Influence of Traverse Velocity and Pump Pressure on the Efficiency of Abrasive Waterjet for Rock Cutting

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Abstract. This paper presents investigations on the behavior of four types of rocks (syenite, granite, marble and sandstone) subjected to abrasive waterjet cutting. The influence of traverse velocity and pump pressure on the efficiency of cutting is analyzed. Moreover, the influence of the physical-mechanical behavior of the rocks on their removal process is investigated. It was found that, in general, the removed volume of rock and the cutting rate tend to increase with the decrease of traverse velocity and with the increase of pump pressure. Moreover, the opposite trend was observed in the analysis of the specific energy of cutting. Optimum conditions of cutting efficiency were found when cutting the studied rocks with a traverse velocity of 200 mm/min and a pump pressure of 400 MPa. Finally, the marble and the sandstone presented the lowest resistance to abrasive waterjet cutting while the syenite and granite presented the highest resistances.

Keywords: Abrasive waterjet, efficiency of cutting, physical-mechanical behavior, rock cutting.

1. Introduction

Abrasive waterjet (AWJ) consists in a versatile and non-conventional cutting technique which has been effectively applied to rock cutting since the late 1980s. In geotechnics, it is also frequently applied in mineral extraction, hydrodemolition and well drilling (Summers, 1995). Until the early 1980s, AWJ machining was considered economically unfeasible, yet researchers made efforts in order to develop technologies which ensured its growth into a full-scale viable production process (Akkurt *et al.*, 2004). The AWJ action involves high impact forces which lead to the generation and propagation of cracks through the affected area of the rock. Cracking occurs along with erosion in order to disaggregate the target, producing a kerf. At the top of the kerf the cracking process is more intense, while at the bottom what predominates is erosion because of AWJ energy loss with increasing depth. AWJ rock cutting is a complicated process due to the turbulent action of the jet and the complexity of the rock material, which is generated in uncontrolled environment without human interference. Moreover, it is composed by different types of minerals with distinct behaviors. Because of that, some researchers have been discouraged to continue developing studies with focus on rock behavior, giving preference to working with a single type of rock, mainly granites, or "rock-like" materials like concrete (Momber *et al.*, 1999; Momber & Kovacevic, 1999; Lauand *et al.*, 2001; Aydin *et al.*, 2012; Karakurt *et al.*, 2012; Aydin *et al.*, 2013; Oh & Cho, 2016). Even presenting mechanical similarities, concrete is similar only to a restricted range of rocks, thus the phenomena involved in AWJ rock cutting must focus on varied rocks as materials studied. Therefore, the present study aims to contribute with an experimental analysis of the behavior of four different types of rocks when subjected to AWJ cutting. The influence of traverse velocity (v_T) and pump pressure (P) on the efficiency of cutting is investigated. The traverse velocity is the velocity with which the AWJ machine nozzle runs across the target surface, *i.e.* the rock surface.

2. Experimental Study

2.1. The abrasive waterjet machine

The machine used in this research is a Flow Mach 2C and the tests performed involved a pressure range from 100 to 400 MPa and a traverse velocity from 100 to 400 mm/min. Figure 1 presents a flowchart which summarizes the machine operating system. Tap water is filtered and maintained under little pressure inside the booster pump to ensure that the intensifier pump is kept fed. The intensifier pump consists of two circuits: the oil circuit and the water circuit. The oil circuit drives the intensifier piston so that it may push the water and amplify its pressure. At the initial condition of the water, the oil is kept in a reservoir and a hydraulic pump maintains it under low pressure. Then, the pressurized water goes through the attenuator, which damps pressure fluctuations assuring a steady water flow through the plumbing to the cutting head. The water passes through the orifice, which is responsible for converting pressurized water into a waterjet. The abrasive material (almandine garnet) joins the waterjet by suction due to the effect of the waterjet and the water and abrasive material are mixed and homogenized inside the nozzle, before leaving the machine and hitting the target as an abrasive waterjet. When the jet leaves the target, it is collected in a water tank.

