geometry [24], and connections between tangential cutting force and chip thickness [25–27]. Some other studies address the effect of processing parameters on tool wear [28–31], the modeling of natural stone cutting with diamond cutting tools [32] and specific grinding energy of chip samples under a scanning microscope [33] in order to determine specific cutting energy and power consumption [34, 35]. Energy and the type of cutting mechanism used in the production of end products from natural rocks lead to the wear of cutting tools. Energy consumption and wear of cutting edges are the important factors affecting processing costs. These factors should be efficiently to reduce processing costs. It is therefore important to determine the cutting performance of natural rocks according to their characteristics. Cut tools should be selected carefully and performance forecast should be proper in order to improve the processing efficiency of natural rocks and reduce costs. Different from the manufacture of plates and panels in which gangsaw and cutter ST are deep cut on the x (length), z (depth) axis, this process requires few depth cut and precision tools with a CNC machine on the x (length), y (width) and z (depth) axis. C_f, S_c and wear of diamond cut tools have a low spindle and V_a in the processability of rocks in the CNC machine with internally cooled cut tools. Carbide coated end mills tools are widely used in the natural stones sectors. In addition, the number of studies on parameters affecting the processability of natural rocks in the CNC machine is less [36–40].

This study investigated the relationship between the values of the C_f, S_e and S_c obtained from the processing of rocks using CNC, and related parameters (i.e., cutting parameters and physicomechanical properties). C_f, S_e and S_c values depending on the d_p and V_a of natural rocks have been analyzed (ANOVA) statistically. Results show that 1.0, 1.2 and 1.6 mm at the d_p and 2000, 2500, 3000 mm/min at the V_a are important cutting parameters in the processability of natural rocks. Regression models were developed for the estimation of C_f, S_e and S_c of the with measured by power and load meter tester. Regression analyses were performed to determine the optimum relationship between the C_f, S_e and S_c dependent variable and physicomechanical properties independent variable in three different groups of natural rocks. Regression models developed in this study can be used by planners and natural stone manufacturing companies for cost analysis and mill cut tool processing programs in natural rocks. We recommend that it be considered in further studies use a larger database to analyze the possibility of regression analyses the C_f, S_e and S_c any of the physico-mechanical parameters of natural rocks.

2. Materials and method

2.1 Materials

These natural rock samples were obtained from the companies operating a quarry in Afyon. The surface of each series was adjusted with the cutting process as a square (30 by 30-cm) and 1 cm thickness. Furthermore, these rock samples were polished on one side. **Table 1** shows sample code, pertographic name, dimensions, main modal compositions, sample number and surface processing of the rocks used in the test.

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Natural rocks	Sample code	Pertographic name	Main modal compositions	Dimensions (mm)	N	Surface processing
Travertine	T1-T5	Sedimentary	Calcite	300 × 300 × 30	15	Polished
Marble	M1-M7	Metamorphic	Calcite	300 × 300 × 30	15	Polished
Limestone	K1-K5	Sedimentary	Calcite	300 × 300 × 30	15	Polished

Table 1.
Characteristics of natural rocks used in experimental tests.

Cut tool (carbide-coated end-mill cutting edge tool) was used in the processing of natural rocks by CNC machine. **Figure 1** shows the image of the end mill cut tool. **Table 2** shows the technical specifications of the end mill cut tool.

2.2 Method

Figure 2 shows that the CNC consists of the machine, electric motors, pneumatic or hydraulic power units, control panel and software.

A 4-Axis CNC (Megatron) machine designed for the natural stone industry in Afyon Kocatepe University Natural Stone Processing Laboratory was used for the tests. The technical features of the machine are given in **Table 3**.

Processability tests were performed on natural rocks according to the d_p and V_a cutting parameters by using CNC machine. Alpha CAM drawing program was used to determine the cutting parameters of natural rocks. As shown in **Figure 3**, 120 × 25 mm in size 18 rectangular samples were produced using a 3D modeling and simulation program for the processability tests.

A power meter, also known as load meter, built in the CNC machine was used in the processability tests. This testing tool consists of a measurement unit, a load cell, a controller unit and Defne Lab Soft program (**Figure 4**).

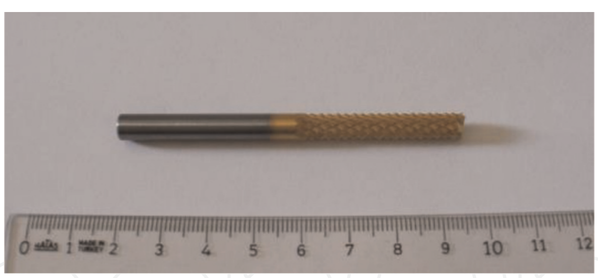

Figure 1.
Image of the end mill cutting edge tool.

Technical properties	Unit	Values
Code	—	MFR-6
Cutting tool diameter/d1	mm	6
Stem diameter/d2	mm	6
Cutting length/l2	mm	25
End length/l1	mm	76
Milling end	—	36,677
Edge number	—	4
Helix angle	(°)	25

Table 2.
Technical properties of end-mill cutting edge tool.

Figure 2.
CNC natural stone processing machines.

Technical properties/unit	Values
Spindle motor (kW)	9.0
Number of axis (number)	4.0
Motor speed (rpm)	24.000
Processing speed (rpm)	24.000
Vamotor x axis (mm/dk)	80.000
Voltage (V)	380
Processing length (mm)	4.000–4.500
Processing width (mm)	2.000–2.500
Processing height (mm)	500–600
Lathe height (mm)	700–750
Lathe length (mm)	2.500–3.000
Coolant (l/dk)	3.0
Automatic number of teams (adet)	8.0

Table 3.
Technical properties of CNC natural stone processing machine.

