RESEARCH ARTICLE

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Investigation of the Relationship Between Texture Coefficient and Electrical Current Consumption of the Cutting Machine with Different Lubricants and Cooling Fluids

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Abstract: Texture coefficient (TC) is one of the most effective physical factors in evaluating the engineering characteristics of rocks in various projects, such as drilling, cutting, and advanced rate of full-face drilling machines. Evaluation of electricity consumption by disc-cutting machines is critical for monitoring and reducing expenses in the stone processing industry. In this study, the relationship between the textural characteristics of the rocks and the amount of electrical current consumed by the cutting machine in cutting hard stones was evaluated. For this purpose, ten samples of hard rock were investigated. For each rock sample, a microscopic slice was prepared. Then, five digital images were taken using the microscope from each division, and the values of textural characteristics, including area, perimeter, largest diameter, and most minor diameter of all grains in each embodiment, were determined. Then, the TC of all studied stone samples was computed based on the determined specifications. Finally, the relationship between the TC and the rate of electrical current consumed by the cutting machine was investigated using statistical models. The results revealed that although the electric current used by the cutting machine decreased when the TC increased in some samples, no significant relationship between the TC and the amount of electric current used by the cutting machine was observed for hard stone samples. It was also found that the impact of lubricant type on the cutting machine performance is negligible.

Keywords: electrical current consumption, cutting machine, texture coefficient, hard rock

1. Introduction

Many studies have been conducted on the efficiency of stone cutting machines considering different physical and mechanical rock characteristics. A summary of these studies can be found in Table 1. Most of these studies have been performed on disc cutting and diamond cutting wire machines. According to Table 1, the uniaxial compressive strength, Brazilian tensile strength, hardness, quartz content, and abrasion parameters have been extensively used in prior studies. Reduced energy usage is one factor influencing the cutting machine's efficiency. Therefore, the machine's energy consumption may be significantly decreased by thoroughly understanding the rock cutting process.

Different qualitative and quantitative methods exist for diagnosing and explaining rock texture in mineralogy and petrology texts (Kamani & Ajalloeian, 2019). Qualitative descriptions of rock texture-related engineering works cannot be beneficial because the geometrical characteristics of grains or particles and crystals of rocks are usually included in the texture of rocks (McKee & Ward, 1983). Therefore, engineers have always tried to quantify the textural properties of rocks. For instance, the parameters of the perimeter, area, largest, and smallest diameter are required for the quantitative surface description. On the other hand, the effect of different cooling

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fluids/lubricants on the performance of the cutting machines is not fully understood. Therefore, a comprehensive investigation is required to quantify the rock texture based on the foregoing parameters and, more importantly, reveal the correlation between the performance of the cutting machine and rock texture with different fluids. In this regard, the current study investigates the relationship between the textural characteristics of hard building stones and the current consumption of disc-cutting machines in various operating settings and with four lubricating fluids. For this purpose, statistical analyses are performed after field and laboratory studies to evaluate the relationship between these factors.

Table 1
Summary of studies on the performance of stone cutting machines

Researchers and Year	Physical and mechanical characteristics										
	UCS	BTS	YM	IS	SS	BS	H	A	D	Gs	Qc
Burgess and Birle (1978)										•	•
Wright and Cassapi (1985)	•	•					•	•			•
Birle and Ratterman (1986)							•				
Jenning and Wright (1989)	•	•					•				•
Clausen et al. (1996)										•	•
Wei et al. (2003)	•						•	•			•
Ersoy and Atici (2004)	•	•	•	•	•	•	•	•	•	•	•
Gunaydin et al. (2004)	•	•		•							
Buyuksagis and Goktan (2005)	•	•					•	•			•
Ersoy et al. (2005)	•	•	•	•	•	•		•	•		•
Sanchez Delgado et al. (2005)							•				•
Kahraman et al. (2007)	•	•							•		•
Tutmez et al. (2007)	•	•		•			•	•			
Buyuksagis (2007)	•	•				•	•	•	•		•
Kahraman and Gunaydin (2008)							•		•		
Yurdakul and Akdas (2012)	•	•				•	•	•	•		
Tumac (2015)							•	•			
Tumac (2016)	•	•						•	•		
Aryafar et al. (2018)	•	•	•				•	•		•	•
Tumac et al. (2018)	•	•		•			•		•		
Zhang et al. (2018)						•	•		•		
Haghshenas et al. (2019)	•	•	•				•	•		•	•
Hosseini, Ataei, Khalokakaei, and Mikaeil (2020)	•	•	•				•	•		•	•
Hosseini, Ataei, Khalokakaei, Mikaeil et al. (2020)	•	•	•				•	•		•	•
Rasti et al. (2021)	•						•	•		•	
Bahri et al. (2021)	•	•					•		•		
Mikaeil et al. (2022)	•	•	•				•	•		•	•
Frequency of the used parameter (%)	74	67	26	19	7	19	78	59	37	33	59

