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Effect of cutting parameters on consumed power in industrial granite cutting processes performed with the multi-disc block cutter

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ABSTRACT

The aim of this study was to investigate the effect of the cutting mode, cutting depth, and feed rate on the level of consumed power, during granite cutting using circular saw blades. In this context, two-column multi-blade block cutters were used to evaluate twelve different cutting conditions conducted with more than three hundred cycles. In these tests performed with 1200 mm saws, the feed rates of 10, 13, 15, and 17 m/min and cutting depths of 3, 6, and 9 mm were used, while the peripheral speed was kept constant (≈ 35 m/s). Based on the evaluation of industrial cutting conditions involving the sawing of relatively large rock blocks with a circular saw blade, it was determined that the down-cutting mode was more advantageous in terms of power consumption. In addition, the effects of the cutting mode, cutting depth, and feed rate on the cutting efficiency and power consumption (one of the most important indicators of cutting performance) were also determined.

1. Introduction

Owing to their solidity, their resistance to environmental influences, and the color alternatives they provide, hard stones are extensively used in the natural stone industry. Blocks cut in granite quarries using various methods are transferred to stone processing plants, where they are converted to finished products. In the cutting of relatively small slices from large granite blocks, one of the most significant costs is power consumption. A proper analysis of the cutting processes is of considerable importance for the effective optimization of operational parameters. The cutting operations of hard stones such as granite are different from that of other stones such as marble, limestone, and travertine. Depending on the hardness of the stones, the cutting depth used during the sawing of granite can be relatively small (generally between 1 and 9 mm). In industrial applications, granite and other hard rocks are generally cut in a sequential manner. Compared to the cutting of relatively soft rocks, another important difference in granite cutting is the widespread use of multidiscs rotated by a single motor.

There are numerous laboratory studies in the literature regarding the cutting of granites and natural stones. The study of Ertingshausen [1], for example, used a bridge saw machine with a motor power of 18.5 kW. This saw blade had a diameter of 600 mm, and a peripheral speed of 45 m/s. The cutting depth used during the study was between 10 and 60 mm, and the tests were performed on Colombo red granite. The results of this study demonstrated that the up-cutting mode was more advantageous in terms of power consumption at cutting depths below 20–25 mm, while the down-cutting mode was more advantageous at greater cutting depths. Konstanty [2], on the other hand, investigated the down-cutting and up-cutting modes, and their effects on segment wear. In this context, Konstanty made several recommendations for increasing saw blade life in both cutting models. In another study conducted by Konstanty [3] regarding the cutting of granite, the segment wear of different types of saw blades was investigated. Unver [4] developed an empirical formula for the prediction of specific wear and cutting forces during granite cutting. Based on the results of Unver's study, statistically significant relationships were identified between the saw blade-specific wear and the quartz grain size, NCB cone indenter value, and mean plagioclase grain size. In a study conducted by Luo [5], the segment wear that occurred during the cutting of hard and relatively soft granite with circular saw blades was evaluated. In Luo's study, 300–350 mm diameter circular saw blades were used, while the peripheral speed was 30–35 m/s, and the cutting depth was 20–30 mm. Based on the results of the study, the authors discussed the effects of diamond grits on the cutting efficiency observed during the cutting of hard and relatively soft granite.

In Webb and Jackson's studies [6], the relationship between saw blade wear and cutting forces during granite cutting were evaluated. In these studies, a strong relationship was identified between the normal cutting force and the tangential cutting force.

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In a study conducted by Xu [7], the interaction that occurs between granite and diamond grits on saw blade segments during the cutting of granite with a diamond saw was evaluated, along with the effect of this interaction on the cutting energy. Based on the study results, Xu concluded that a very large portion of the cutting energy was lost as a result of the friction between the granite and the diamond grit. Sun et al. [8], on the other hand, performed tests regarding a new type of matrix and the cutting performance of the saw blade. Sun et al. used a 105 mm saw blade during their study. In the tests performed within the context of the said study, the effect that adding SiC whiskers to the matrix had on the saw cutting performance was investigated. In this context, it was determined that the addition of SiC whiskers to the saw blades resulted in higher cutting efficiencies.

In a study conducted by Li et al. [9], the authors proposed a new cost-effective machining method for sawing granite materials with diamond impregnated tools. The authors of the study emphasized the importance of the interaction between the diamond tool surface and the workpiece. According to the results of the study, it was determined that high segment performance is dependent on the bonding and wetting that exists between the matrix alloys and diamonds by using a Ti–Cr alloy coating on diamonds. Furthermore, the study illustrated the possibility to improve the level of wetting, and to increase the debris storage capacity. This, in turn, has the effect of decreasing friction during the saw's operation. The study of Xu et al. [10] performed a quantitative evaluation on the forces and loads acting on diamonds grits during the cutting of two varieties of granite with a circular saw consisting of a segmented diamond blade. According to the results of this study, the wear of the diamond grits was associated with the high temperatures generated at the cutting point, and the heat transferred to the segment by diamonds breaking-off/separating from the matrix.