Natural stone samples were bond and stabilized to the platform on the measurement unit with cut tools. There were 4 on the Z axis, 4 on the X and Y axis total 8 load cells on the testing machine to calculate the C_f. Defne Lab-Soft program was recorded into the data input screen of types and sizes of natural rocks, cutter information, and constant and variable parameters. NC codes from Alphacam drawing program were transferred to the CNC machine with Recon program interface. The cut tool was balanced to the engine of the CNC machine connected to the tool holder. The reset operation was performed when the cutting tool was guided by the function and operation keys to the reference point on the test specimen surface. NC code was selected using the function and operation keys on the control unit and the measurement was performed by pressing the start button. Depending on the different process parameters, the natural stones were processed in the cooling process from the water flow rate of 1 l/min. A rectangle of 120 × 25 mm was processed for 40 s to obtain 100 data per second. All samples were processed in a total of 84 min. **Figure 4** shows a schematic view of the test apparatus.

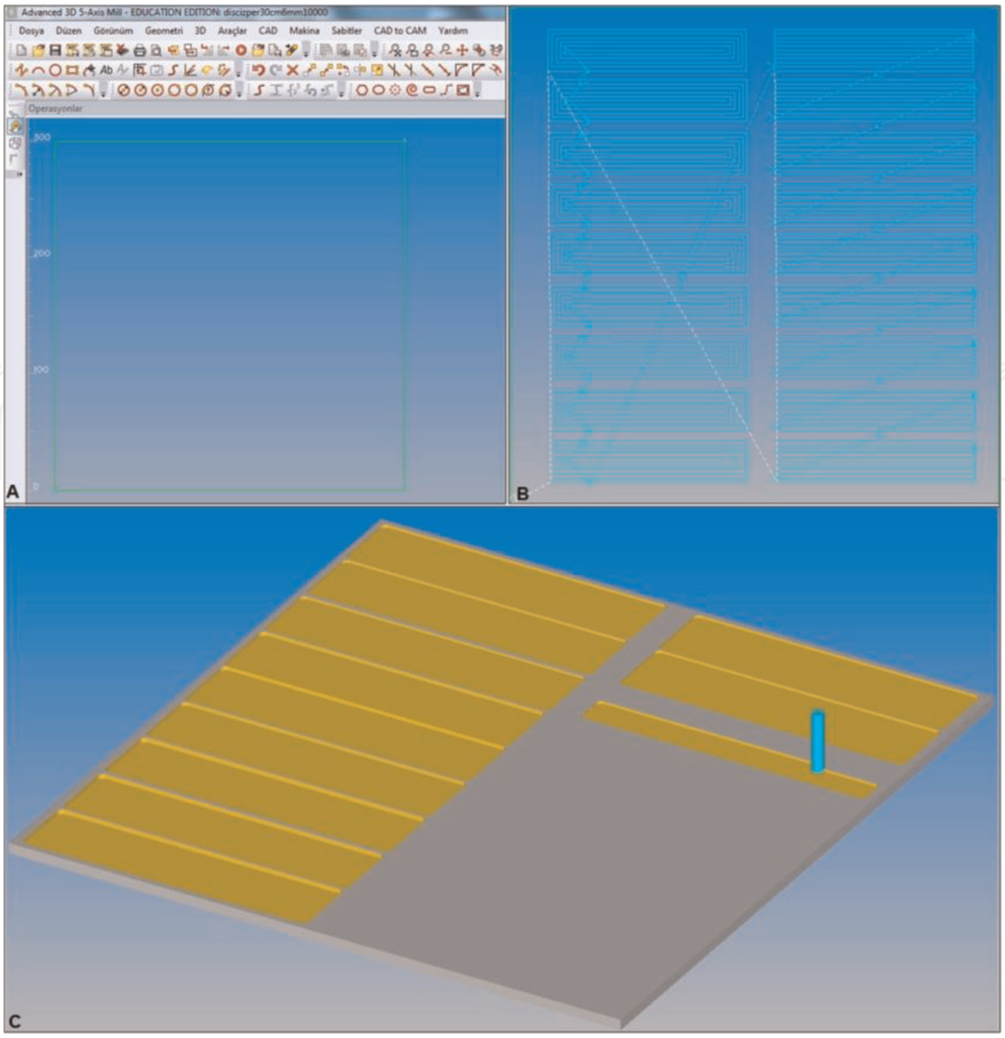

Figure 3.
Test specimens on (a) alpha CAM drawing program, (b) modeling, (c) simulation.

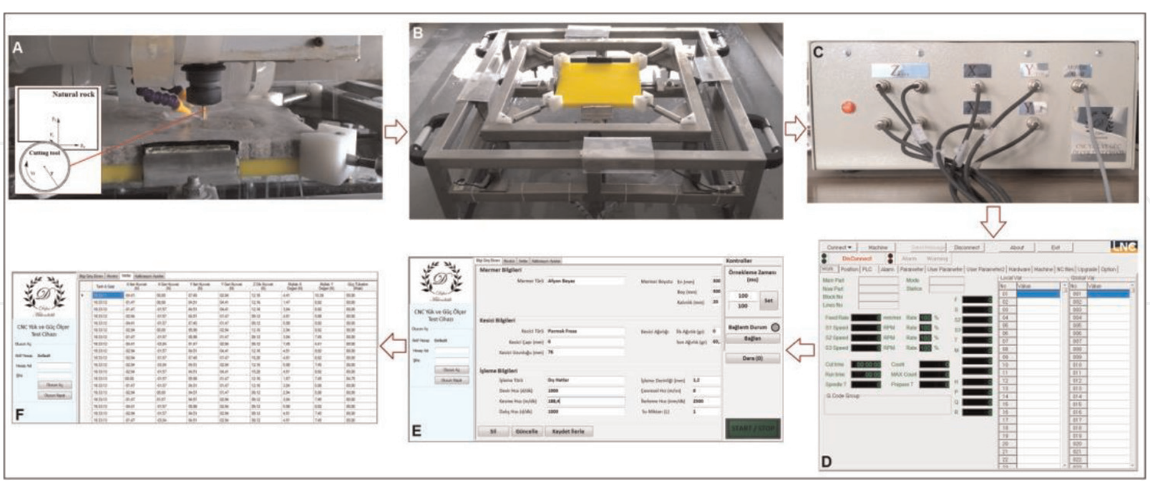

Figure 4.
Processability tests (a) vector representation of forces (F_x, F_y, F_c and F_t), cutting speed (V_t) and Va(V_a), (b) power and load meter tester and load cells, (c) control unit, (d) Defne lab-soft natural stone test program interface, (e) recon program interface, (f) views of database.