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Submitted on December 19, 2016; Final Acceptance on September 11, 2017; Discussion open until April 30, 2018.
DOI: 10.28927/SR.403255

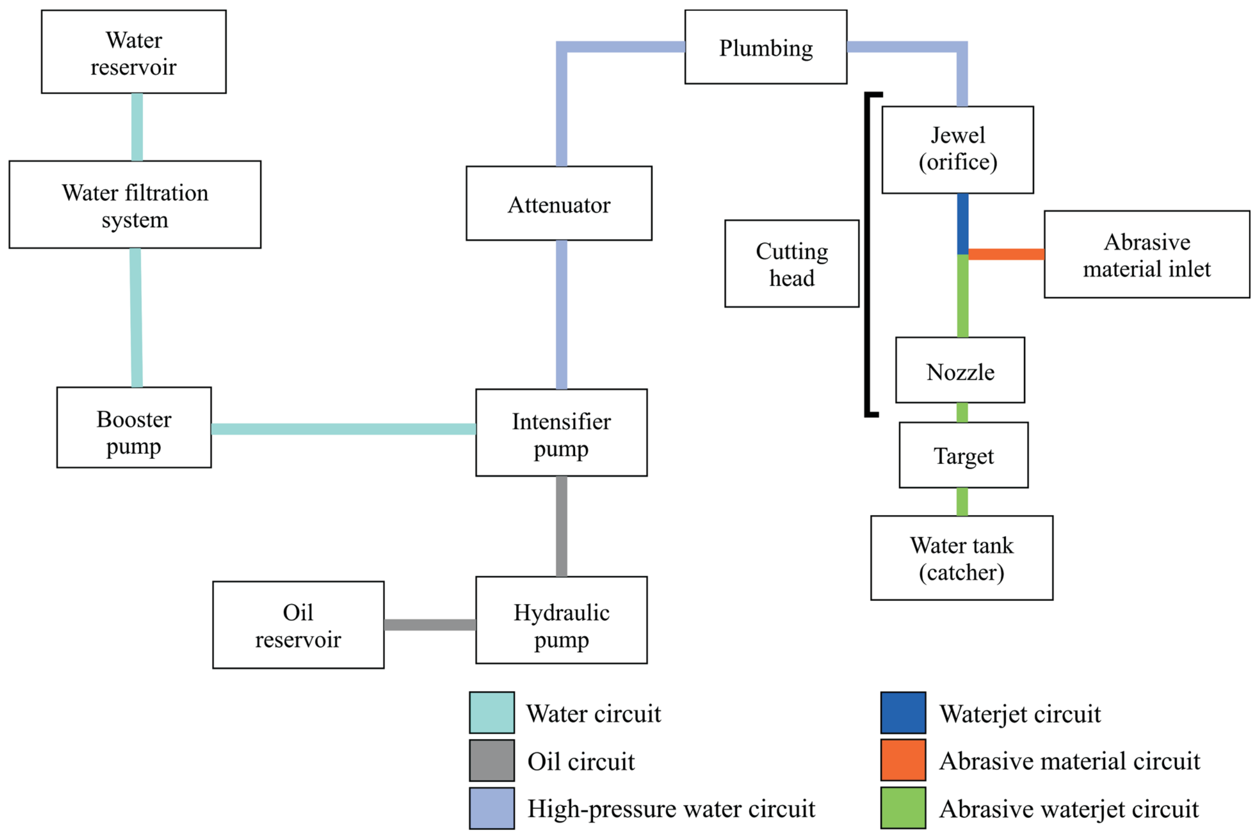

Figure 1 - Flowchart of the AWJ machine operating system.

2.2. Tested rocks

Four types of Brazilian rocks were selected based on their distinct physical-mechanical characteristics: syenite, granite, marble and silicified sandstone. Rock blocks were collected in single batches at quarries in the States of São Paulo and Espírito Santo. The main properties and mineralogical compositions of the specimens are shown in Table 1. The tensile strength and the Schmidt hardness were determined based on the ISRM Suggested Methods (1978, 2009). The compressive strength and the Young's modulus were determined according to the ISRM Suggested Methods (1979), while the dry density, porosity and Amsler wear were determined according to the Brazilian standards NBR 12766 (ABNT, 1992a) and NBR 12042 (ABNT, 1992b). Thin sections of the rocks were examined for determination of the mineralogical composition and texture.