Di Ilio and Togna [11] proposed a theoretical model for describing the saw blade wear process. According to this model, the matrix material should not only support (or hold) the diamond grits on the segment, but it should also wear at a rate that allows the cutting efficiency to remain constant. In the study of Wei et al. [12], the fuzzy ranking method was used to evaluate and categorize the sawability of various types of granite. In the study, the dependence function and the fuzzy relationship of the granite's hardness, compressive strength, abrasiveness, quartz grain size, and quartz content with the sawing force and tool wear were determined by developing a new fuzzy mathematics method. The saw blades used in this study were 600 mm diameter circular saws, while the cutting depth was 10 mm, the peripheral speed was 35 m/s, and the feet rate was 3 m/min. The study concluded that the fuzzy ranking method could effectively determine and select a suitable saw blade by taking into consideration the petrographic and mechanical characteristics of granites. In an experimental study conducted by Xu et al. [13], the forces acting on a saw blade during the cutting of granite with a diamond impregnated saw blade were investigated. According to the results of the study, the cutting depth was the leading factor that affected the tangential and normal force components, and the cutting depth's effect was more significant than that of the workpiece velocity. Despite significant differences in sawing difficulty, the difference between different types of granites with respect to force components and force component ratios was less than expected.

Ersoy et al. [14] conducted an experimental study regarding the wear characteristics of saw blades during the cutting of abrasive and hard types of rocks. Within the context of their study, they developed a statistical predictive model for saw blade wear that took into consideration the specific cutting energy, the total silica content of rock, the bending strength and the Schmidt rebound hardness parameters. Delgado et al. [15], on the other hand, evaluated the relationship between the sawability of Pink Porrino granite and the Vickers microhardness. The results of Delgado et al.'s study demonstrated a strong correlation between the sawing rate and rock hardness. Wright and Cassapi [16] also conducted a study to predict beforehand the sawability of hard rocks such as granite. To this end, they used and evaluated eight different types of rocks in their study. Based on their study results, they concluded that there was no significant relationship between the mineralogic–petrographic characteristics of the rocks and the saw blade wear and consumed power, and that it was necessary to evaluate the physico-mechanical characteristics of the rocks. On the other hand, a strong relationship was identified between the forces acting of the saw and the saw wear and power consumption during cutting.

In a study conducted by Wright [17], the wear characteristics of diamond grits located at five different points selected on two types of segments were evaluated within the context of experiments involving the sawing of Cornish grey granite. The results of the study demonstrated that the wear of the diamond grits was associated with the distribution of these grits on the segment. Hausberger [18] conducted a study investigating the sawability characteristics of hard rocks. Within the context of this study, Hausberger performed mineralogical–petrographical analyses on these rocks and evaluated their physical and mechanical characteristics. He also evaluated the pieces that separated from the rocks during cutting. The mineralogical–petrographical analyses performed within the context of this study revealed that stones consisting of more than 5% quartz were relatively more difficult to cut. In addition to this, Hausberger also determined that the presence of cleavage planes and of minerals such as mica, homeblend, and pyroxene in the rocks favorably affected their sawability.

Jennings and Wright [19] attempted to theoretically describe the factors that affect saw performance during cutting. In this context, they suggested that the saw blade life could be predicted by using the Shore hardness value. Based on their theoretical study, Jennings and Wright described the factors that should be taken into consideration when selecting and using a diamond saw blade for cutting hard rocks. Luo and Liao [20], on the other hand, investigated the wear of diamond grits on saw segments during the cutting of Indian red granite, and evaluated how the diamond grits affected the performance of the saw blade. During the experiments, a saw diameter of 205 mm was used, while the cutting depth was 0.2 mm, and the feed rate was 1.0 m/min. The tests performed during the study demonstrated that in case the diamond concentration within the segments remained the same, segments with smaller diamond grits exhibited higher cutting performance when sawing Indian red granite.

In a laboratory study conducted by Ersoy and Atici [21], very hard and abrasive rocks were cut using 400 mm diameter saws. The results of the study demonstrated that an increase in cutting depth was associated with a decrease in specific cutting energy. In addition to this, an excellent relationship was observed between the cutting performance (in terms of specific cutting energy) and the physical and mechanical properties of rocks (such as their compression resistance, relative abrasion resistance, and abrasion factor). Luo and Liao [22] conducted a study in which three types of one-segmented diamond saw blades with different matrix hardnesses and diamond grit surfaces were used. The study evaluated the effects of the diamond grit surface properties and matrix hardness on the wear performance and the forces acting on the saw blade segment. The results of the study demonstrated that segments with smooth diamond grit surfaces and high matrix hardness exhibited better performance during the cutting of granite. In a laboratory study conducted by Buyuksagis [23], a 400 mm diameter saw blade was used to investigate the effects of the cutting mode on the granite cutting performance. In the experiments, both the up-cutting and down-cutting modes were tested. During the cutting tests, a peripheral speed of 65 m/s, a feed rate of 0.45 m/min, and a cutting depth of 20 mm were used. Based on the results of the study, it was determined that the up-cutting method resulted in lower specific cutting energy and specific wear values in comparison to the down-cutting method, which indicated that the up-cutting method was more efficient. In addition, the study results also indicated that higher specific energy values led to higher levels of specific wear during cutting. In the studies of Li et al. [9] and Xu and Yu [24], various experiments were performed in order to obtain low tool wear, low energy consumption, and high cutting efficiency. Within the context of these experiments, the sawing process of granite with Ti–Cr coated diamond grits was investigated, and the sawing performances of the specimens were evaluated in terms of their wear performance.