In the processability tests, variable and constant parameters were taken into consideration. Constant cutting parameters were the cut tool diameter of 6.0 mm, spindle speed of 10,000 d/min, cutting width of 3.0 mm and plunge speed of 1000 d/min. Variable cutting parameters were the d_p of 1.20, 1.60 and 2.0 mm and Va of

2500, 3000, 3500 mm/min. **Table 4** shows the CNC cutting parameters for the natural rocks processed in the tests.

Figure 5 explains the vector representation of the forces (F_x, F_y, F_c and F_t), V_t and V_a that occurred during the processing of the natural rocks.

Calculation of F_x cutting force according to CNC processing parameters is as shown in Eq. (1).

F_x cutting force Eq. (1);

$$F_x = |F_{x1}| + |F_{x2}| \tag{1}$$

F_x = cutting force (N); F_{x1} = absolute forward cutting force (N); F_{x2} = absolute back cutting force (N).

F_y cutting force Eq. (2);

$$F_y = |F_{y1}| + |F_{y2}| \tag{2}$$

F_y = cutting force (N); F_{y1} = absolute forward cutting force (N); F_{y2} = absolute back cutting force (N).

Calculation by using R resultant force, F_x and F_y cutting forces, Eq. (3):

$$R = \sqrt{F_x^2 + F_y^2} \tag{3}$$

R = resultant force (N); F_x = cutting force (N); F_y = cutting force (N).

β angle between R and Fx, Eq. (4),

Processing parameters	Unit	Values
Cutting tool diameter	mm	6.0
Depth of cut	mm	1.20–1.60–2.00
Spindle speed	d/min	10,000
Feed speed	mm/min	2000–2500–3000
Plunge speed	d/min	1000
Cutting speed	m/min	188.4
Cutting width	mm	3.0

Table 4.
CNC processing parameters.

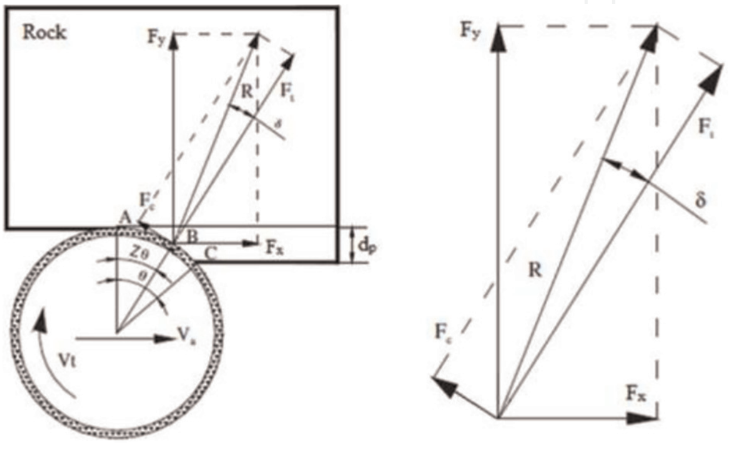

Figure 5.
Vector representation of the forces (F_x, F_y, F_c and F_t), V_t and V_a that occur during the processing.

$$\beta = tan^{-1}\left(\frac{F_y}{F_x}\right) \tag{4}$$

Contact angle θ between tool diameter (d) and natural rocks, Eq. (5);

$$\theta = cos^{-1}\left(1 - \frac{2dp}{d}\right) \tag{5}$$

Calculating F_c tangential force and radial force F_t components of the cutting forces with the R value obtained.

Eqs. (6) and (7):

$$F_c = Rsin\delta \tag{6}$$

$$F_t = Rcos\delta \tag{7}$$

δ angle between F_t and F_c.

Eq. (8):

$$\delta = \beta - Z\theta \tag{8}$$

Parameter Z depends on the location of the application point of the compound forces R on the arc AC, which is contact between cutting edges and natural rocks.

Parameter Z, Eq. (9):

$$Z = \frac{AB}{AC} \tag{9}$$

V_t cutting speed Eq. (10):

$$V_t = \frac{\pi \times D \times n}{1000} \tag{10}$$

V_t = cutting speed (m/min); n = spindle speed (d/min); D = cutter diameter (mm).

Specific cutting energy depending on tangential force and cutting speed is shown in Eq. (11).

$$S_c = \frac{F_c \times V_t}{V_a \times d_p \times b} \tag{11}$$

F_c = tangential cutting force (N); V_t = cutting speed (m/min); V_a = feed speed (mm/min); d_p = cutting depth (mm); b = cutting width (mm).

S_e values were calculated using the power P and Q_w obtained from the main electric motor of 7.5 kW where the cutting end of the natural rocks was connected during the processability time (t).

The chip volume is shown in Eq. (12).

$$Q_w = b \times l \times dp(1, 2, 3) \tag{12}$$

Q_w = chip volume (mm^3); b = size of the sample (mm); l = the width of the sample (mm); d_p(1,2,3) = cutting depth (mm).

The total specific energy is shown in Eq. (13).

$$S_e = \frac{\frac{\sum_{j=1}^{n} \mathrm{Pj}}{n} \times \sum_{j=1}^{n} \mathrm{tj}}{Q_{w(1,2,3)}} \tag{13}$$

S_e = total specific energy (J/mm^3); P = power consumption (W); t = total time (s); Q_w = chip volume (mm^3).

3. Findings and evaluations

3.1 Petrographic, chemical and physicomechanical properties

The petrographic analysis was carried out in the MTA (General Directorate Mineral Research and Exploration) mineralogical and petrographic analysis laboratory in Ankara/Turkey. Chemical properties of natural rocks were performed using the XRF (X-ray fluorescence) method in ACME (Analytical Laboratory in Turkey/ Ankara). The metamorphic (marble) and sedimentary (travertine, and limestone) origin natural rocks used in this study had different textures. All natural rock types were composed of CaO as main calcite crystals and at least 99.0% calcite minerals ranging from 53.10 to 55.70%. The petrographic analysis results and chemical analysis of the samples are presented in **Tables 5** and **6**, respectively. Petrographic and chemical analysis results of samples are given in **Tables 5** and **6**, respectively.