2.3. Rock specimens for cutting tests

Rock blocks were cut and rectified as rectangular prisms with minimum dimensions of 100 x 100 x 160 mm. The machine parameters were adjusted so that the specimens were not cut through. The intention was to generate kerfs in order to investigate parameters related to the volumes of the kerfs. For the same type of rock and the same conditions of cutting, five tests were performed to increase the reliability of the results.

2.4. Tests performed

According to Momber (2004) the most important machine parameters which influence the cutting performance of brittle materials are traverse velocity (v_T), pump pressure (P) and abrasive flow rate (m_A). In the present study, the first two parameters were investigated.

The experimental program involved tests with two main different conditions: variation of traverse velocity and variation of pump pressure. The other parameters were kept constant during the experiments (Table 2). Data analysis was made through scatter diagrams and basic regression. For the analysis of pump pressure data, second order polynomial curves fitted adequately. However, it was observed that the scatter diagrams for traverse velocity data showed more complex behavior, which could not be described by basic functions in consistency with reality. Therefore, fitting for these cases is not shown.

The volumes of the kerfs were determined by filling them with mercury. Eq. 1 describes the calculation of the mercury volume inside a kerf, which corresponds to the volume of removed rock. V is the volume of the kerf (cm^3), m_{Hg} is the mass of mercury (g), m_s is the mass of the syringe

Table 1 - Main properties and mineralogical compositions of the rocks studied.

Features		Syenite	Granite	Marble	Sandstone
Physical and mechanical	Dry density (g/cm^3)	2.71	2.61	2.82	2.31
	Porosity (%)	0.064	0.182	0.313	2.830
	Amsler abrasion wear (mm/1000 m)	0.86	0.68	7.96	1.53
	Tensile strength (MPa)	13.20	10.17	4.22	12.11
	Compressive strength (MPa)	257.17	182.41	69.75	191.85
	Schmidt hardness	47.60	46.90	39.10	41.20
	Young's modulus (GPa)	75.34	73.91	54.84	34.72
Mineralogical composition (%)	Alkali feldspar	40	45	-	traces
	Plagioclase	20	16	-	-
	Quartz	-	35	-	100
	Augite	12	-	-	-
	Nepheline	12	-	-	-
	Biotite	2	2	-	-
	Hornblende	1	-	-	-
	Apatite	5	traces	-	-
	Olivine	3	-	-	-
	Opaque minerals	5	2	-	-
	Calcite/Dolomite	-	-	100	-
	Lithic fragments	-	-	-	traces
	Epidote	-	-	traces	-
	Zircon	traces	traces	-	-

Table 2 - Machine parameters adopted in the tests.

Machine parameters	Test 1 (v_t variation)	Test 2 (P variation)
Pump pressure - P (MPa)	400	100, 200, 300, 400
Nozzle angle (°)	90	90
Traverse velocity - v_T (mm/min)	100, 200, 300, 400	200
Stand-off distance - h_S (mm)	5.00	5.00
Orifice diameter - d_0 (mm)	0.33	0.33
Nozzle diameter - d_F (mm)	1.02	1.02
Abrasive flow rate - m_A (g/min)	408.23	408.23
Abrasive diameter - d_A (mesh)	80	80

(g) and 13.58 corresponds to the specific mass of mercury (g/cm^3):

$$V = \frac{m_{Hg} - m_s}{13.58} \quad (1)$$

The main results obtained from the cutting tests are summarized in Table 3. The specific energy of cutting (SE_C) is defined as the ratio between the total amount of energy provided by the AWJ machine and the removed volume of rock (V_R). The total amount of energy was calculated according to the procedure presented in Momber & Kovacevic (1999). The cutting rate (CR) is the ratio between the volume of the kerf and the time elapsed during the cutting process. Each result presented in Table 3 is the average of results of 5 tests.

3. Results and Discussion

Figure 2 presents the relationship between the removed volume of rock and the traverse velocity. A general trend of decrease of the removed volume of rock with the

Table 3 - Results obtained from the AWJ cutting tests.