A review of recent studies in the literature indicates that researchers are continuing to investigate and evaluate cutting processes through laboratory studies. Bayram and Yasitli [25] investigated the effects of parameters such as the saw blade diameter, diamond concentration on segments, and sawing depth on the sawing performance. Yurdakul and Akdas [26], on the other hand, investigated the industrial cutting processes for six different types of carbonate rocks, and developed a statistical model for predicting the specific cutting energy required by these processes. Based on experiments evaluating the sawing of Wulian red granite, Zhang et al. [27] investigated the relationship of the cutting force with the feed rate and cutting depth. All these studies from the literature are laboratory studies. The data used in the current study are not based on laboratory data, but instead on data obtained from the industry.

We did not find any previous studies in the literature that involved the use of a multi-blade block cutter in a laboratory or industrial setting. All previous studies regarding the cutting of granite were performed under laboratory conditions with a single blade. The current study involved the investigation of a cutting process that simultaneously used both the up-cutting and down-cutting modes. This type of mixed system is used by the natural stone industry for the cutting of hard stones, and also in sequential cutting processes. There are no previous studies in the literature that use both cutting modes within the same cycle. The current study investigated the effect of factors such as the cutting depth, sawing mode, and feed rate on power consumption during industrial granite cutting.

2. Cutting conditions testing procedures

The data used in this study were obtained from a natural building stone processing plant that produces slabs from the stone blocks. These collected data were based on measurements performed during the cutting of 2–6 m^3 granite blocks with a multi-blade block cutter.

2.1. Machine

Sawing tests were performed on a two-column block cutter (SIMEC NT2 50S). The maximum spindle power of the machine was 220 kW. The machine possesses two independent bridges that can simultaneously perform horizontal and vertical cuttings. The fact that the horizontal and vertical blades are separate serves to reduce and eliminate vibrations. The machine can be simultaneously fitted with sixty discs with a diameter of 1600 mm. The cutting center can be easily managed and controlled from the machine's control panel. For the cutting process, stone blocks of similar dimensions are placed on a block carrying trolley. To achieve a proper and effective cutting process, it is crucially important to accurately control the movements of the block carrying trolley. For this reason, it is necessary to place and position the blocks properly into the trolley. Vertical cutting processes are often performed in a sequential manner, especially during the cutting of hard rocks. In each cutting sequence, a cutting depth of 3 mm to 9 mm was employed.

2.2. Saw blades

The tests were performed using 23 saw blades with a diameter of 1200 mm. Eighty diamond impregnated segments with a thickness of 7.5–8 mm, a height of 12 mm high, and a length of 24 mm were brazed to a steel core using a silver solder. As a part of the diamond circular saw blade and the bearing part of the diamond segments, the steel body is very important for the cutting quality and life of the saw blade. In this study, 75 Cr1 steel blades with a Rockwell harness of 42–45 were used. In addition, sandwich conical type segments with a Rockwell harness of B90 were also used. The segments contained 40/50 US mesh diamonds at a concentration of 1 kg/20–22 g. The rotational speed of the saw blade was selected as 544 rpm, or 34.16 m/s. The rotational speed was measured during the cutting processes by using a contactless optical tachometer.

2.3. Workpiece characteristics

The sawing tests were performed on Balmoral red granite (Rapakivi granite) blocks with dimensions varying between 2 and 6 m^3. Samples taken from the Balmoral red granite blocks were sent to the Geological Survey of Finland for evaluation, and were subject to physical and mechanical tests at the Research Laboratory of the Geological Survey of Finland. According to the results of the tests performed on these samples, it was determined that Balmoral red granite consists of K-feldspar (39.6%), quartz (30.1%), plagioclase (22.1%), biotite (5.2%), muscovite (1.3%), and other minerals (1.8%). The general properties of the Balmoral red granite are listed in Table 1. Knowledge of the workpiece material's properties is important for effectively predicting the cutting characteristics of rocks with similar properties.

2.4. Collection of electrical data

The electrical energy that powers the saw blades of the block cutters are transmitted to the motor through a control panel. In this study, the amount of electrical power being transmitted to the vertical cutting motor was measured using a digital power meter. This digital power meter was placed on a power line that passed through the control panel and connected to the motor. As the

Table 1
Some of the physical and mechanical properties of the workpiece material.

