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EFFECT OF SAWING RATE ON FORCE AND ENERGY REQUIREMENTS IN THE CIRCULAR SAWING OF GRANITES

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ABSTRACT: *In the stone processing industry, sawing rate and sawblade life are the main parameters economically affecting the process. However, the relative importance ranking of these parameters may vary depending on the needs and priorities of the plant. In this study, utilizing a fully instrumented circular side-cutting machine, the effect of sawing rate on force and energy requirements of two selected granite types were investigated. It was concluded that, when it is intended to achieve higher sawing rates, employing a higher feed velocity and a shallower cutting depth improves the efficiency of the process in terms of cutting forces, power and specific energy. However, the magnitude of this improvement varies according to the mineralogical properties of the tested rock.*
Keywords: *Sawing Rate, Specific Energy, Circular Saw, Granite.*

GRANİTLERİN DAİRESEL TESTERELERLE KESİLMESİNDE KESME HIZININ KUVVET VE ENERJİ GEREKSİNİMLERİ ÜZERİNDEKİ ETKİLERİ

ÖZET: *Doğal taş sektöründe, kesme hızı ve testere ömrü kesme işleminin ekonomikliği üzerinde rol oynayan başlıca parametrelerdir. Bununla birlikte, bu parametrelerin taşıdığı önem sırası, tesisin gereksinimleri ve öncelikleri tarafından belirlenmektedir. Bu çalışmada, bilgisayar tabanlı bir yan-kesme makinası kullanılarak, kesme hızının kuvvet ve enerji gereksinimleri üzerindeki etkileri iki farklı granit örneği üzerinde incelenmiştir. Sonuç olarak, kesme hızının arttırılması hedeflendiğinde, kesme derinliğinin azaltılıp ilerleme hızının arttırılması şeklindeki bir uygulamanın kesme kuvvetleri, güç tüketimi ve özgül enerji gereksinimleri üzerinde daha olumlu bir rol oynadığı görülmüştür. Bununla birlikte, elde edilen bu avantajın büyüklüğü kesimi yapılan taşın mineralojik özelliklerine bağlı olarak farklılıklar göstermektedir.*
***Anahtar kelimeler*:** *Kesme Hızı, Özgül Enerji, Dairesel Testere, Granit.*

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I. INTRODUCTION

There is a growing use of granite as a construction and decorative material due to its high abrasive resistance, resistance to environmental influences, and aesthetic properties. However, mainly due its relatively high abrasivity and hardness, the processing productivity of granite is far less than that of other natural stones such as marble, travertine and limestone. Hence, for improving production efficiency and reducing the costs, there is a need for a better understanding of the influence of various process parameters in the sawing of granites.

Processing of granites and other natural stones by using circular diamond sawblades has a wide field of application in the stone industry. However, processing of stone by diamond segmented circular sawblades is a multidimensional problem of great complexity [1]. The sawing performance of a circular sawblade is influenced by a variety of operational parameters (cutting depth, sawblade peripheral speed, feed rate, cutting mode, blade specifications, coolant flow rate etc.), as well as by the properties of the sawn stone (abrasivity, mechanical strength, mineralogical and petrographic properties, etc.). Due to the complexity mentioned above, various aspects of circular sawing of granites have been investigated in the literature. These topics include the analysis of sawblade wear [1 - 10], cutting forces and energy [2, 6, 8, 11-14], effect of coolants [15], sawability classification [16, 17], effect of diamond grit type and concentration [18], effect of granite micro-hardness [19], bond specification [20], and effect of cutting mode [21].

In practical applications, the sawing of natural stones may be performed in a series of relatively shallow cuts (step cutting) or in one deep cut (single-pass cutting). Step cutting is generally applied in hard stone such as granite, while single-pass cuts are mainly used when sawing softer stones. Single-pass cutting avoids the constant alteration of down and up-cutting, which can have an adverse effect on blade life [4]. However, in a continuous operation of granite processing which employ single-pass cutting, cutting depths greater than approximately 25 mm are not desired due to thermal and mechanical overloading of the sawblade [22]. Another advantage of single-pass cutting is that, if sufficiently deep cuts can be realized, higher sawing rates can be achieved. Consequently, an increased sawing rate reduces the labor costs, as the production time per unit cut material is reduced. Considering the benefits to be gained, many attempts are being made to obtain fundamental information about single-pass deep cutting of granite [22].

This work was undertaken to analyze the cutting forces and power requirements during single-pass cutting of granites under varying sawing rates. To achieve this goal, force and power measurements were made at different levels of cutting depth and feed velocity to achieve sawing rates of 100, 150 and 200 cm^2/min. Two granite types having diverse mechanical strength and mineralogical characteristics were selected as the workpiece materials. Finally, basing on the obtained experimental data, the effect of sawing rate on cutting forces, power and specific energy were analyzed.