UCS: Uniaxial compressive strength; BTS: Brazilian tensile strength; YM: Young's modulus; IS: Impact strength; SS: Shear strength; BS: Bending strength; H: Hardness; A: Abrasivity; D: Density; Gs: Grain size; Qc: Quartz content.

2. Texture Coefficient

Texture plays a critical role in the engineering behavior of rocks in different applications, such as drilling and boring machines, building stone cutting machines, and fully mechanized tunnel drilling machines. The texture is one of the intrinsic properties of a rock, explained qualitatively based on the size, shape, and amount of cement. In conventional engineering applications, based on the size and shape of the grains, generally, there are four distinct classes of rock texture: grainy, porphyry, glassy, and destructive. The most characteristic texture in this classification is the granular texture, which in igneous rocks, according to the grain size, has several subcategories: very large (grain size > 10 mm), large (grain size: 5–10 mm), average (grain size: 2–5 mm)mm, fine (grain size: 0.25–2 mm), and very fine (grain size: <0.25 mm) (Howarth & Rowlands, 1987). Functional parameters in rock texture evaluation include area, perimeter, largest and smallest diameter, equal diameter, compaction, shape factor (SF), grain condition ratio, locking index, and grain uniformity index. The area is considered the most specific parameter in evaluating the texture of rocks. In other words, it is equivalent to the thin section's average grain surface area. The grain perimeter indicates the length of the grain boundary in the rocks. The largest and smallest diameter is among the quantitative texture parameters widely used. Larger and smaller diameters are two of the most often utilized quantitative texture characteristics, the mathematical combination of which is geometrically representational of different qualities of grains and rock texture. The equal diameter (D_{equi}) indicates the average grain size of the rock, which can be computed based on equation 1 (Haghshenas et al., 2019).

$$D_{equi} = \sqrt{\frac{4A_i}{\pi}} \quad (1)$$

where Ai shows the area of grain (mm^2).

Compactness indicates the compaction in the cross-sectional shape of the grains. The general state of the reduction concept is defined as "grain shape in the state of transition and conversion from closed line to linear state." Equation 2 is used to calculate compactness (C):

$$C = \frac{L_P^2}{A_i} \quad (2)$$

where L_p represents the perimeter of grain (mm). The *SF* indicates the roundness of the rock grains. This parameter is directly associated with the grain level and inversely related to the grain perimeter. The *SF* can be computed based on equation 3.

$$SF = \frac{4\pi A_i}{L_P^2} \quad (3)$$

The grain conditions ratio (AR) is determined by dividing the largest grain diameter by its most minor diameter. Based on the geometric characteristics of an ellipse and the definition of AR, it can be inferred that this index is an appropriate criterion for evaluating the ovality of rock grains. Equation 4 is used to calculate this index.

$$AR = \frac{D_{\max}}{D_{\min}} \quad (4)$$

where $D_{\max}$ and $D_{\min}$ represent maximum and minimum diameter (mm), respectively.