Standard	Test	Rock Balmoral red
EN 13755	Mean water absorption (%)	0.12
	Standard deviation	0.00
EN 1936	Apparent density (kg/m^3)	2640
	Standard deviation	5.00
EN 1936	Mean open porosity (%)	0.39
	Standard deviation	0.00
EN 1926	Mean compression strength (MPa)	171
	Standard deviation	54.5
EN 12371	Mean compression strength after frost (MPa)	179
	Standard deviation	45.7
EN 12372	Mean flexural strength (MPa)	13.4
	Standard deviation	0.60
EN 12371	Mean flexural strength after frost (MPa)	13.9
	Standard deviation	1.30

multi-blade block cutter was operating and cutting the granite blocks, electrical data was collected with the aid of voltage test leads and clamp sensors. During these measurements, the mean value for a total of twenty cycles that was determined. During the cutting process, parameters such as current, voltage, and power were recorded for each phase by using a digital power meter. The recorded data was then analyzed on a computer. The amount of power consumed was evaluated at the end of each cutting process, and the study parameters were adjusted accordingly.

2.5. The sawing test procedures and the collection of cutting data

Industrial granite cutting processes performed with multi-blade block cutters differ from cutting processes performed under laboratory conditions in that the machine will perform cuts in both the forwards and backwards direction to complete a full cycle. In routine cutting processes, different values can be selected for the forwards and backwards feed rate and cutting depth of the saw blade. To determine how the cutting mode affected the power consumption values, the forwards and backwards feed rate and cutting depth of the saw blade were set at equal values within the context of this study (Table 2). For each one of the cutting conditions listed in Table 2, the mean values for a total of 20 cuttings were determined. The feed rate and cutting depth values listed in Table 2 represent the values that were selected by the process engineer and used for cutting the selected stone under industrial conditions. These values also represented the limit values of the multi-blade block cutter. The machine uses the down-cutting mode when moving forwards, and the up-cutting mode when moving backwards. This is because the rotational direction of the saw blade remains the same when it is moving forwards and backwards.

3. Results

Nearly 300 pieces of cutting data were evaluated in this study. To avoid any confusion concerning the data on the figures, only values that were considered as being noteworthy results were shown. Fig. 1 provides data that were recorded during one of the cutting process and collected over four consecutive cycles of the saw blades.

The time-power consumption curve illustrated the changes that occurred in power consumption depending on the cutting conditions. This curve facilitated the accurate analysis of each second of the cutting process. Each peak on Fig. 1 indicates the maximum cutting depth reached by the saw blades. In this figure, the first curve represents the forwards movement of the saw blades. In other words, the curves on this figure are arranged according to a sequence in which each down-cutting mode is followed by an up-cutting mode. Power consumption increases rapidly following the initial contact of the saw blades with the granite block. The increase in power consumption ends once all of the segments performing the cut enter into the block. When all the cutting segments enter the block, the power consumption curve reaches its peak. This region of the curve is called the mid-region. Once past the mid-region, the segments begin to move out of the cutting area. In this area of the curve, the power consumption values begin to decrease. The first stage of the cutting cycle ends once all the cutting segments move out of the block, and the saw begins to move in the backwards direction. In the first stage of the cutting process, the saw blades will be in the down-cutting mode when moving forwards, and the up-cutting mode when moving backwards. To increase the cutting efficiency, it is necessary to carefully analyze the time-power consumption curve. On the condition that all of the other cutting parameters remain the same, the kurtosis of the time-power consumption curve (or a descent of the curve on the *y*-axis) will indicate a decrease on the level of power being consumed. Fig. 1 shows that during the down-cutting mode, the middle sections of the curves that should normally be horizontal are actually downwards-sloping. This was due to the fact that the lengths of the blocks were not the same. For the cutting process, the blocks were placed side by side, such that the sides of the blocks where the cutting began process were aligned with one another. The length difference between the blocks can reach 20–25 cm.

Table 2
The working parameters of multi-blade block cutter.

Cutting depth (mm) (forwards–backwards)	Feed rate (m/min) (forwards–backwards)
3–3	10–10
	13–13
	15–15
	17–17
6–6	10–10
	13–13
	15–15
	17–17
9–9	10–10
	13–13
	15–15
	17–17

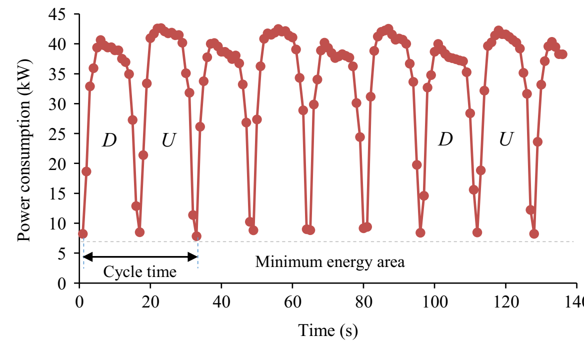

Fig. 1. Analysis of the cutting cycles and of the time-dependent change in power consumption.