II. EXPERIMENTAL PROCEDURES

Circular sawing tests were performed on a high-precision fully instrumented experimental side-cutting machine. The experimental-set up consists of three main units. These are the sawing unit, instrumentation, and personal computer. The sawblade motor is controlled by a 5.5 kW invertor, and the spindle speed can be adjusted between 0 – 4000 rev/min. The horizontal feed rate of the workpiece is controlled by a 0.50 kW Siemens invertor, between 0-4 m/min. The rig has also two 0.50 kW motors to facilitate sawblade movements up-down in the vertical plane and forward-backward in the horizontal plane. Energy consumption of sawblade motor is measured by a three-phase energy analyzer (Shark 100). Forces acting on the sawblade during any sawing operation are measured by a loadcell (Esit PWI-P). The outputs of the energy analyzer and the loadcell are fed into a 24 bytes A/D converter and sampled at high frequency by a PC. The flow rate of cooling water fed during any sawing test is controlled by a 0.50 kW motor. In order to control the main units of the experimental set-up, and also to facilitate recording of the experimental data, a Pentium II PC of 160 MHz with specially developed software is used. An industrial I/Q card, Advantech PCI-1716, is used for the main data gathering system. Full details of the experimental rig can be found in [23].

The diamond segmented sawblade used in the sawing experiments was of 400 mm diameter, commercially recommended for the sawing of granitic rocks. The sawblade consisted 24 segments (3.20 mm width, 40 mm length, and 9 mm height). The diamonds (SDA 85 type) were sized at 40/50 US mesh with a 20 concentration (a 100 concentration equals 4.4 carats of diamonds per cubic centimeter of matrix volume). Tap water was used as the cooling fluid at a flow rate of 15-20 l/min. Considering the commonly used industrial range of process parameters for granites, the peripheral speed of the sawblade was kept at 30 m/s throughout the tests. At the beginning of a new series of tests (e.g. before changing the cutting depth or the feed velocity), the sawblade was dressed by sawing a specially prepared concrete block.

Two commercially available granites, showing similar mineralogical compositions, but diverse grain-size distributions were selected from a stone processing plant and used as the workpiece materials. To characterize the studied rocks, each rock was analyzed to determine its mechanical properties and mineralogical properties (Table 1). Uniaxial compressive strength and flexural strength of the samples were determined according to Turkish standards TS EN 1926 [24] and TS EN 13161 [25], respectively. Thin sections were examined under a petrographic microscope for the determination of modal composition and grain-size of the samples. However, especially for the coarse-grained granite, hand specimens were also examined for grain-size distribution characterization.

Table 1. *Mechanical and mineralogical properties of the tested rocks*

Rock Sample	Uniaxial Compressive Strength , UCS (MPa)	Flexural Strength, (MPa)	O (%)	P (%)	Q (%)	B (%)	A (%)	E (%)	Other (%)	Grain Size (mm)
G1	143.2 ± 8.28	14.3 ± 1.81	48	9	36	6	-	-	1	0.8 - 30
G2	186.0 ± 17.5	18.9 ± 2.61	30	29	24	8	5	2	2	0.2 - 0.8

Orthoclase (O); Plagioclase (P); Quartz (Q); Biotite (B); Amphibole (A); Epidote (E).

III. EXPERIMENTAL RESULTS AND DISCUSSION

The circular sawing experiments were performed in the down-cutting mode (Figure 1) on rectangular granite blocks having 500 mm length , 70 mm depth, and 120 mm width. The cutting depth (d) and horizontal feed velocity (V_f) were varied at different levels to achieve different sawing rates. Each series of tests consisted of twelve passes on each sawn granite block. For each series of tests, measurements of horizontal force (F_h), vertical force (F_v), active power consumption (P) were made.