The locking index (g) has been proposed to express the degree of complexity of the grain-to-grain relationship in the structure and texture of rocks (Hosseini et al., 2020). This parameter compares the amount of grain area and the part of the grain boundary in contact with the adjacent grain. An increase in the index increases the complexity of the grain relationship, which is generally obtained from equation 5.

$$g = \frac{1}{n}\sum \frac{L_{Pi}}{\sqrt{A_i}} \quad (5)$$

where n is the number of grains. The particle size uniformity index (t) indicates the particle size distribution in the rock texture, which is generally obtained from the following equation:

$$t = \frac{A_{ave}}{\sqrt{\sum (A_i - A_{ave})^2}} \quad (6)$$

where A_{ave} represents the average area of the grains (mm^2). Based on the above parameters, one of the essential textural characteristics of the stone, that is, the texture coefficient (TC), can be calculated as follows (Hosseini et al., 2020):

$$TC = AW\left[\left\{\frac{N_0}{N_0 + N_1} \times \frac{1}{FF_0}\right\} + \left\{\frac{N_0}{N_0 + N_1} \times AR_1 \times AF_1\right\}\right] \quad (7)$$

where AW is the area weight or grain density, which can be calculated using the following equation:

$$AW = \frac{Total\ Area}{Complete\ Grain\ Area} \quad (8)$$

$\boldsymbol{N_0}$: The number of grains whose ratio of large diameter to small diameter is less than 2.

$\boldsymbol{N_1}$: The number of grains whose ratio of large diameter to small diameter is greater than 2.

$\mathbf{FF_0}$: Geometric mean for all grains with a large to small diameter ratio of less than 2.

$\mathbf{AF_1}$: Geometric mean for all grains with large to small diameter ratios greater than 2.

$\mathbf{AR_1}$: This parameter is used to load grains whose ratio of large diameter to small diameter is greater than 2. All the available angles for the large diameter of the horizon surface must be determined. In this regard, the angle (orientation) factor (AF) is calculated based on equation 9.

$$AF = \sum_{i=1}^{n}\left[\frac{X_i}{\frac{N(N-1)}{2}}\right] \quad (9)$$

where N is the number of elongated grains and X_i is the number of different angles in each class, which is determined according to Table 2.

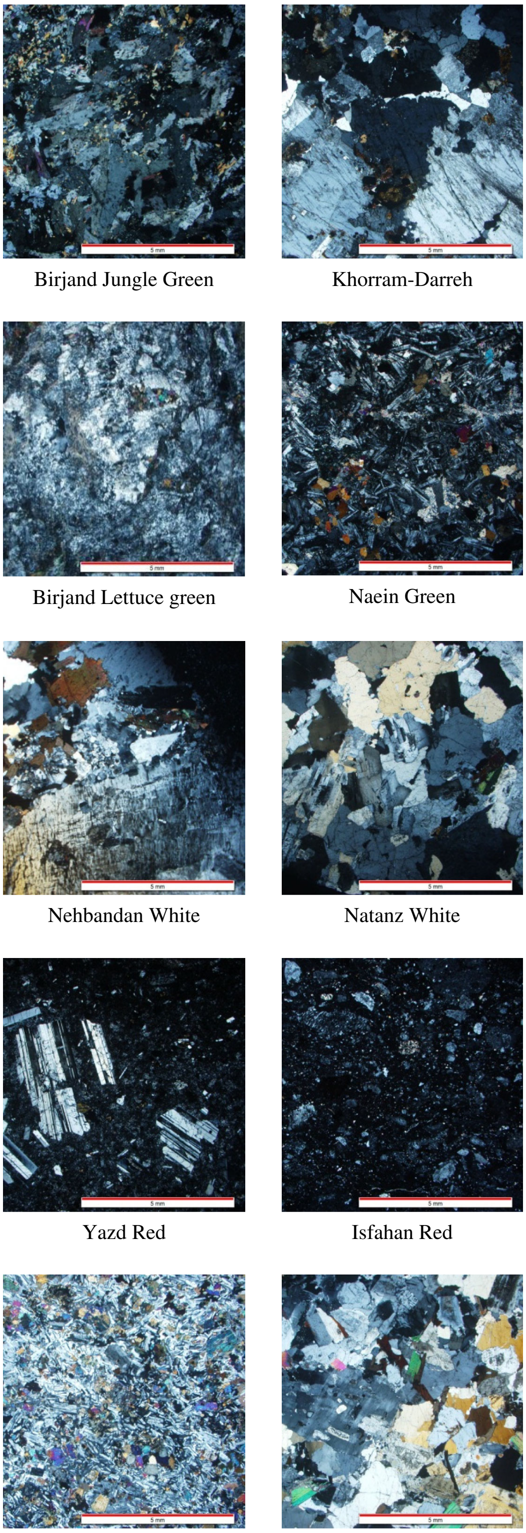
Table 2
X_i values for different angle domains