Rock	v_T (mm/min)	P (MPa)	V_R (cm^3)	CR (cm^3/min)	SE_C (J/cm^3)
Syenite	100	400	17.04	11.36	144.09
Syenite	200	400	17.31	19.39	84.73
Syenite	300	400	8.27	16.54	99.00
Syenite	400	400	4.98	13.28	123.71
Syenite	200	100	2.40	3.20	101.87
Syenite	200	200	6.16	8.22	95.56
Syenite	200	300	9.38	12.50	100.73
Granite	100	400	15.29	10.19	160.63
Granite	200	400	18.30	17.77	92.15
Granite	300	400	7.69	15.39	106.79
Granite	400	400	5.17	13.78	118.81
Granite	200	100	2.49	3.32	98.65
Granite	200	200	4.29	5.71	137.43
Granite	200	300	8.05	10.73	115.45
Marble	100	400	29.36	19.57	83.77
Marble	200	400	28.78	37.56	43.60
Marble	300	400	18.09	36.20	45.27
Marble	400	400	8.57	22.85	71.93
Marble	200	100	3.21	4.28	74.70
Marble	200	200	9.89	13.19	59.68
Marble	200	300	18.33	24.44	50.60
Sandstone	100	400	29.62	19.75	82.91
Sandstone	200	400	33.24	39.34	43.60
Sandstone	300	400	15.07	30.14	54.33
Sandstone	400	400	9.41	25.08	65.78
Sandstone	200	100	4.01	5.35	59.86
Sandstone	200	200	10.87	14.49	54.30
Sandstone	200	300	18.22	24.29	50.97

increase of traverse velocity is observed, in spite of the results obtained for 100 mm/min. An optimum traverse velocity exists around 200 mm/min for the rocks studied. Low values of removed volume are observed for traverse velocity of 100 mm/min. Lower velocities imply higher exposure time of an area to the action of the AWJ. Thus, a larger loss of energy is expected mainly due to damping effects regarding larger accumulation of water and abrasive material inside the kerf, which reduces the impact of the AWJ. In contrast, at higher velocities (300 and 400 mm/min) water and abrasive material do not have time enough to accumulate inside the kerf, thus losses are smaller. However, as the exposure time is too short, there is not enough time to remove a considerable amount of rock. In addition, since the removed volume is larger at 100 mm/min than beyond 300 mm/min, it may be inferred that the exposure time plays a more important role in the removal of rock than the damping effects. At higher traverse velocities, the range of rock removal is small, while at lower traverse velocities the removal of the less resistant rocks (*i.e.* the marble and sandstone) is more efficient.

Figure 3 presents the influence of the pump pressure (P) on the removed rock volume. For the rocks studied, the removed volume increases with the increase of pump pressure. A steeper gradient is observed for the marble and sandstone, indicating a lower resistance of these rocks to removal due to the action of the AWJ. Curve fitting the data points adopting second degree polynomial equations resulted in $R2$ higher than 0.99 (Eq. 2 to 5):

$$\text{Syenite: } V_R = 2.6\times10^{-5}P^2 + 0.027P - 0.344 \quad (2)$$

$$\text{Granite: } V_R = 9.4\times10^{-5}P^2 - 0.012P + 2.975 \quad (3)$$

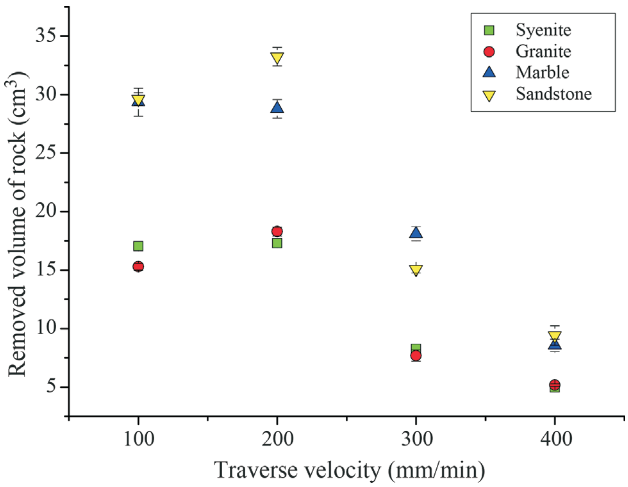

Figure 2 - Influence of traverse velocity on the removed volume of rock.