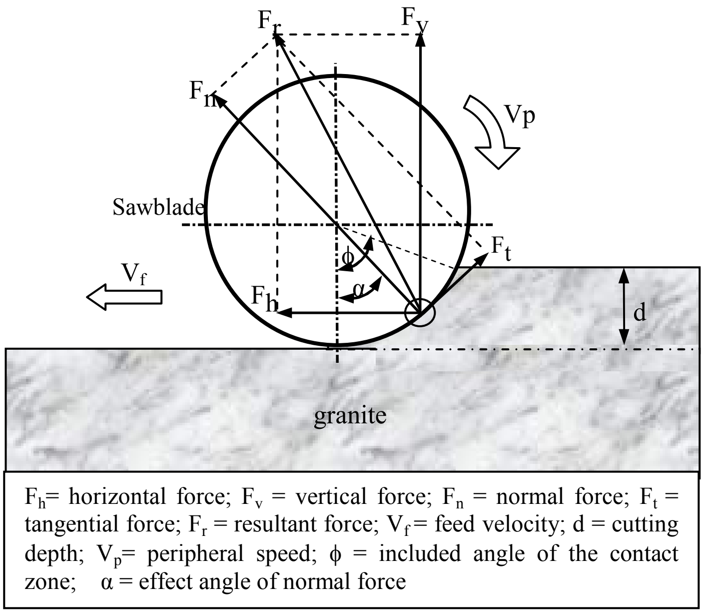


Fig. 1. *Kinematics of the down-cutting process [4].*

During any series of sawing tests, force and power signals were recorded at every ¼ of a second. Examples of the recorded power and force signal curves are illustrated in Fig.2. Typically, force and the active power values tend to increase progressively during the running-in (entry) period of the sawblade, thereafter remaining fairly stabilized before progressively diminishing during the running-out (exit) period. In this study, following the common practice in circular sawing analyses [6,11,26], the 'stabilized' period was considered for the force and power recordings of the tested workpiece materials.

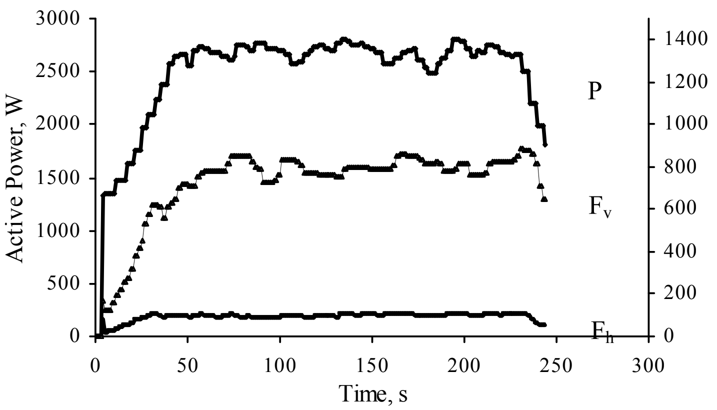


Fig. 2. *Typical force and power signal curves.*

III.1. Normal and Tangential Cutting Forces

Although vertical (F_v) and horizontal (F_h) forces are the measured cutting forces, it is the normal (F_n) and tangential (F_t) components (Fig. 1) that are of more fundamental significance in sawability analyses [6, 11, 12]. Therefore, in this study, the (F_t) and (F_n) values were calculated by using the following equations [6,11,12]:

$$F_t = P/V_c \tag{1}$$

$$F_n = [(F_h)^2 + (F_v)^2 - (F_t)^2]^{1/2} \tag{2}$$

where all the notations are as described in Fig. 1. The calculated force values for each series of tests are given in Table 2.