No.	Angle domain	Weight (i)	X_i	(X_i * i)
1	Lesser than 10	1	9	9
2	Between 10 and 20	2	19	38
3	Between 20 and 30	3	11	33
4	Between 30 and 40	4	8	32
5	Between 40 and 50	5	15	75
6	Between 50 and 60	6	10	60
7	Between 60 and 70	7	10	70
8	Between 70 and 80	8	10	80
9	Between 80 and 90	9	20	180

3. Laboratory Study

The experimental tests were performed to assess the relationship between the cutting machine's energy consumption rate and the textural features of hard rock samples. Firstly, ten samples of different granite, including Khorram Dareh granite, Birjand jungle green, Nain green, Birjand lettuce green, Natanz white, Nehbandan white, Isfahan and Yazd red, Mashhad pearl, and black Chayan, in 30 cm × 30 cm × 30 cm dimensions were extracted from the studied mines. The samples were then sent to the thin section laboratory in plastic bags for interpretation and texture analysis. Then, four sections were prepared from each sample, and digital images of the desired areas were taken. Figure 1 displays the photographs of the studied rock samples taken during the thin section analysis. To determine the textural characteristics, the images were digitized in AutoCAD software. After grading the grains, the parameters of the total number of grains, area, perimeter, most extensive, and smallest diameter, equivalent diameter, compaction, SFr, grain condition ratio,

Figure 1
Thin sections prepared for the studied rock samples



locking, and uniformity index were determined. Finally, the TC was calculated using equation 7. Table 3 lists the textural features of the studied rock samples.

Table 3
Textural characteristics of the studied rock samples

Rock type	Total number of grains	Mean area	Mean perimeter	Largest diameter	Smallest diameter	Equivalent diameter	Compression index	Shape factor	Grain condition ratio	Locking index	Uniformity index	TC
Khorram-Darreh	122	769,680.69	3,758.71	1.117	0.458	990.194	18.356	0.684	2.438	5.185	0.043	3.664
Birjand Jungle Green	95	385,471.94	3,135.946	0.9619	0.358	700.748	25.512	0.492	2.688	5.428	0.079	3.515
Nain Green	138	265,422.25	2,344.547	0.8114	0.343	581.479	20.71	0.606	2.364	4.968	0.075	2.36
Birjand Lettuce green	93	98,406.017	1,438.345	0.4549	0.192	354.059	21.023	0.597	2.366	5.123	0.087	3.591
Natanz White	67	1,394,921.7	5,718.169	1.7635	0.78	1333.03	23.44	0.536	2.261	5.259	0.078	4.951
Nehbandan White	84	435,272.11	3,118.144	0.9667	0.394	744.639	22.337	0.562	2.453	5.281	0.073	5.192
Isfahan Red	33	44,259.885	869.3528	0.2568	0.102	237.449	17.076	0.736	2.513	4.995	0.093	5.405
Yazd Red	34	269,474.68	2,346.464	0.6629	0.288	585.901	20.432	0.615	2.301	5.012	0.157	3.096
Mashhad Pearl	135	692,709.11	3,653.082	1.1655	0.518	939.379	19.265	0.652	2.252	5.017	4E-09	6.604
Chayan Black	226	40,529.977	919.595	0.293	0.133	227.224	20.865	0.602	2.207	5.022	0.047	8.947