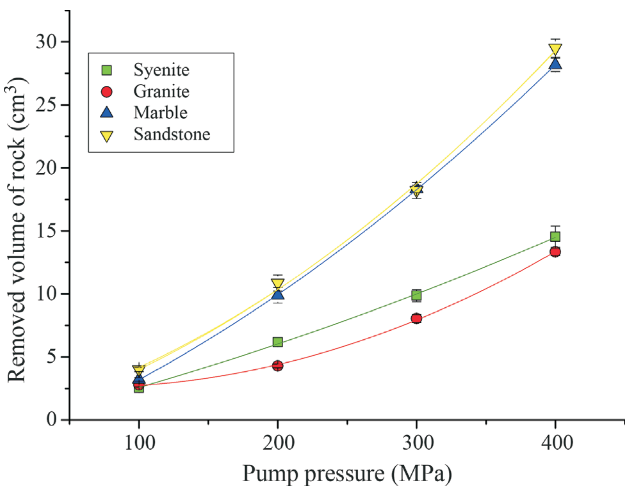

Figure 3 - Influence of pump pressure on the removed volume of rock.

$$\text{Marble: } V_R = 7.9 \times 10^{-5} P^2 + 0.044P - 1.983 \quad (4)$$

$$\text{Sandstone: } V_R = 1.1 \times 10^{-4} P^2 + 0.032P - 0.192 \quad (5)$$

Momber & Kovacevic (1999) state that for brittle materials there is a threshold pressure under which the AWJ is no longer able to remove material. Those authors estimate this critical value by a linear fit of the erosion depth *vs.* the applied pump pressure data regarding kerf depth. In contrast, Engin (2012) investigated the correlation between the erosion depth and the applied pump pressure regarding AWJ cutting of granites and a nonlinear correlation below 100 MPa was observed. In the case of the present study, it seems that the relationship between the removed volume of rock (V_R) and the pump pressure is also not linear. A linear extrapolation would suggest a lower threshold pressure for the syenite and granite. However, this is not consistent with the fact that these rocks are more resistant to AWJ removal when compared to the marble and sandstone. Bortolussi *et al.* (1988) observed that even with 34 MPa an AWJ is able to cut granite samples up to 5 mm depth with machine parameters similar to those adopted in this study. Therefore, more tests would have to be performed between 0 and 100 MPa in order to determine the threshold pressure with certainty.

Figure 4 presents the influence of traverse velocity on the specific energy of cutting (S_{EC}), *i.e.* the total energy provided by the machine per removed volume of rock. In spite of the results for a traverse velocity of 100 mm/min, the specific energy of cutting increases linearly with the increase of the traverse velocity. This means that with traverse velocity of 200 mm/min the AWJ machine expends less energy in kerf generation. Moreover, as already discussed, much energy is lost because of damping effects at very low traverse velocities, which explains the large expenditure of energy when cutting rocks with 100 mm/min.

Figure 5 presents the relationship between the pump pressure and the specific energy of cutting. The general trend is the decrease of the specific energy of cutting with the increase of pump pressure. The granite presented a different behavior with a specific energy peak at 200 mm/min, which may be influenced by the variability of the rock. It is interesting to notice that the range of specific energy values is larger for the tests with varying traverse velocity in comparison to the tests with varying pump pressure. Eq. 6 through 9 are the results of polynomial curves fitting the data from the rocks studied. *R*2 values were much better for the marble and sandstone.

$$\text{Syenite: } SE_C = -2.5 \times 10^{-4} P^2 + 0.093P + 87.441 \quad R^2 = 0.91 \quad (6)$$

$$\text{Granite: } SE_C = -1.7 \times 10^{-3} P^2 + 0.861P + 21.763 \quad R^2 = 0.61 \quad (7)$$