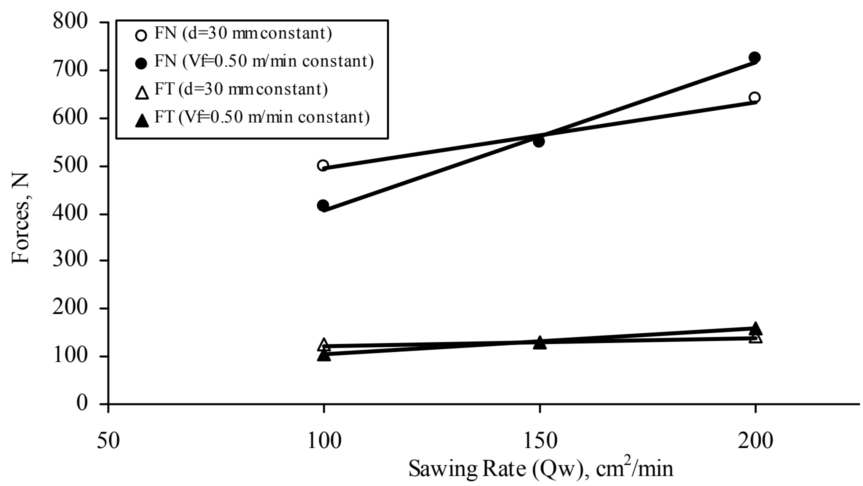
Table 2. *Sawing test data*

Constant Feed Velocity (Vf= 0.50 m/min)									
Rock Type G1					Rock Type G2				
d (mm)	F_N (N)	F_T (N)	P (W)	SE (J/mm^3)	d (mm)	F_N (N)	F_T (N)	P (W)	SE (J/mm^3)
10	248.55	65.03	1950.87	6.688	10	215.77	60.25	1807.53	6.170
20	412.70	103.96	3118.99	5.347	20	351.90	91.71	2751.32	4.717
30	550.32	127.78	3833.27	4.380	30	524.30	120.50	3624.89	4.143
40	723.62	158.67	4760.23	4.080	40	613.22	137.71	4131.29	3.541
Constant Cutting Depth (d= 30 mm)									
Rock Type G1					Rock Type G2				
Vf (m/min)	F_N (N)	F_T (N)	P (W)	SE (J/mm^3)	Vf (m/min)	F_N (N)	F_T (N)	P (W)	SE (J/mm^3)
0.33	500.48	124.02	3720.69	6.381	0.33	453.77	115.87	3476.18	5.965
0.50	550.32	127.78	3833.27	4.380	0.50	524.30	120.50	3624.89	4.143
0.66	641.24	141.15	4234.45	3.631	0.66	569.78	132.16	3964.82	3.402

In practice, from the point view of achieving maximum productivity, it is desirable to achieve high sawing rates while taking into account the available machine power. In a particular sawing process, the cutting rate (Q_w) is governed by the cutting depth (d) and workpiece feed velocity (V_f), which is given by:

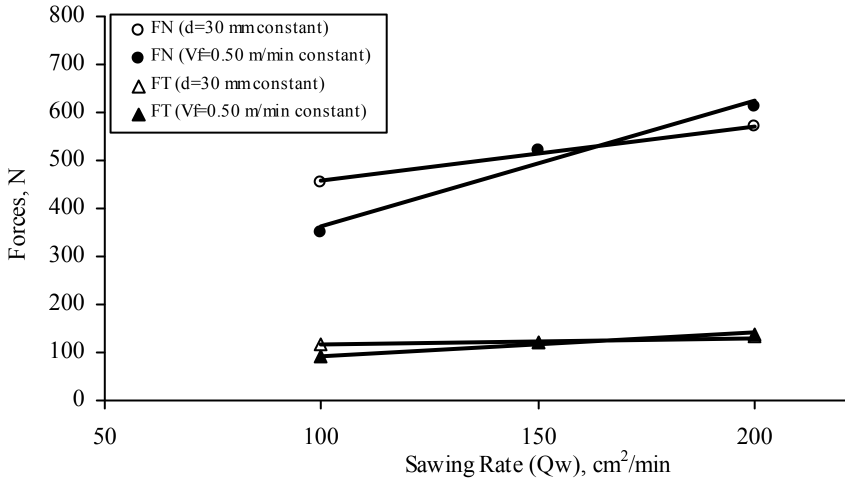
$$Q_w = d \times V_f \tag{3}$$

Using the experimental data given in Table 2, plots of average force components versus different levels of sawing rates have been illustrated in Fig. 3. Valid for both workpiece materials G1 and G2, it can be seen that the normal force (F_n) values are about 4-5 times higher than tangential force (F_t) values, where both force components increase with increasing sawing rates. However, the increasing rate of normal force is considerably higher than that of the tangential force, indicating that normal forces are relatively more influenced when sawing rate is increased. This can be explained by the fact that a higher sawing rate means a higher load on the blade which results in increased wear [1]. It has been experimentally observed that normal force is closely associated with flattened diamond particles on the worn working surface of the segment, leading to low cutting capability, high temperatures and forces [13]. Another important conclusion that can be drawn from Fig. 3 is that, for a given sawing rate, employing a shallower cutting depth and higher feed velocity can reduce the normal and tangential forces.



(a)

Fig. 3. *Cutting forces versus sawing rate for workpieces G1 (a) and G2 (b).*



(b)

Fig. 3. *(Continued) Cutting forces versus sawing rate for workpieces G1 (a) and G2 (b).*

III.2. Power

Cutting forces and energy play an important role in all stone machining [27]. Since energy is one of the major cost items in the processing of natural stones, determination of this parameter is of vital importance from the point view of cost estimation. Consequently, power consumed during the process has been widely used in the literature as a sawability criterion of granites [6, 11, 12, 14, 22, 28].

Experimentally obtained results are presented in Fig. 4 as plots of active power (P) versus cutting rate (Q_w). It can be seen that power consumption is proportional to the sawing rate.

With increasing sawing rate, the volume of chips produced at the segment-granite contact zone increases, and consequently it becomes more difficult to eject the swarf from the cutting zone [29], eventually leading to increased blade wear and higher power consumption. Similar to the cutting force - sawing rate relations illustrated in Fig. 3; when it is intended to achieve higher sawing rates, the processing technique of increasing the feed velocity and employing a shallower cutting depth leads to reduced power consumption (Fig. 4). Such a trend has also been confirmed by the experimental works of other authors [14].