4. Relationship Between TC and Cutting Machine Performance

In this section, the performance of the cutting process was assessed considering four cooling and lubricating fluids. To do so, the stone plates were prepared, as shown in Figure 2. The most important task is to construct a fluid reservoir and a disc-scale device for cutting discs to record and measure the intensity of current consumption and select the appropriate cooling fluid and lubricant with individual specifications. Figure 3 indicates an example of a disc cutter with a coolant and lubricant supply tank used in this study. During laboratory studies, four cooling and lubricating fluids, including water, water mill powder, and soap water with a ratio of 1 to 40 and 1 to 20, were used. The general characteristics of the four fluids studied are listed in Table 4.

The results of laboratory tests were evaluated based on the maximum and minimum cutting depth and advance rate. Thus, the current consumption of the cutting machine was measured and recorded with cutting depths of 13 mm and 5 mm, and advance rates of 90 and 45 cm/s for all four fluids studied. Tables 5 and 6

Figure 3
View of a laboratory-scale disc cutter

Figure 2
Sample plates prepared for cutting tests

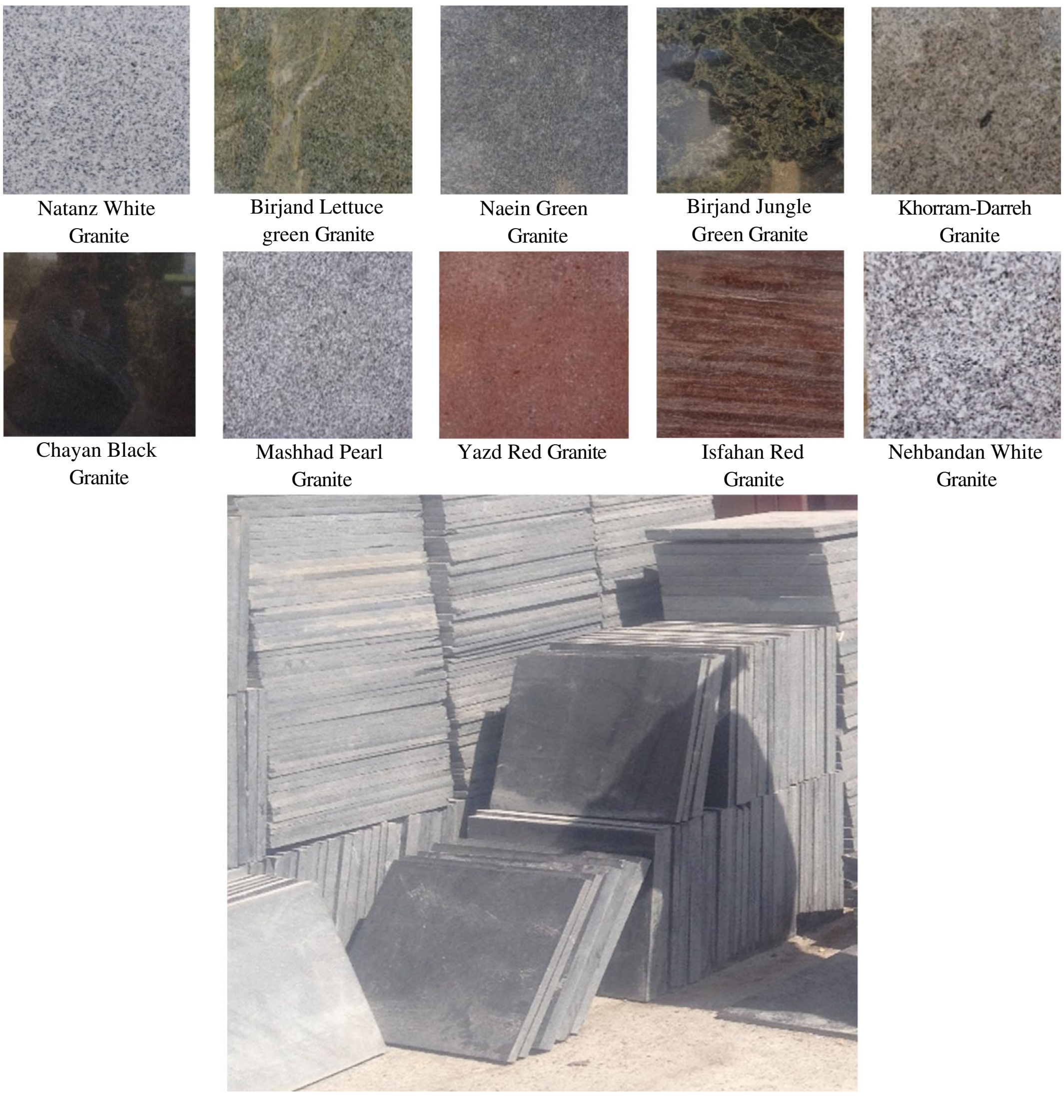


Table 4
General specifications of the used lubricants

Viscosity (mPa·s)	Hardness (PH)	Fluid	Fluid ID
1.069	7.88	Water	F1
1.839	7.96	Watermill powder	F2
0.9851	7.87	Soap water with a rate of 1/40	F3
0.9754	8.23	Soap water with a rate of 1/20	F4

Table 5
The electrical current consumption of cutting machine consumption in terms of maximum operating parameters

Rock type	Tc	Imax with different fluids			
		F_1	F_2	F_3	F_4
Khorram-Darreh	3.66	8.6	7.9	7.6	8
Birjand Jungle Green	3.51	13.8	9.6	9.5	6.4
Nain Green	2.36	10.9	8.6	9.2	8.8
Birjand Lettuce green	3.59	12.3	8.3	8.5	11.7
Natanz White	4.95	9.7	7.2	7.5	9.3
Nehbandan White	5.19	9.6	7.7	7.2	9.8
Isfahan Red	5.40	9.1	8.1	8.7	9.1
Yazd Red	3.10	9.3	8.9	8.5	10.1