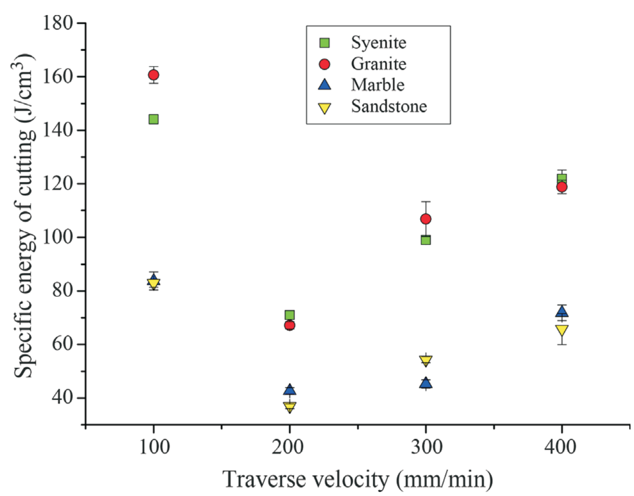

Figure 4 - Influence of traverse velocity on the specific energy of cutting.

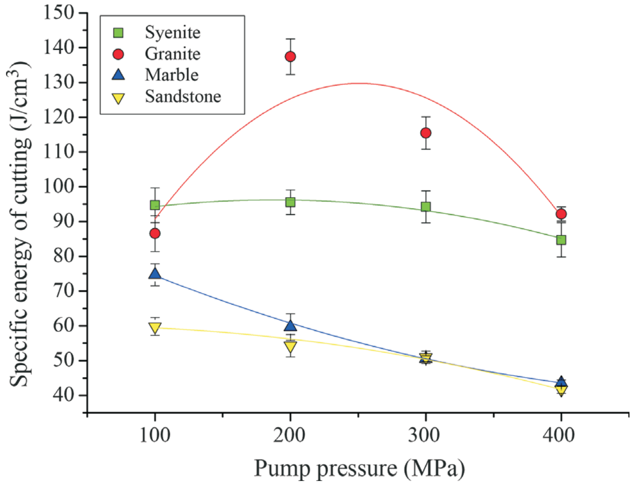

Figure 5 - Influence of pump pressure on the specific energy of cutting.

$$\text{Marble: } SE_C = 1.7 \times 10^{-4} P^2 - 0.186P + 91.411 \quad R^2 = 0.99 \tag{8}$$

$$\text{Sandstone: } SE_C = -1.4 \times 10^{-4} P^2 + 0.009P + 59.898 \quad R^2 = 0.97 \tag{9}$$

Figure 6 shows the relationship between the cutting rate and the traverse velocity. In spite of the results for 100 mm/min, the cutting rate decreases with the increase of the traverse velocity. Again, the traverse velocity of 200 mm/min is the optimum condition for cutting with the highest cutting rates. At 100 mm/min the rock removal is complicated by the large amount of water and abrasive material inside the kerf, damping the impact and useful power of the AWJ.

Figure 7 presents the relationship between the cutting rate and the pump pressure. The cutting rate increases with the increase of the pump pressure. As observed in other relationships, a steeper gradient is observed for the marble and sandstone because of their lower resistance to rock removal. Eq. 10 through 13 describe the fitted curves for this relationship.

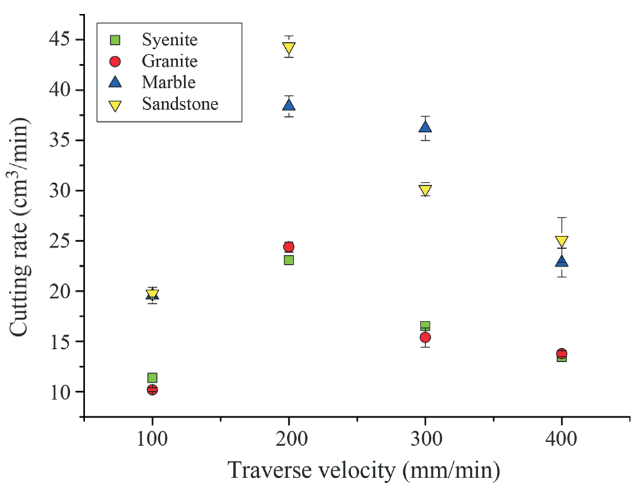

Figure 6 - Influence of traverse velocity on the cutting rate.