The CNC processability tests were conducted in the Rock Mechanics and Technology Application and Research Center Laboratory of the Department of Mining Engineering of Afyon Kocatepe University. The tests were performed in accordance with Standard No. TS EN 1936: 2010 [41], Standard No. TS EN 13755: 2014 [42], Standard No. TS EN 14205: 2004 [43], Standard No. TS EN 1926: 2007 [44], Standard No. TS EN 13161: 2014 [45], Standard No. TS 699 [46] and Standard No. TS EN 1341 (Appendix-C: 2013) [47]. The physicomechanical properties of the natural rocks are presented in **Table 7**. The rock samples were 40×40 mm^3, $70 \times 70 \times 70$ mm^3 and $30 \times 50 \times 180$ mm^3. The tests were carried out using at least six samples.

3.2 Variance analysis (ANOVA) of cutting forces

In processability tests, the F_c and F_t measurements were conducted using two-factor analysis of variance (ANOVA) (17 natural rocks $\times$ 2 $C_f \times$ 3 $d_p \times$ 3 V_a) randomized experimental design with 100 replications (n = 100). A total of 30,600 data were obtained on the rocks. In terms of the C_f (F_c, F_t), among the d_p and V_a there was a statistically significant difference ($P < 0.001$) (**Table 8**).

In processability tests for natural rocks, the mean F_c and F_t increase with an increase in the d_p and V_a was given in **Figure 6**. K4 and K5 samples have high values of the C_f at the d_p of 2.0 mm while T1, T2, and T3 samples have low values of the C_f at the d_p of 1.2 mm. Processability of the C_f values of K4 and K5 samples the d_p of 2.0 mm is more forced than that of the other samples. K4 and K5 samples have high values of the C_f at a V_a of 3.000 mm/min while T1, T2, and T3 samples have low values of the C_f at a V_a of 2.000 mm/min. Processability of the C_f of K4 and K5 samples at a V_a of 3.000 mm/min is more forced than that of the other samples.

3.3 Variance analysis (ANOVA) of specific cutting energy and specific energy

In processability tests, the S_c and S_e measurements were conducted using two-factor analysis of variance (ANOVA) (S_c and S_e for 12 natural rocks $\times$ 3 $d_p \times$ 3 V_a)

Natural Rocks	Petrographic descriptions	Minerals
T1	Fine-grained calcite is the dominant mineral. Consist of micro-mesocrystalline calcite minerals with a little amount of clay. Often contains pores. Micritic (intraclast) texture. Travertines	77% Calcite (mic), 22% Calcite (spr)
T2		78% Calcite (mic), 21% Calcite (spr)
T3		79% Calcite (mic), 20% Calcite (spr)
T4		78% Calcite (mic), 21% Calcite (spr)
T5		77% Calcite (mic), 22% Calcite (spr)
M1	Fine, medium, medium-coarse and coarse-grained with polysynthetic twins, granoblastic texture. Marbles	98.5% Calcite
M2		97.5% Calcite
M3		98% Calcite
M4		98.5% Calcite
M5		98.5% Calcite
M6		99% Calcite
M7		97% Calcite, 2% dolomite
K1	Fine-grained. Consists of cryptocrystalline calcite within crypto microcrystalline calcite. Micritic texture. Limestones	96% Calcite (mic), 2% Calcite (spr)
K2		96% Calcite (mic), 2% Calcite (spr)
K3		95% Calcite (mic), 3% Calcite (spr)
K4		95% Calcite (mic), 3% Calcite (spr)
K5		95% Calcite (mic), 3% Calcite (spr)

Table 5.
Petrographic descriptions of natural rock samples.

randomized experimental design with 100 replications (n = 100). A total of 30,600 data were obtained on the rocks. In terms of the S_c and S_e, among the d_p and V_a there was a statistically significant difference ($P < 0.001$) (**Table 9**).

In processability tests for natural rocks, the mean S_c and S_e values at the d_p of 1.2 mm are lower than those at the d_p of 1.6 and 2.0 mm was given in **Figure 7**. S_c and S_e values at the V_a of 2000 mm/min are higher than those at the V_a of 2500 and 3000 mm/min. S_c and S_e values at the V_a of 3000 mm/min are lower for T1, T2, and T3 samples while those at the V_a of 2000 mm/min are higher for both K4 and K5 samples. The natural rocks should have the V_a of 3000 mm/min according to the S_c and S_e values.

3.4 Relationships between cutting forces and specific cutting energy

Regression models were applied to examine the relationship between the C_f and S_c values for each of the natural rocks. The results of the simple linear regression analysis are given in **Figure 8**.

Natural Rocks	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	MnO (%)	LoI (%)
T1	55.70	0.01	0.01	0.01	0.01	0.015	0.01	0.03	0.02	43.96
T2	55.44	0.06	0.01	0.02	0.06	0.11	0.01	0.02	0.03	44.02
T3	55.45	0.01	0.01	0.01	0.28	0.12	0.01	0.02	0.01	44.08
T4	55.47	0.01	0.01	0.01	0.21	0.10	0.01	0.02	0.01	44.01
T5	55.48	0.06	0.01	0.02	0.09	0.11	0.01	0.02	0.03	43.95
M1	55.59	0.01	0.01	0.01	0.11	0.21	0.01	0.04	0.01	44.00
M2	54.40	0.95	0.31	0.05	0.21	0.04	0.01	0.01	0.01	44.00
M3	54.16	0.89	0.27	0.09	0.81	0.08	0.02	0.01	0.04	43.60
M4	53.37	1.57	0.57	0.29	0.75	0.27	0.03	0.03	0.04	43.06
M5	55.38	0.17	0.03	0.09	0.31	0.21	0.01	0.02	0.01	43.76
M6	55.08	0.27	0.03	0.19	0.33	0.19	0.01	0.02	0.01	43.86
M7	53.10	0.55	0.30	0.19	1.92	0.05	0.01	0.03	0.03	43.81
K1	55.57	0.10	0.02	0.01	0.37	0.16	0.01	0.04	0.01	43.71
K2	54.92	0.10	0.01	0.01	0.41	0.13	0.01	0.04	0.01	44.36
K3	54.80	0.22	0.01	0.01	0.40	0.11	0.01	0.04	0.01	44.39
K4	54.68	0.46	0.01	0.01	0.56	0.12	0.01	0.03	0.01	44.11
K5	54.37	0.75	0.01	0.01	0.35	0.14	0.01	0.04	0.01	44.31

Table 6.
Chemical characteristics of natural rock samples.