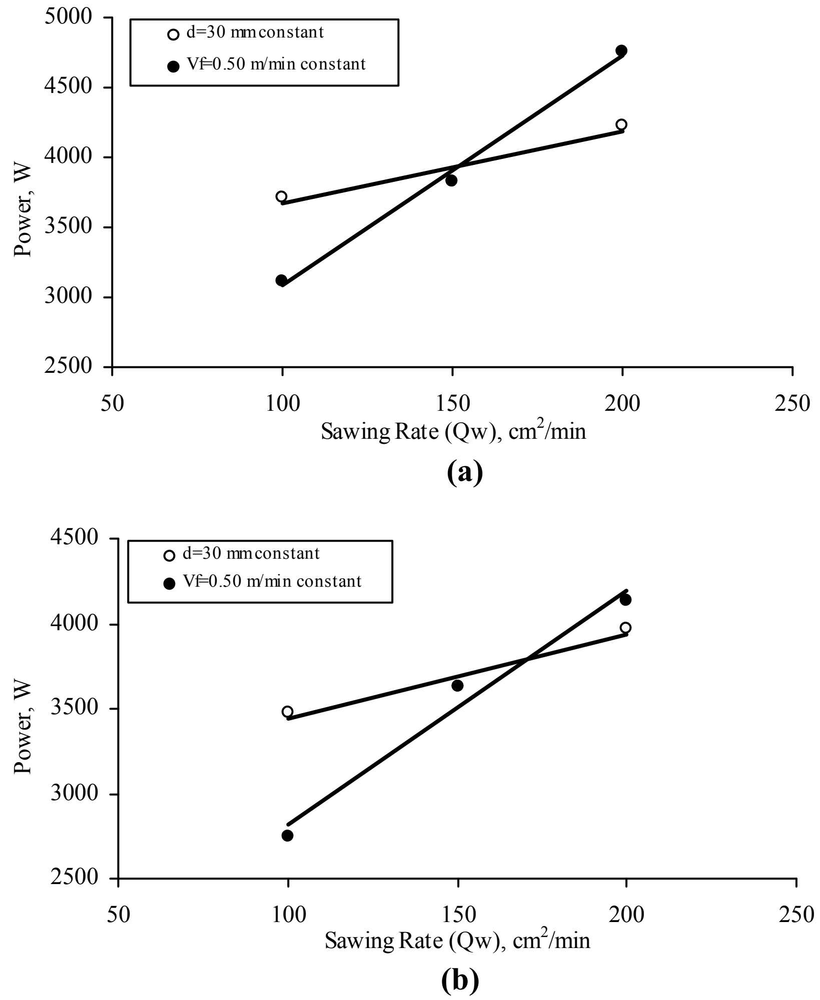


Fig. 4. *Sawing rate versus power consumption for workpieces G1 (a) and G2 (b).*

Fig. 5 shows examples of typical power consumption curves as a function of number of sawing passes. As can be followed from Fig. 5, with increasing number of sawing passes the power consumption also increases, which may attributed to the gradual wear of diamond particles during a continuous sawing process [30]. Therefore, it is possible to suggest that in a particular sawing operation, power consumption data can also be used for the real-time monitoring of sawblade wear performance.

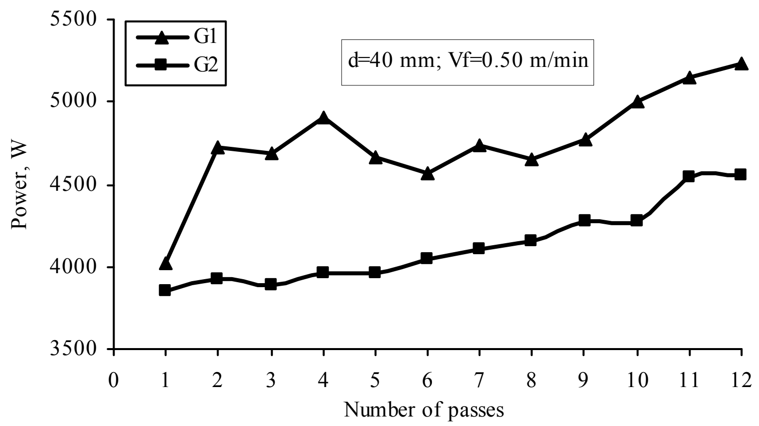


Fig. 5. *Power consumption versus number of sawing passes.*

When sawing workpiece G1, the active power values fluctuate more sharply than those of workpiece G2 (Fig. 5). This can be mainly attributed to the differences in the textural properties of the workpiece materials. As can be followed from table 1, G2 is a fine-grained granite with a relatively narrow grain-size range of 0.2-0.8 mm, whereas G1 is a coarse-grained granite with a much wider grain size range of 0.8-30 mm and higher quartz content. Therefore, it is logical to suggest that softer power fluctuations observed in the sawing process of G1 might be due to its relatively homogenous grain-size distribution compared to that of G2.