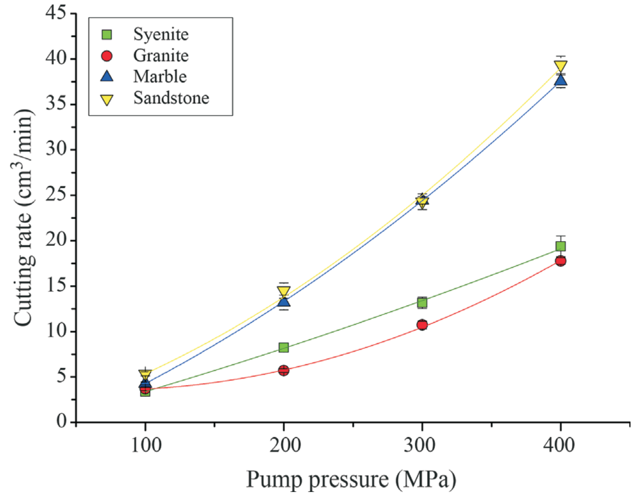

Figure 7 - Influence of pump pressure on the cutting rate.

Atici & Ersoy (2009) state that a good indication of the cutting performance can be assessed by analyzing the relationship between the specific energy of cutting and the cutting rate. When the lowest specific energy is associated to the highest cutting rate, then the most efficient condition is achieved. Also, the specific energy of cutting is directly related to the costs of production/cutting. In the case of this study, the most efficient condition is observed when cutting rocks with a traverse velocity of 200 mm/min and a pump pressure of 400 MPa. In this condition, the removed volume of rock is also larger for all rocks studied.

$$\text{Syenite: } CR = 2.3 \times 10^{-5} P^2 + 0.0407P - 0.9149 \quad R^2 = 0.99 \tag{10}$$

$$\text{Granite: } CR = 1.3 \times 10^{-4} P^2 - 0.019P + 4.2271 \quad R^2 = 0.99 \tag{11}$$

$$\text{Marble: } CR = 1.03 \times 10^{-4} P^2 + 0.0593P - 2.6807 \quad R^2 = 0.99 \tag{12}$$

$$\text{Sandstone: } CR = 1.4 \times 10^{-4} P^2 + 0.0422P - 0.2565 \quad R^2 = 0.99 \tag{13}$$

The marble and the sandstone presented similar behavior regarding the response to the AWJ cutting and the same can be stated for the syenite and the granite. The marble is easily cut by the AWJ due to two main reasons: primarily it is practically a monomineralic rock composed by calcite, a mineral which presents three perfect cleavage directions. Thus, the abrupt impact of the AWJ on the surface of this rock leads to the generation of a dense network of cracks through its cleavage planes, easily disaggregating it.

Secondly, since much of the rock is removed by erosion, the process is facilitated because calcite hardness is 3 according to the Mohs scale. In the case of the sandstone, a different situation occurs. Although it is a sedimentary rock, its tensile and uniaxial compressive strength are very high due to its silica cement and the lack of weak structures like cleavage. However, when subjected to high impact like during AWJ cutting, fast propagation of cracks occurs due to its high brittleness (high UCS strength, but low rigidity), easily generating kerfs.

Finally, both syenite and granite present similar properties and both are igneous rocks. Their lower cutting rate and higher AWJ specific energy, in comparison to the other rocks studied, are a result of their higher strength and rigidity. These rocks have a main difference regarding their strength: while the granite presents quartz, the syenite has an imbricated structure. Both features increase strength and may compensate for weaker features like the presence of phenocrysts in the granite and the lack of quartz in the syenite.

4. Conclusions

The effects of traverse velocity and pump pressure on cutting parameters related to cutting efficiency were investigated for different types of rocks. The condition with which the best cutting efficiency is achieved is cutting with a traverse velocity of 200 mm/min and a pump pressure of 400 MPa. The removed volume of rock and the cutting rate both decrease from 200 mm/min to 400 mm/min and also to 100 mm/min, thus an optimum traverse velocity exists around 200 mm/min. The opposite trend is observed for the specific energy of cutting. Both the removed rock volume and the cutting rate increase with the increase of pump pressure and, in general, the opposite trend is observed for the specific energy of cutting. The mineralogical composition of the rocks and their physical-mechanical behavior play a major role on how the studied rocks are disaggregated in order to generate kerfs. It was found that the marble and sandstone present a lower and similar resistance to AWJ cutting and the syenite and granite present a higher and similar resistance to AWJ cutting.