In industrial-scale granite cutting processes, the cutting depths generally varies between 3 to 9 mm. Cuts with a depth of 3 mm are called shallow depth cuttings, while cuts with a depth of 9 mm are called deep cuttings.

This study first evaluated the effect of increasing the cutting depth on the power consumed while the feed rate was held constant. It is known that increasing the cutting depth will also increase the amount of power consumed. However, the main emphasis in this study was to determine the quantitative relationship between the increase in cutting depth and the increase in power consumption. The data for all cutting conditions used during the study are shown in Table 3.

According to the cutting data in Table 3, with the down-cutting mode and a cutting depth of 3 mm, the feed rates of 10, 13, 15, and 17 m/min resulted in a power consumption of 21.98, 24.76, 27.28, and 30.51 kW, respectively. Independent of saw blade wear, a cutting feed rate of 10 m/min required a power consumption of 21.98 kW, while a cutting feed rate of 17 m/min increased the power consumption by 8.53 kW (30.51–21.98). In other words, as the amount of power consumed per 1 m was 2.198 kW when the cutting process was performed at a feed rate of 10 m/min, the amount of power necessary to cut an additional 7 m when using the same feed rate was 15.386 kW (7 × 2.198). On the other hand, a

Table 3
Data obtained at different cutting depths and feed rates.

Cutting no	Cutting depth (mm)		Feed rate (m/min)		Mean consumed power (kW)	
	Forwards	Backwards	Forwards	Backwards	Forwards	Backwards
1	3	3	10	10	21.98	24.20
2	3	3	13	13	24.76	27.51
3	3	3	15	15	27.28	30.23
4	3	3	17	17	30.51	32.20
5	6	6	10	10	32.94	34.60
6	6	6	13	13	39.75	42.57
7	6	6	15	15	42.41	45.07
8	6	6	17	17	46.85	49.68
9	9	9	10	10	43.23	45.31
10	9	9	13	13	51.54	55.31
11	9	9	15	15	59.21	61.38
12	9	9	17	17	65.58	67.94

cutting feed rate of 17 m/min only required an additional power expenditure of 8.53 kW in comparison to the cutting feed rate of 10 m/min. Additionally, the fact that a single movement of the saw blade covered an additional 7 m also meant a reduction of the labor costs and time required during the cutting process. Thus, it is possible to state that at a cutting depth of 3 mm, a relatively faster cutting feed rate (17 m/min) is more advantageous in terms of power consumption than a slower cutting feed rate (10 m/min). When the data on Table 3 is evaluated for the 6 mm cutting depth, it can be seen that the power consumption at a feed rate of 10 m/min was 32.94 kW, while the power consumption at a feed rate of 17 m/min was 46.85 kW. Thus, for a cutting depth of 6 mm, the difference in power consumption between the 10 m/min and 17 m/min cutting feed rates was 13.91 kW (46.85–32.94). As the amount of power consumed per 1 m was 3.294 kW when a cutting feed rate of 10 m/min was used, the amount of power necessary to cut an additional 7 m at the same feed rate was 23.058 kW (7 × 3.294). On the other hand, a cutting feed rate of 17 m/min only required an additional power expenditure of 13.91 kW in comparison to the cutting feed rate of 10 m/min. The same situation was also applicable for the cutting depth of 9 mm. Based on these results, it is possible to state that increasing the feed rate at all of the evaluated cutting depths was more advantageous in terms of energy efficiency. The main problem that requires resolution in this context is determining the level of additional wear caused by the faster feed rate, and the increase this caused on the saw-related costs. In the case that the cutting depth remains the same, increasing the feed rates during the cutting processes would be more advantageous, as the reduction of power and labor costs associated with the faster feed rates are greater than the additional costs associated with the saw blade wear. However, in case the reduction of power and labor costs at faster feed rates is lower than the additional costs associated with the saw blade wear, then the use of the faster feed rates would not be advantageous.

An evaluation of the cutting conditions listed in Table 3 reveals that the difference between the down-cutting and up-cutting modes in terms of power consumption was not very significant. At more than 300 cutting cycles, the difference between the two modes was determined as 3 kW. This difference was mainly due to the different horizontal and vertical forces acting on the saw blade during down-cutting and up-cutting [2,20]. Fig. 2 illustrates the difference in terms of power consumption between the down-cutting and up-cutting modes. An evaluation of Fig. 2 indicates that the down-cutting mode is more advantageous in terms of power consumption.

This study also evaluated the effect of the feed rate and cutting depth on the level of power consumption at an industrial-scale. Engineers and operators generally seek to reduce power consumption by optimizing the feed rate and cutting depth. The effects of the feed rate and cutting depth on industrial granite cutting processes are shown in Figs. 3–6.