III.3. Specific Energy

The efficiency of a given rock cutting process is measured by the specific energy (SE), which is defined as the energy expended in removing a unit volume of rock. It is a widely used parameter as a sawability criterion in the circular sawing of natural stones [12, 21, 26 31, 32], the lower SE values indicating improved sawing efficiency. However, SE is not a fundamental intrinsic property of rock. It is mainly influenced by the operational parameters (cutting depth, sawblade peripheral speed, feed rate, cutting mode, blade specifications, etc.) and the properties of the rock.

In this work, specific energy was obtained by dividing the total power consumed during the stabilized period of the sawing process by the corresponding volume of material removed.

Depending on the operational parameters and workpiece properties, SE values from 3.53 to 6.68 J/mm^3 were obtained (Table 2). These results are in agreement with the results of a literature survey carried out by Xu et al. [12], where values ranging from 3.2 to 6.9 J/mm^3 have been reported in the circular sawing of granites.

Experimental results presented in Table 2 are illustrated in Fig. 6 as plots of sawing rate versus specific energy. It can be followed from Fig. 6 that increasing the sawing rate, either by increasing the cutting depth (Fig. 6a) or the feed velocity (Fig. 6b), improves the efficiency of the process. However, when cutting rate is increased, it is essential that there should be a corresponding increase in available power. It is also clear that, for a constant feed velocity, the efficiency of the process improves when deeper cuts are made (Fig. 6a). The rate of SE reduction is steeper in shallow cuts, but has a tendency to level off at relatively higher cutting depths. Similar trends are also observed between feed velocity and SE (Fig. 6b) where it is seen that, for a constant depth of cut, the efficiency of the process improves with increasing feed velocity. Also, for a given sawing rate, employing a shallower cutting depth and higher feed velocity is more advantageous from the point view of process efficiency (Fig. 7).

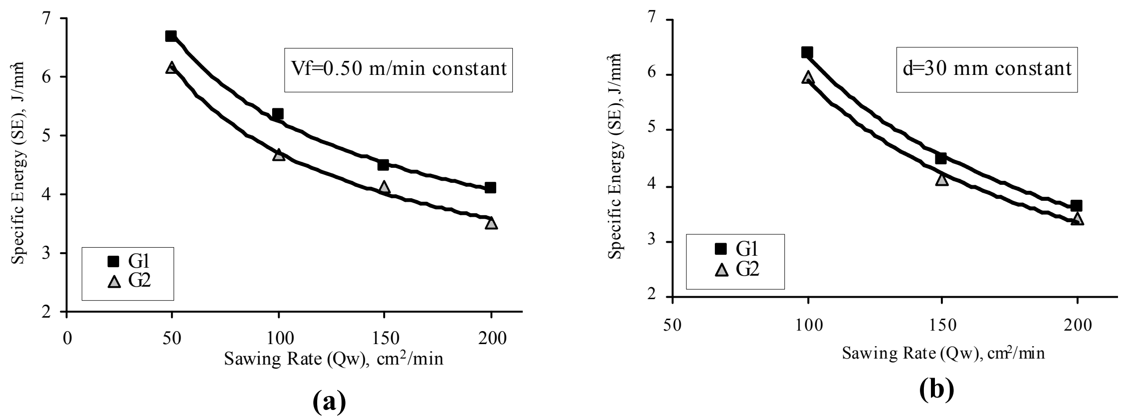


Fig. 6. *Sawing rate versus cutting depth (a) and feed velocity (b).*

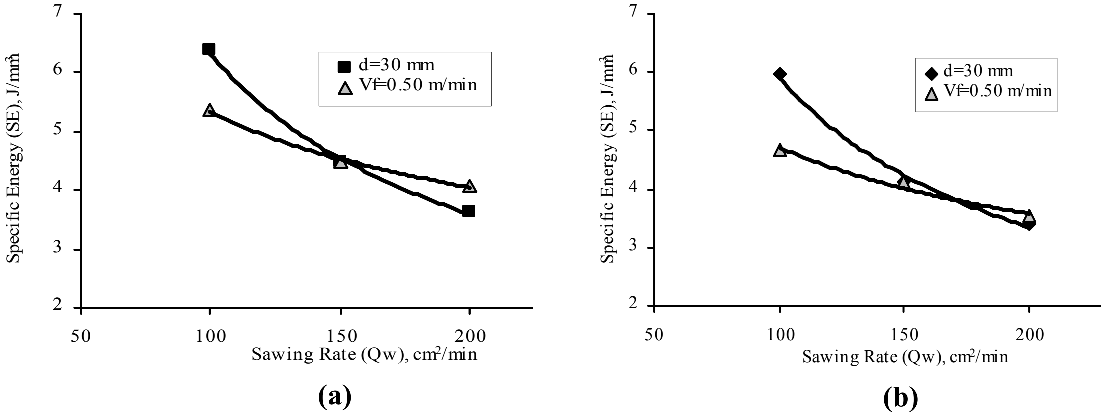


Fig. 7. Sawing rate versus SE for workpiece G1 (a) and G2 (b).