Mashhad Pearl	6.60	9.5	7.3	7.9	7.8
Chayan Black	8.95	8.8	8.2	8.1	8.5

summarize the obtained results from the conducted tests. According to these tables, no significant trend can be observed for the current intensity of the machine at maximum and minimum operating conditions for all fluids used. Figures 4 and 5 show the trend of changes in the current intensity of the cutting machine. By further examining these results and changes in maximum operating conditions, it could be shown that it is possible to reduce the cutting machine's electrical current consumption (Imax) by increasing the amount of rock texture in some samples. These changes are more evident when using only water as a lubricant. The changes are also close to their minimum value for other lubricants. Although this study tried to use enough samples; however, more samples with a wider range of strength values can still be tested in future studies to better represent the findings of the current study.

5. Conclusion

One of the most important aspects of the dimension stone industry is the development of ever-more-efficient stone processing plants. Therefore, it is essential to have a firm grasp of the cutting process and the elements that affect it. Rock TC is one of rock's most influential physical parameters in evaluating and predicting rock engineering characteristics, including drilling rate, shear rate, advance rate of full-section drilling rigs, etc. Determining the current consumption of disc-cutting machines is

Table 6
The electrical current consumption of cutting machine consumption in terms of minimum operating parameters

Rock type	Tc	Imax with different fluids			
		F_1	F_2	F_3	F_4
Khorram-Darreh	3.66	5.7	5.5	5.7	5.2
Birjand Jungle Green	3.51	5.7	5.6	5.3	5
Nain Green	2.36	6.8	5.7	5.4	5.8
Birjand Lettuce green	3.59	6.5	5.3	5.3	5.7
Natanz White	4.95	5.7	5.5	5.1	5.3
Nehbandan White	5.19	5.5	5.4	4.9	5.4
Isfahan Red	5.40	5.8	5.4	5.5	5.1
Yazd Red	3.10	5.7	5.8	5.2	5.6
Mashhad Pearl	6.60	7.1	5.3	5.2	5
Chayan Black	8.95	6.1	5.4	5.6	5.4