According to Fig. 3, with the down-cutting mode and at a constant feed rate of 10 m/min, a cutting depth of 3 mm resulted in a power consumption of 21.98 kW, while a cutting depth of 9 mm resulted in a power consumption of 43.23 kW. These results indicated that a threefold increase in the cutting depth was not associated with a threefold increase in power consumption. Similar results were observed at the feed rates of 13, 15, and 17 m/min. These observations can be explained as follows: The segment height of the saw blades used during the study was 12 mm. As the segment penetrated deeper into the rock (in other words, as the cutting depth increased), the number of diamond grits contacting the rock increased, as well. While proportion of the segment that was in contact with the material was 25% at a cutting depth of 3 mm, this proportion increased to 75% at a

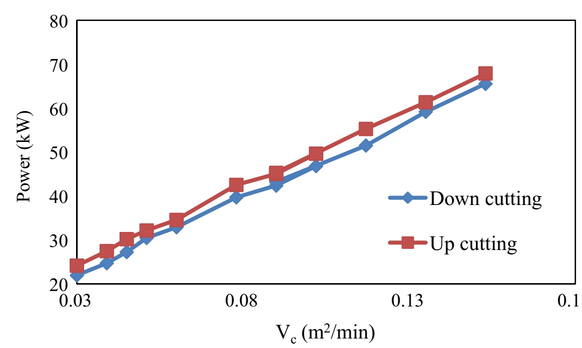

Fig. 2. The relationship between the cutting feed rate and power consumption under all cutting conditions.

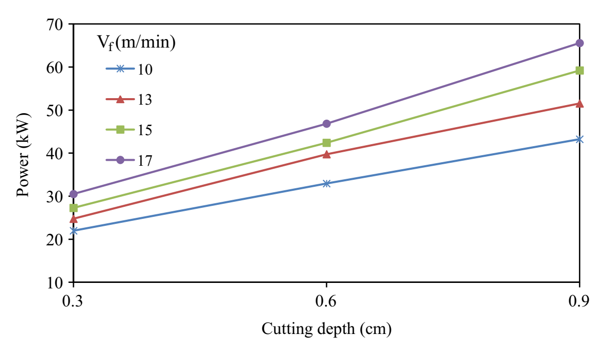

Fig. 3. The effect of cutting depth on power consumption in the down-cutting mode when the feed rate was held constant.

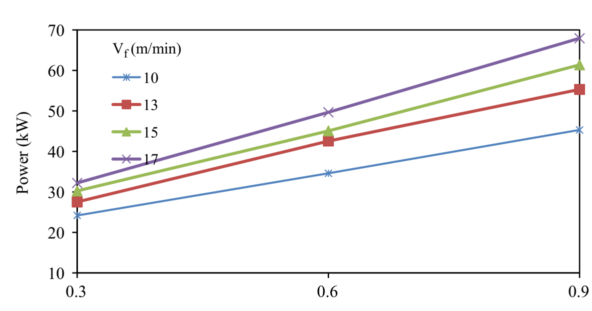

Fig. 4. The effect of cutting depth on power consumption in the up-cutting mode when the feed rate was held constant.

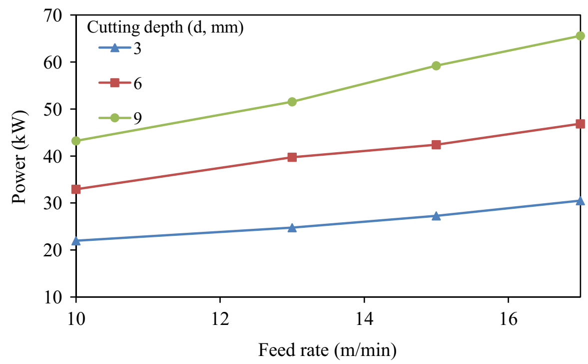

Fig. 5. The effect of feed rate on power consumption in the up-cutting mode when the cutting depth was held constant.

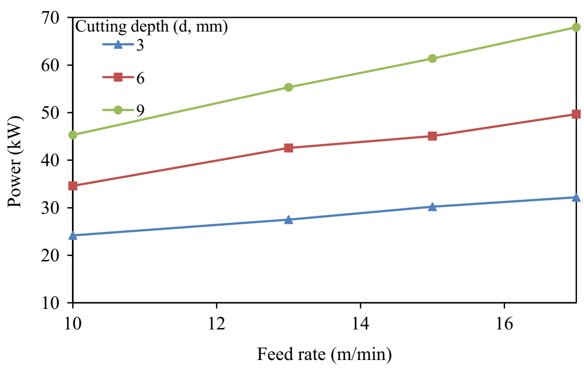

Fig. 6. The effect of cutting depth on power consumption in the up-cutting mode when the feed rate was held constant.

cutting depth of 9 mm. The increase in the level of contact between the segment and the rock resulted in an increase in the level of forces acting on the saw blade and the power consumption. In addition to this, the increase in the number of diamond grits contacting the material will lead to a decrease in the saw blade life. The increased level of contact also resulted in a threefold increase in the production output. Operators will evaluate the benefit of increasing the level of contact by comparing the saw blade-related costs with the cost advantages provided by the higher cutting depths. A similar situation was applicable for all cutting conditions performed using the up-cutting mode (Fig. 4).