III.4. Effect of Workpiece Properties

Although the main aim of the present study was to be able to establish force and energy requirements at varying levels of sawing rates, an attempt was also made to interpret the experimental data from the point view of mechanical and mineralogical properties of the tested granites.

From the general test results presented in Table 2, it may be interesting to note that workpiece G1 exhibits relatively higher sawability difficulties in terms of cutting forces, power and specific energy, despite the fact that it has a lower mechanical strength than workpiece G2 (Table 1). While it is not conclusive with testing only two types of granites, there is further evidence in the literature showing that mechanical properties might not have a significant effect on granite sawability, and therefore, importance should be given to mineralogical properties [14, 33]. If this argument is provisionally accepted, then it is logical to suggest that the relatively higher sawability difficulties observed in workpiece G1 may be attributed to its mineralogical properties. As seen from Table 1, compared to workpiece G2, workpiece G1 has a larger mineral grain-size range and also higher quartz content. This could be a significant factor because the larger the mineral grain size and higher proportion of quartz, the greater the effect on blade wear, cutting forces and power [22, 33]. In this respect, rather than the mechanical strength indices, some hardness tests (such as the Shore hardness) can be expected to give some indication of granite sawability, since textural characteristics of the stone are already reflected in the measurements.

IV. CONCLUSIONS

The following main conclusions can be drawn from the experimentally obtained sawing data:

i) Although it is limited by available machine power, increasing the sawing rate improves the efficiency of the process in terms of specific energy. However, achieving higher sawing rates by increasing the feed velocity and employing a shallower cutting depth is more advantageous than the alternative of increasing the cutting depth and employing a lower feed velocity. It is shown that the latter processing technique results with relatively higher force and power requirements.
ii) The recorded power consumption curves show that power consumption values increase with increasing number of sawing passes, which is attributed to the gradual wear of the sawblade. Therefore, it is suggested that, in practice, real-time monitoring of sawblade wear performance can be conveniently realized by the evaluation of power consumption data.
iii) Although it has a lower mechanical strength, the coarse-grained granite (G1) was observed to exhibit higher sawability difficulties compared to the fine-grained granite (G2). Also supported by some other research work in the literature, this observation suggests that mechanical strength may not be a significant parameter in the sawability analyses of granitic rocks. It is thought that the relatively high grain-size distribution of G1 coupled with a high quartz content causes faster sawblade wear, leading to higher cutting forces and power consumption. However, it is appreciated that with only two workpiece materials the statement made above is not conclusive, and in this respect further analyses on other granitic rocks are needed.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

[1] J. Konstanty, "Theoretical analysis of stone sawing with diamonds", *Journal of Materials Processing Technology*, Vol.123, pp.146-154, 2002.

[2] B. Unver, "A statistical method for practical assessment of sawability of rocks", Proc. of ISRM Int. Symp.Eurock 96', 1996, Barla (Edt.), Rotterdam, Balkema, pp.59-65.

[3] H.K. Tonshoff, J. Asche, "Wear of metal-bond diamond tools in the machining of stone", *Industrial Diamond Review*, Vol. 1, pp.7-13, 1997.

[4] W. Ertingshausen, "Wear processes in sawing hard stone", *International Diamond Review*, Vol.5, pp.254-258, 1985.

[5] S.Y. Luo, "Investigation of the worn surfaces of diamond sawblades in sawing granite", *Journal of Materials Processing Technology*, Vol.70, pp.1-8, 1997.

[6] X.P. Xu, Y. Li, W.Y. Zeng, L.B. Li, "Quantitative analysis of the loads acting on the abrasive grits in the diamond sawing of granites", *Journal of Materials Processing Technology*, Vol.129, pp.50-55, 2002.

[7] A.S. Eyuboglu, Y. Ozcelik, S. Kulaksiz, I.C. Engin, "Statistical and microscopic investigation of disc segment wear related to sawing Ankara andesites", *International Journal of Rock Mechanics & Mining Sciences*, Vol.40, pp.405-414, 2003.

[8] A. Ersoy, S. Buyuksagis, U. Atici, "Wear characteristics of circular diamond saws in the cutting of different hard and abrasive rocks", *Wear*, Vol.258, pp.1422-1436, 2005.

[9] A.D. Ilio, A. Togna, "A theoretical wear model for diamond tools in stone cutting", *International Journal of Machine Tools and Manufacture*, Vol. 43, pp.1171-1177, 2003.