Natural Rocks	D (kg/m^3)	P (%)	WA (%)	KH	UCS (MPa)	FS (MPa)	IS (MPa)	AR ($cm^3/50\ cm^2$)
T1	2640	1.52	1.38	113.38	54.56	7.92	17.00	24.01
T2	2650	1.46	1.24	117.96	55.25	8.09	19.00	23.48
T3	2660	1.28	1.06	122.54	56.85	8.46	21.00	23.05
T4	2670	1.15	0.94	126.28	57.94	8.89	22.00	22.61
T5	2680	1.04	0.87	129.35	58.65	8.95	23.00	22.04
M1	2690	0.96	0.82	131.14	59.85	9.03	24.00	21.79
M2	2700	0.88	0.78	135.76	62.16	9.28	25.00	19.95
M3	2705	0.75	0.66	137.89	64.85	9.46	26.00	19.01
M4	2710	0.71	0.55	141.52	66.85	9.86	27.00	18.72
M5	2715	0.68	0.43	143.78	68.75	9.98	28.00	18.13
M6	2720	0.66	0.38	145.78	70.45	10.12	29.00	17.79
M7	2730	0.52	0.32	155.45	77.04	10.94	31.00	17.58
K1	2735	0.38	0.28	168.25	84.10	12.85	33.00	17.29
K2	2745	0.25	0.21	173.56	87.25	13.94	34.00	16.57
K3	2755	0.23	0.18	178.24	90.84	14.96	36.00	16.05
K4	2775	0.20	0.16	184.58	93.26	16.24	38.00	15.34
K5	2800	0.16	0.14	190.95	97.08	18.45	40.00	14.12

D, density; P, porosity; WA, water absorption; KH, knoop hardness; UCS, uniaxial compressive strength; FS, flexural strength; IS, impact strength; AR, abrasion strength.

Table 7.
Physico-mechanical properties of natural rocks.

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Cf (N) dependent variable	d_p (mm)		Mean difference (I-J)	Std. Error	Sig.	95% confidence interval	
	Mean (I)	Mean (J)				Lower bound	Upper bound
F_c	1.20	1.00	−3.8214*	0.27897	<0.001	−4.4787	−3.1642
		2.00	−7.4694*	0.27897	<0.001	−81267	−6.8122
	1.60	1.20	3.8214*	0.27897	<0.001	3.1642	4.4787
		2.00	−3.6480*	0.27897	<0.001	−4.3052	−2.9907
	2.00	1.20	7.4694*	0.27897	<0.001	6.8122	8.1267
		1.60	3.6480*	0.27897	<0.001	2.9907	4.3052
F_t	1.20	1.60	−3.7896*	0.27690	<0.001	−4.4420	−3.1372
		2.00	−7.5726*	0.27690	<0.001	−8.2250	−6.9202
	1.60	1.20	3.7896*	0.27690	<0.001	3.1372	4.4420
		2.00	−3.7830*	0.27690	<0.001	−4.4354	−3.1306
	2.00	1.20	7.5726*	0.27690	<0.001	6.9202	8.2250
		1.60	3.7830*	0.27690	<0.001	3.1306	4.4354
Va(mm/dk)							
F_c	2000	2500	−2.2064*	0.27897	<0.001	−2.8637	−1.5491
		3000	−3.7687*	0.27897	<0.001	−4.4259	−3.1114
	2500	2000	2.2064*	0.27897	<0.001	1.5491	2.8637
		3000	−1.5623*	0.27897	<0.001	−2.2195	−0.9050
	3000	2000	3.7687*	0.27897	<0.001	3.1114	4.4259
		2500	1.5623*	0.27897	<0.001	0.9050	2.2195
F_t	2000	2500	−2.1094*	0.27690	<0.001	−2.7618	−1.4570
		3000	−3.3713*	0.27690	<0.001	−4.0236	−2.7189
	2500	2000	2.1094*	0.27690	<0.001	1.4570	2.7618
		3000	−1.2619*	0.27690	<0.001	−1.9142	−0.6095
	3000	2000	3.3713*	0.27690	<0.001	2.7189	4.0236
		2500	1.2619*	0.27690	<0.001	0.6095	19142

**The mean difference is significant at the, 05 level.*

Table 8.
Statistical analysis of C_f of natural rocks depending on the d_p and V_a.

Figure 8 shows that there is a statistically significant relationship between S_c and C_f values. Correlation coefficient (R^2) values obtained from the natural rocks in the F_c at depths of cut of 1.2, 1.6 and 2.0 mm are 0.895, 0.871 and 0.859, respectively. Correlation coefficient (R^2) values obtained from the natural rocks in the F_t at depths of cut of 1.2, 1.6 and 2.0 mm are 0.890, 0.878 and 0.880, respectively. Correlation coefficient (R^2) values obtained from the natural rocks in the F_c at the V_a of 2000, 2500 and 3000 mm/min are 0.771, 0.780 and 0.780, respectively. Correlation coefficient (R^2) values obtained from the natural rocks in the F_t at the V_a of 2000, 2500 and 3000 mm/min are 0.745, 0.781 and 0.781, respectively.

3.5 Relationships between specific cutting energy and specific energy

The results of the correlation coefficient and regression model are given in **Figure 9**. Correlation coefficient (R^2) obtained from the natural rocks is 0.784, indicating that there is a linear relationship between the S_c and S_e.