The power consumption values obtained with the up-cutting and down-cutting modes when the cutting depth was kept constant and the feed rates were increased are shown in Figs. 5 and 6. With the down-cutting mode and at a constant cutting depth of 3 mm, a feed rate of 10 m/min resulted in a power consumption of 21.98 kW, while a feed rate of 17 m/min resulted in a power consumption of 30.51 kW. Under these conditions, the difference between 10 m/min and the 17 m/min feed rates in terms of power consumption was 8.53 kW. When the feed rate was kept constant and the cutting depth was increased in the down-cutting mode, the highest level of increase in power consumption was observed with the cutting depth of 9 mm. A similar observation was made for the up-cutting mode (Fig. 6).

An evaluation of the relationship between the power consumption values and the cutting depths and feed rates shown in Figs. 3–6 indicated that increasing the feed rate while keeping the cutting depth constant led to a relatively lower increase in power consumption than increasing the cutting depth while keeping the feed rate constant.

Based on the results of this study, a new approach was developed to optimize cost cutting for shallow and deep cutting conditions. Determining the quantitative relationship between the cutting depth and the power consumption is very important for production engineers. To determine this relationship, the up-cutting mode data obtained for the cutting tests numbers 1 and 9 (shown on Table 3) were evaluated. Similar data and relationships were also evaluated for the cutting tests 2 and 10, the cutting tests 3 and 11, and the cutting tests 4 and 12.

In the cutting test number 1, the cutting depth "*d*" of the forwards (or down-cutting) mode was 3 mm, while the feed rate "V_f" was 10 m/min. Under these conditions, the mean power consumption of the forwards cutting saw blade was measured as 21.98 kW (average of 20 cuttings). In the cutting test 9, the cutting depth was 9 mm, while the feed rate was 10 m/min. Under these conditions, the mean power consumption was measured as 43.23 kW. Compared to cutting test 1, the cutting depth was three times higher for cutting test 9, while the other conditions were the same. However, this threefold increase in cutting depth was not associated with a threefold increase in power consumption for cutting test 9. The difference in power consumption was also evaluated for the other cases in which the cutting depth was increased threefold while the feed rate was kept constant (cutting test 2 and cutting test 10; cutting test 3 and cutting test 11; and cutting test 4 and cutting test 12). According to the obtained results, the power used in cutting test 9 was 1.967 times higher than the power used in cutting test 1; the power used in cutting test 10 was 2.082 times higher than the power used in cutting test 2; the power used in cutting test 11 was 2.170 times higher than the power used in cutting test 3; the power used in cutting test 12 was 2.149 times higher than the power used in cutting test 4. Based on these results, it is possible to state that when the cutting feed rate was kept constant, a threefold increase in cutting depth was associated with a nearly twofold increase in power consumption.

4. Discussion

In nearly all of the laboratory studies in the literature, the up-cutting mode was described as leading to a lower power consumption than the down-cutting mode when all of the other cutting parameters were kept the same [2,14,24]. The reason for this is that in the down-cutting mode, the cutting process starts with the maximum chip thickness, which causes high impact loads on the diamond grits. It is known that high impact loads on diamond grits can cause them to break off or to be pulled-out of the matrix prematurely. This observation is valid for the small-sized saw blades that have been used in the literature. However, in contrast to laboratory applications, the cutting of larger-sized granite blocks in industrial settings involves the use of large saw blades. The diameters of these saw blades varied between 1000 and 2000 mm. The segment and matrix structure of large diameter saw blades can also vary depending on the design of the saw body and water grooves. The diamond grits used in large diameters saw blades is different than those used is small diameter saw blades. Although the depth of cut might be similar to those used laboratory-scale applications, all other conditions in industrial-scale cuttings are different than those used in laboratory-scale cuttings, especially during sequential cuttings.

Based on the results of this study obtained from more than 300 cutting data, it was determined that the up-cutting mode consumed more power than the down-cutting mode. This observation can be explained by the production process of large diameter circular saws. All the studies in the literature were performed under cutting conditions involving the use of relatively small diameter ($\leq$600 mm) saw blades. The production process of small diameter saw blades, as well as the manner in which their segments are brazed to their steel cores and the characteristics of the diamond grit used in their segments, differs considerably from those of large diameter saw blades. As described by the studies in the literature, the high impact loads caused by the cutting forces on the saw blade leads to the fracturing and pulling-out of the diamond grits. On the other hand, in granite cutting processes involving the use of large scale saw blades, the diamond grits within the matrix of the segment are designed to withstand high impact loads. Moreover, owing to their advanced design characteristics of these saw blades, the industrial cutting of relatively large blocks can be performed in both the forwards and backwards directions—in other words, with both the up-cutting and down-cutting mode. In addition, the higher power consumption observed during the up-cutting mode in comparison to the down-cutting mode can be explained by the diamond grits causing chips to break off from the rock during the cutting process. In the down-cutting mode, the cutting process begins with the maximum penetration of the diamond grits into the rock. This facilitates the breaking off of chips from granite, which are known to be brittle rocks. Owing to the moment generated by the mass and rotational speed of saw blade and to the force of the impact, brittle rocks are cut more easily with the up-cutting mode. The up-cutting mode begins to cut with the minimum chip thickness, and takes longer to break off chips from the rock than the down-cutting mode. For this reason, the up-cutting mode has a higher power consumption, although the difference is not very large. As the power consumption values of these two modes are relatively close to one another, the machines used in industrial granite block cutting processes perform cuts in both the forwards and backwards directions. This reduces the time period for which the machine stands idle, thereby increasing the cutting period by twofold, and reducing both the amount of labor and time used during the processes.