[10] H.K. Tonshoff, H. Hillman-Apman, J. Asche, "Diamond tools in stone and civil engineering industry: cutting principles, wear and applications", *Diamond and Related Materials,* Vol.11, pp.736-741, 2002.

[11] X. Xu, Y. Li, Y. Yu, "Force ratio in the circular sawing of granites with a diamond segmented blade", *Journal of Materials Processing Technology*, Vol.139, pp.281-285, 2003.

[12] X. Xu, Y. Li, S. Malkin, "Forces and energy in circular sawing and grinding of granite", *Journal of Manufacturing Science and Engineering*, Vol.123, pp.13-22, 2001.

[13] A.G. Mamalis, R. Schulze, H.K. Tönshoff, "The slotting of blocks of hard rock with a diamond segmented circular sawblade", *Industrial Diamond Review*, Vol.39, pp. 356-365, 1979.

[14] M. Jennings, D. Wright, "Guidelines for sawing stone", *Industrial Diamond Review*, Vol.2, pp.70-75, 1989.

[15] C.Y. Wang, X. Wei, Z.L. Tang, Z.C. Pan, "The role of coolant in granite sawing", *Industrial Diamond Review*, Vol.4, pp.156-160, 1995.

[16] X. Wei, C.Y. Wang, Z-H. Zhou, "Study on the fuzzy ranking of granite sawability", *Journal of Materials Processing Technology*, Vol.139, pp.277-280, 2003.

[17] P. Hausberger, "Stone Machineability", *Industrial Diamond Review*, Vol.5, pp.258-261, 1990.

[18] H.K. Tönshoff, G. Warnecke, "Research on stone sawing", *Advances in Ultrahard Materials Application Technology*, Vol. 1, pp.36-49, 1982.

[19] N.S. Delgado, A. Rey-Rodrigez, L.M. Suarez del Rio, I.D. Sarria, L. Calleja, V.G. Ruiz de Argandona, "The influence of rock microhardness on the sawability of Pink Porrino granite (Spain)", *International Journal of Rock Mechanics & Mining Sciences*, Vol. 42, pp.161-162, 2005.

[20] S. Lan, P. Jinsheng, L. Changjian, "A new approach to improve the performance of diamond sawblades", *Materials Letters*, Vol.57, pp.1010-1014, 2002.

[21] I.S. Buyuksagis, "Effect of cutting mode on the sawability of granites using segmented circular diamond blades", *Journal of Materials Processing Technology*, Vol.183, pp.399-406, 2007.

[22] J. Asche, "Deep grinding- a new dimension in cutting granite", *Industrial Diamond Review*. Vol.2, pp.110-122, 1999.

[23] S.M. Çınar, "Optimization of Electric Energy Consumption in Marble Cutting Machines", Afyon Kocatepe Üniversitesi Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi (In Turkish), 2007.

[24] Turkish Standard TS EN 1926, Natural stone test methods – Determination of compressive strength, April 2000.

[25] Turkish Standard TS EN 13161, Natural stone test methods – Determination of flexural strength, February 2003.

[26] Y. Li, H.Huang, J.Y. Shen, X.P. Xu, Y.S. Gao, "Cost-effective machining of granite by reducing tribological interactions", *Journal of Materials Processing Technology*, Vol.129, pp.389-394, 2002.

[27] W. Polini, S. Turchetta, "Force and specific energy in stone cutting by diamond mill", *International Journal of Machine Tools & Manufacture*, Vol.44, pp.1189-1196, 2004.

[28] B. Brook, "Principles of diamond tool technology for sawing rock", *International Journal of Rock Mechanics and Mining Sciences*, Vol.39, pp. 41-58, 2002.

[29] X. XU, "Friction studies on the process in circular sawing of granites", *Tribology Letters*, Vol.7, pp.221-227, 1999.

[30] W. Polini, S. Turchetta, "Monitoring of diamond disk wear in stone cutting by means of force or acceleration sensors", *International Journal of Advanced Manufacturing Technology*. Vol.35, pp.454-467, 2007.

[31] Y. Ozcelik, S. Kulaksiz, A.S. Eyuboglu, "Investigation of the effect of rock parameters on the specific energy in cutting process of Ankara-Cubuk Andesites with disc cutter", Proc. of the ISRM Regional Symposium Eurock, 2001, pp. 597-602.

[32] I.S. Buyuksagis, R.M. Goktan, "Investigation of marble machining performance using an instrumented block-cutter", *Journal of Materials Processing Technology*, Vol.169, pp. 258-262, 2005.

[33] V.B. Cassapi, "Factors influencing the sawability of stones", Ph.D. Thesis, University of Nottingham, England, 1987.