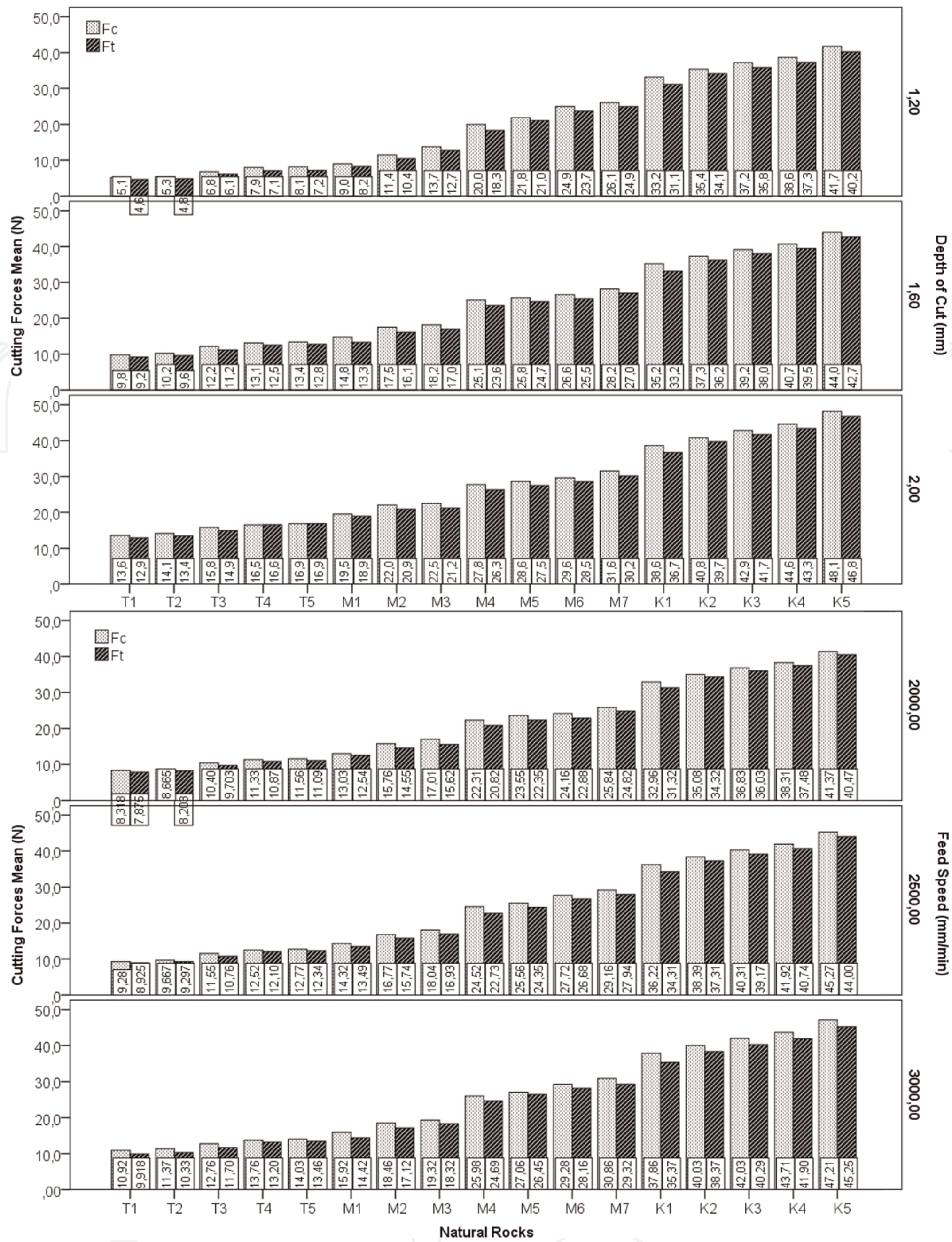

Figure 6.
C_f according to the d_p and V_a in natural rocks.

3.6 Relationships between cutting forces, specific cutting energy and specific energy natural rocks properties

The relation between the F_c, F_t, S_c and S_e values, and the physico-mechanical properties of the natural stones were evaluated through regression analysis. The results of the regression analysis are given in **Tables 10** and **11**, respectively.

Correlation coefficient (R^2) values of the natural rock samples, a linear relationship between the C_f values and the physicomechanical characteristics is observed. As a result of the analysis, the following correlation coefficient (R^2) values have been obtained: R^2 coefficient range from 0.887 to 0.981 in the F_c and from 0.883 to 0.983 in the F_t. All values confirm the linear relationship among physicomechanical properties in natural rocks with the C_f. Accordingly, as porosity, water absorption and abrasion strength decrease in the natural rocks, C_f values increases. Moreover,

S_c and S_e dependent variable	d_p (mm)		Mean difference (I-J)	Std. Error	Sig.	95% confidence interval	
	Mean (I)	Mean (J)				Lower bound	Upper bound
S_c	1.20	1.60	72898*	0.70556	<0.001	56.275	89.521
		2.00	10.9091*	0.70556	<0.001	92.468	12.5714
	1.60	1.20	−72898*	0.70556	<0.001	−89.521	−56.275
		2.00	36193*	0.70556	<0.001	19.569	52.816
	2.00	1.20	−10.9091*	0.70556	<0.001	−12.5714	−92.468
		1.60	−36193*	0.70556	<0.001	−52.816	−19.569
V_a(mm/dk)							
S_c	2000	2500	45448*	0.70556	<0.001	28.825	62.071
		3000	95051*	0.70556	<0.001	78.427	11.1674
	2500	2000	−45448*	0.70556	<0.001	−62.071	−28.825
		3000	49603*	0.70556	<0.001	32.980	66.226
	3000	2000	−95051*	0.70556	<0.001	−11.1674	−78.427
		2500	−49603*	0.70556	<0.001	−66.226	−32.980
S_e	1.20	1.60	14500*	0.02103	<0.001	14.004	14.996
		2.00	23077*	0.02103	<0.001	22.582	23.573
	1.60	1.20	−14500*	0.02103	<0.001	−14.996	−14.004
		2.00	.8577*	0.02103	<0.001	.8082	0.9073
	2.00	1.20	−23077*	0.02103	<0.001	−23.573	−22.582
		1.60	−0.8577*	0.02103	<0.001	−0.9073	−0.8082
V_a(mm/dk)							
S_e	2000	2500	0.6747*	0.02103	<0.001	0.6252	0.7243
		3000	11701*	0.02103	<0.001	11.205	12.197
	2500	2000	−0.6747*	0.02103	<0.001	−0.7243	−0.6252
		3000	0.4954*	0.02103	<0.001	0.4458	0.5449
	3000	2000	−11701*	0.02103	<0.001	−12.197	−11.205
		2500	−0.4954*	0.02103	<0.001	−0.5449	−0.4458

**The mean difference is significant at the, 05 level.*

Table 9.
Statistical analysis of S_c and S_e of natural rocks depending on the d_p and V_a.

as knoop hardness, uniaxial compressive strength, flexural strength and impact strength increase, the C_f values also increase.