In laboratory-scale stone cutting, machine stability can be a problem when up-cutting, and can lead to the lifting of the workpiece [19]. This problem can be encountered during the cutting of slabs from strips, and the cutting of relatively smaller pieces. However, in the real cutting conditions involving the cutting of relatively larger blocks with volumes of 2 to 6 m^3, the workpiece will be stabilized on the block carrying trolley by its own weight. During the sawing process, stability is not a problem owing to the fact that only the saw blade on the bridge is moving, and/or because fixed head machineries are used. As the forces acting on the saw blade are relatively close for the up-cutting and down-cutting modes, an increase in the cutting rate will cause the power consumption values and, hence, the power consumption curves of the two modes to by similar (Fig. 2).

An evaluation of Figs. 3–6 indicate that when the cutting depth was held constant and the feed rate increased, the increase observed in the power consumption values of the up-cutting and down-cutting modes were lower than the cases in which the feed rate was held constant and the cutting depth was increased. This result is in agreement with the findings of many studies from the literature [1,2,6,19]. Based on these results, it is possible to state in industrial granite cutting processes, increasing the feed rate at shallow cutting depths is more advantageous in terms of power consumption. However, one important aspect that needs to be considered in industrial cutting processes is how the amount of cut performed per unit time will vary between the shallow and deep cutting approaches. Both the literature and this study have demonstrated that there is a significant difference in terms of power consumption between the forwards and backwards cutting movement of the saw blade, and between cutting at a depth of 3 mm and cutting at a depth of 9 mm. However, the main problem that the operator must resolve is whether a threefold increase in cutting depth entails a threefold increase in expenditure of power. This study demonstrated that the rate of increase in cutting depth is different from the rate of increase in power consumption. Thus, while increasing the cutting depth threefold results in a nearly threefold reduction of labor costs and many other costs, this increase in cutting depth does not engender a threefold increase in power consumption. In addition to this, it is known that a threefold increase in cutting depth will also reduce the saw blade life (due to increased saw blade wear), and thereby increase the cutting costs in the long-term [5,6,23,28]. Considering the fact that increasing sawing depth achieves saving on labor and energy consumption, it must be justified if savings meet sawing costs. For the practitioner (or operator), each cutting process is associated with a specific order, and a balance needs to be made between the profit resulting from that order and the cutting costs. In this balance, it is also necessary and important to consider factors such as the timely completion of the cutting, the relationship between cost and time, and labor costs. In all cutting processes for natural stones, the main requisite for optimizing the cutting parameters is having a good and accurate understanding of the process. This study elaborately discussed industrial granite cutting process performed with multi-blade block cutter, and a novel approach has been suggested to optimize cutting conditions.

5. Conclusions

In the industrial-scale cutting processes of large sized natural stones, the cutting of hard rocks such as granite is particularly important. In contrast to other stones, hard stones are cut using a sequential approach. Reaching the desired cutting depth is hence a time-consuming process. For this reason, it is important to carefully select the appropriate balance between power consumption, time, and costs for applications involving the cutting of hard rocks, and to accurately determine and employ the optimum cutting conditions. No previous studies were identified in the literature that described granite cutting process in an industrial setting, or industrial-scale studies regarding the parameters that affect cutting efficiency. This study was performed by evaluating cutting conditions in their own industrial setting, and it attempted to provide a new approach and perspective regarding the industrial cutting process of relatively large blocks. The sawing tests were performed on a two-column block cutter (SIMEC NT2 50S). The maximum spindle power of the machine was 220 kW. For all cutting conditions, the rotational speed was 35 m/s. According to the cutting conditions, the granite used in this study was a medium hard rock. An evaluation of other studies in the literature indicated that the power consumption/requirement characteristics of granite were similar to those of other rocks with similar properties. For cutting processes, it is important to establish a proper balance between costs and return based on the applicable operating conditions. In future studies, it would be more appropriate to analyze different cutting conditions of the same rock with a single saw blade, rather than analyzing processes in which the same saw blade is used for cutting more than one type of rock (as is often the case in numerous studies in the literature). It should be remembered that this study reflects real-world conditions regarding the cutting of relatively hard rocks. Cutting tests performed on hard rocks under laboratory conditions by using relatively small diameter saw blades at high cutting depths might ultimately yield misleading results.

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