Figure 4
Changes in the electrical current consumption of cutting machine with texture coefficient under maximum operating parameters

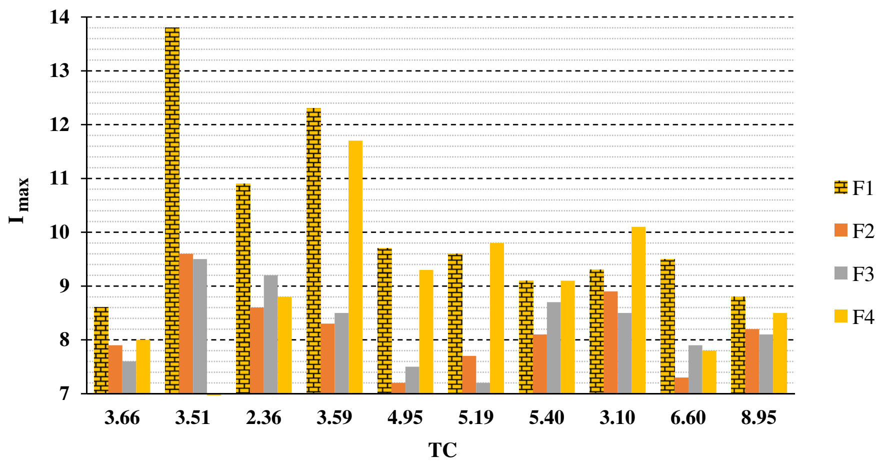
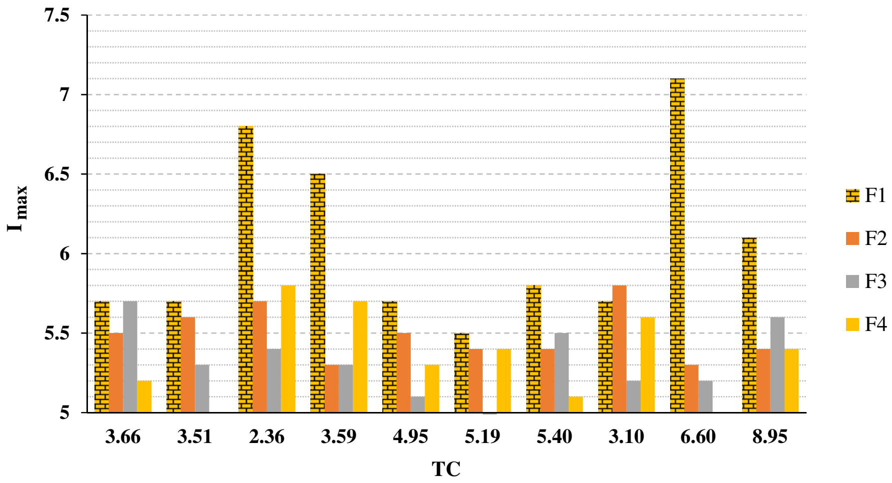


Figure 5
Changes in the electrical current consumption of cutting machine with texture coefficient under minimum operating parameters



one of the most critical factors in estimating cutting costs in the stone processing industry. In this study, the relationship between the textural characteristics of the stone and the amount of electrical current consumed by the cutting machine when cutting hard rocks using different cooling and lubricating fluids. The laboratory study was conducted on ten samples of hard rock in maximum and minimum operating conditions with cutting depths of 13 mm and 5 mm and advance rates of 90 cm and 45 cm per second. It was found that lubricating fluid has no significant effect on electrical current consumption. This was more evident in the minimum operating conditions for all used lubricants. Changes under maximum operating conditions showed a decreasing trend in the current power of the cutting machine with an increasing amount of TC in some samples. The changes were more significant when using water lubricant fluid because, with the addition of lubricants, the pitch of these changes is close to its minimum value. For future studies, it is recommended to perform the tests for a higher number of samples with different strength values and using more lubricants.

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Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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