Correlation coefficient (R^2) values of the natural rock samples, a linear relationship between the S_c and S_e values and the physicomechanical characteristics is observed. As a result of the analysis, the following correlation coefficient (R^2) values have been obtained: R^2 coefficient range from 0.887 to 0.977 in S_c and from 0.616 to 0.858 in the S_e. All values confirm the linear relationship among physicomechanical characteristics in natural rocks with the S_c and S_e. Accordingly, as porosity, water absorption and abrasion strength decrease in the natural rocks, S_c and S_e value increases. Moreover, as Knoop hardness, uniaxial compressive strength, flexural strength and impact strength increase, the S_c and S_e values also increases.

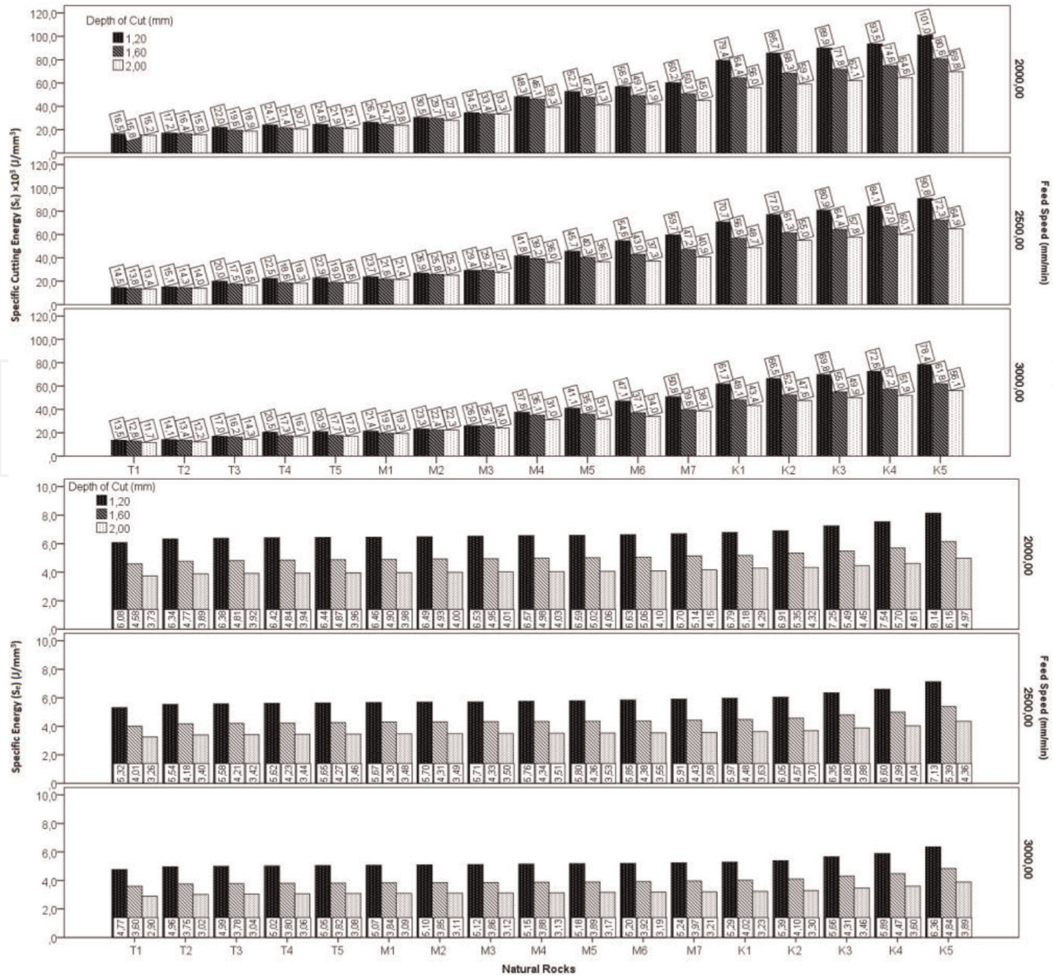

Figure 7.
S_c and S_e values according to the d_p in processability tests of rocks.

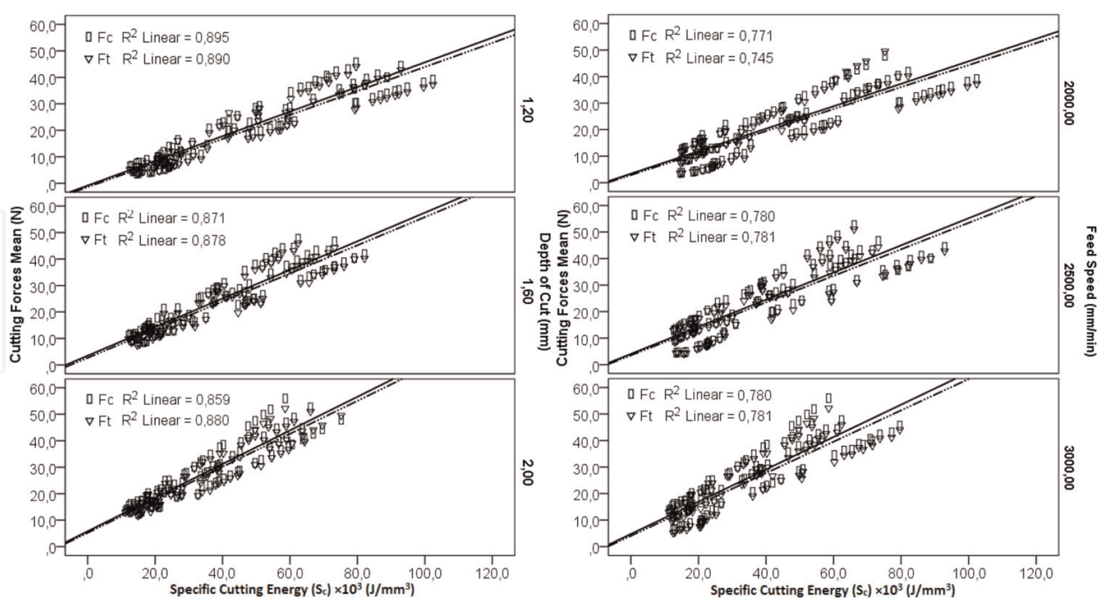

Figure 8.
Relationship between the C_f of natural rocks and S_c according to cutting depth and feed speed.