Acknowledgments

The authors are grateful to CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for financial support throughout this research.

References

ABNT (1992a). NBR 12.766: Rochas para Revestimento: Determinação de Massa Específica Aparente, Porosidade Aparente e Absorção D'água Aparente - Método de Ensaio.

ABNT (1992b). NBR 12.042: Materiais Inorgânicos - Determinação do Desgaste por Abrasão.

Akkurt, A.; Mustafa, K.K.; Ulvi, S.C. & Fevzi, E. (2004). Effect of feed rate on surface roughness in abrasive water jet cutting applications. Journal of Materials Processing Technology, 147(1):389-396.

Atici, U. & Ersoy, A. (2009). Correlation of specific energy of cutting saws and drilling bits with rock brittleness and destruction energy. Journal of Materials Processing Technology, 209(5):2602-2612.

Aydin, G.; Karakurt, I. & Aydiner, K. (2012). Performance of abrasive waterjet in granite cutting: influence of the textural properties. Journal of Materials in Civil Engineering, 24(7):944-949.

Aydin, G.; Karakurt, I. & Aydiner, K. (2013). Prediction of the cut depth of granitic rocks machined by abrasive waterjet (AWJ). Rock Mechanics and Rock Engineering, 46(5):1223-1235.

Bortolussi, A.; Yazici, S. & Summers, D.A. (1988). The use of waterjets in cutting granite. Proc. 9th Int. Symp. on Jet Cutting Tech., Sendai, paper E3, 15 p.

Engin, I.C. (2012). A correlation for predicting the abrasive water jet cutting depth for natural stones. South African Journal of Science, 108(9-10):1-11.

ISRM (1978). Suggested Methods for Determining Tensile Strength of Rock Materials. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstract, 15(3):99-103.

ISRM (1979). Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstract, 16(2):135-140.

ISRM (2009). Suggested Method for Determination of the Schmidt Hammer Rebound Hardness: Revised Version. International Journal of Rock Mechanics and Mining Sciences, 46(3):627-634.

Karakurt, I.; Aydin, G. & Aydiner, K. (2012). An experimental study on the depth of cut of granite in abrasive waterjet cutting. Materials and Manufacturing Processes, 27(5):538-544.

Lauand, C.T.; Martín, C.G.R.; Hennies, W.T. & Agus, M. (2001). Performance of abrasive waterjet in granite cutting: influence of the textural properties. WJTA American Waterjet Conference, pp. 427-449.

Momber, A.W. (2004). Wear of rocks by water flow. International Journal of Rock Mechanics and Mining Sciences, 41(1):51-68.

Momber, A.W. & Kovacevic, R. (1999). An energy balance of high-speed abrasive water jet erosion. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 213(1):463-472.

Momber, A.W.; Mohan, R.S. & Kovacevic, R. (1999). On-line analysis of hydro-abrasive erosion of pre-cracked materials by acoustic emission. Theoretical and Applied Fracture Mechanics, 31(1):1-17.

Oh, T.M. & Cho, G.C. (2016). Rock cutting depth model based on kinetic energy of abrasive waterjet. Rock Mechanics and Rock Engineering, 49(3):1-14.

Summers, D.A. (1995). Waterjetting Technology. 1st ed. Chapman & Hall, London, 624 p.

List of Symbols

AWJ: abrasive waterjet
CR: cutting rate
d_0: orifice diameter
d_A: abrasive diameter
d_F: nozzle diameter
h_S: stand-off distance
m_A: abrasive flow rate
m_{Hg}: mass of mercury
m_s: mass of the syringe
P: pump pressure
*R*2: coefficient of determination
SE_C: specific energy of cutting
V: volume of the kerf
V_R: removed volume of rock
v_T: traverse velocity