Proper selection and performance estimation of mill cutting tools are important factors in improving the efficiency of processability and decrease costs in natural rocks. Performance cutting parameters and 3D design of mill cutting tools are cutting tool diameter, d_p, V_a, F_c, and F_t, S_c and S_e. A contribution was made to the literature by proposing new correlation coefficients (R^2) for natural rocks.

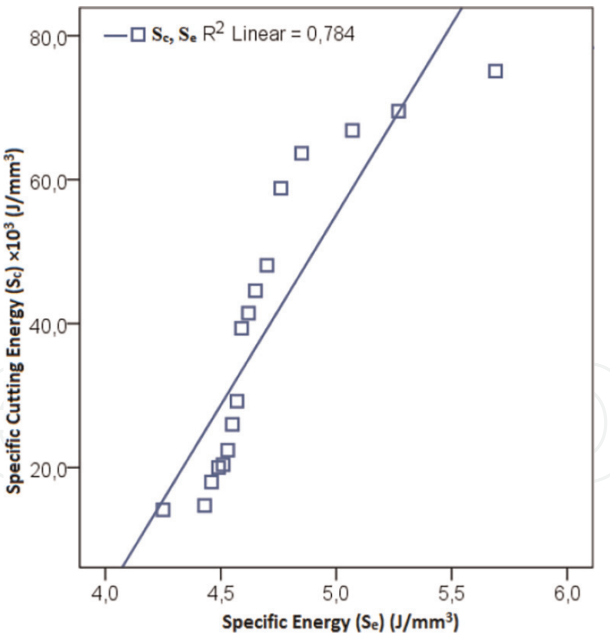

Figure 9.
Relationship between the S_c and S_e of natural rocks.

Independents/ C_f	Dependents/physico-mechanical properties	Custom equation	R^2 Linear Model
F_c	D	y = 3.506 * x + 2625.962	0.931
	P	y = −0.035 * x + 1.595	0.923
	WA	y = −0.031 * x + 1.356	0.887
	KH	y = 1.982 * x + 99.007	0.976
	UCS	y = 1.842 * x + 53.365	0.981
	FS	y = 0.244 * x + 5.129	0.889
	IS	y = 0.547 * x + 14.612	0.968
	AR	y = −0.245 * x + 25.189	0.932
F_t	D	y = 3.588* x + 2627.838	0.930
	P	y = −0.035 * x + 1.575	0.919
	WA	y = −0.031 * x + 1.338	0.883
	KH	y = 2.030 * x + 100.026	0.978
	UCS	y = 1.217 * x + 42.861	0.983
	FS	y = 0.251 * x + 5.237	0.896
	IS	y = 0.560 * x + 14.902	0.968
	AR	y = −0.251 * x + 25.047	0.928

Table 10.
Relationships between F_c and F_t cutting forces natural rock properties.

Independents/S_c and S_e	Dependents/physico-mechanical properties	Custom equation	R^2 linear model
S_c	D	y = 2.017* x + 2630.804	0.929
	P	y = −0.020*x + 1.547	0.922
	WA	y = −0.017 * x + 1.314	0.887
	KH	y = 1.142 * x + 101.696	0.977
	UCS	y = 0.684 * x + 43.858	0.983
	FS	y = 0.140 * x + 5.456	0.892
	IS	y = 0.315 * x + 15.357	0.968
	AR	y = −0.141 * x + 24.845	0.929
S_e	D	y = 115.7 * x + 2166.149	0.858
	P	y = −1.032 * x + 5.610	0.686
	WA	y = −0.883 * x + 4.766	0.616
	KH	y = 63.347 * x + −151.219	0.844
	UCS	y = 37.511 * x + −105.578	0.829
	FS	y = 8.647 * x + −29.663	0.944
	IS	y = 17.500 * x + −54.520	0.837
	AR	y = −7.476 * x + 54.445	0.732

Table 11.
Relationships between S_c and S_e natural rock properties.

4. Conclusion

The rocks in this study were determined according to by taking into account the C_f, S_c and S_e. value in accordance with the statistical analyses. C_f, S_c and S_e values vary depending on the d_p and V_a used in natural rocks. Results of the experimental study are summarized below:

- F_c and F_t values are high at the d_p of 2.0 mm and V_a of 3.000 mm/min.
- S_c and S_e, values are high at the d_p of 1.2 mm and V_a of 2.000 mm/min.
- Due to the increased friction force due to the increase in the amount of natural rock chips to be cut by the cutter edge at the d_p of 2.0 mm, the processability is most difficult.
- The cutting parameters with the highest specific energy volume are considered to be the toughest moments of the CNC machine.
- The values of S_c and S_e are reduced and the efficiency increases with an increase in the d_p which results from the increase in the cutting edge of the

chip volume in natural rocks. S_c and S_e are significantly increased at the d_p of 1.2 mm.

- There is a significant relationship between C_f, S_c and S_e depending on the d_p and V_a, the correlation coefficient (R^2) values of which are 0.859 to 0.895, and 0.745 to 0.781 respectively.

- A significant relationship between the S_c and S_e was identified as R^2 (0.784).

- There is a significant relationship between the C_f and physicomechanical properties. R^2 ranges from 0.887 to 0.981 in the Fc and from 0.883 to 0.983 in the F_t.

- There is a significant relationship between the S_c, S_e, and physicomechanical properties. R^2 ranges from 0.887 to 0.983 in the S_c and from 0.616 to 0.944 in the S_e.

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