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Rock technological parameters useful to water jet cutting systems

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ABSTRACT: High pressure water jet technology for cutting rocks is currently employed for a very wide range of materials including rocks, more specifically ornamental rocks. This advanced technology is applied not only to drilling or excavation of hard rocks for winning the blocks with the opening of holes or slots, but also for end products in the field of ornamental rocks. In recent years, the increasing worldwide use of advanced machinery, as new and advanced technology replaces conventional procedures, has led to fully automated technique that use CAD/CAM processes to manufacture high quality end products. A Brazilian Research Program in this field began last year with the installation of a sophisticated equipment of high pressure abrasive water jet system that was imported from the USA. This paper presents the first results of researches about the main technological characteristics of Brazilian ornamental rocks, determined in laboratory with granite and marble samples using this advanced technology. Laboratory determination of these parameters on test samples of appropriate geometry were performed and the first results indicate that this procedure will provide important data for the optimization of the cutting process. The tests were performed on samples of commercial granite and marble that are very appreciated in the domestic market and also on rocks exported to the international markets.

1 INTRODUCTION

In a paper published by Kovacevic et al, (1997) there is the following reference: "Thermodynamic analysis of material removal mechanisms indicates that an ideal tool for shaping of materials is a high energy beam, having infinitely small cross-section, precisely controlled depth, and direction of penetration, and does not cause any detrimental effects on the generated surface. The production of the beam should be relatively inexpensive and environmentally sound while the material removal rate should be reasonably high for the process to be viable. A narrow stream of high energy water mixed with abrasive particles comes close to meeting these requirements because abrasive waterjet machining has become one of the leading manufacturing technologies in a relatively short period of time."

To make high precision parts with automatic computer-aided control, the international market currently offers sophisticated systems for cutting hard materials with the abrasive water jets or soft materials with only water at high pressure.

Last year, one of such high technology equipment was bought by the São Paulo University with the help of FAPESP, the São Paulo State Foundation of Research Development (Lauand et al.,2000), to implement an advanced technology workshop.

The abrasive water jet Module was installed at the Rock Mechanics Laboratory and a Brazilian Program for cutting Ornamental Rocks has begun as part of a Masters of Engineering Graduation Course. The purpose is to develop research projects on technological parameters for cutting rocks.

The system requires high quality garnet for proper operation. Whenever a quality equivalent product is not available in Brazil, it is necessary to import from foreign countries, and the recommended 80 mesh grain size is the most expensive abrasive that can be used in the system. As in Brazil there are quality suppliers of manufactured, cheaper abrasives, two samples were also tested. These materials are aluminum oxide and silicon carbide, 80 mesh grain size, supplied by Alcoa, with facilities located in Salto de Itú, São Paulo, at a convenient distance from our Institution.

2 GENERAL ASPECTS

For the first studies intended to check the new equipment behavior and its performance for cutting different kinds of rocks.

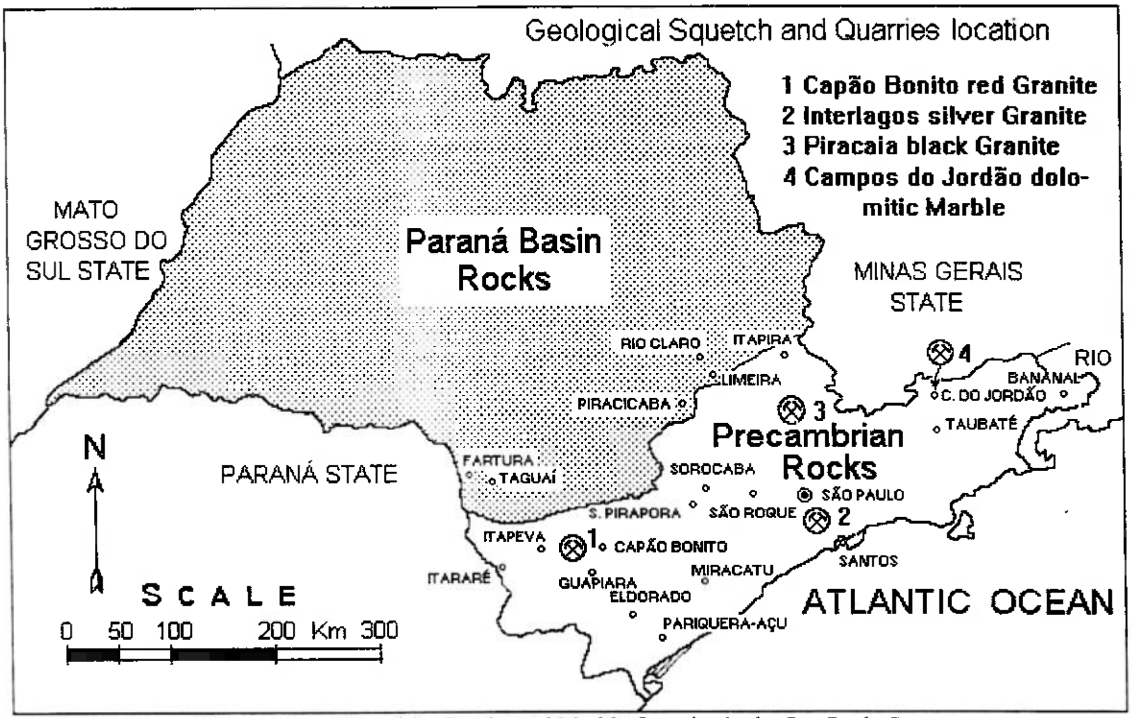

Figure 1. Location of the Granite and Marble Quarries in the São Paulo State.

For the first studies, three granite and one marble specimens of commercial quality ornamental rocks from the State of São Paulo were selected. and preliminary samples cut for testing the system. as well as to determine major technological parameters and behavior of this rocks under the new cutting system.

Another purpose was to determine test parameters of different abrasive options for the water jet system, not only because of the issues with imported garnet, as mentioned above, but also because of the fact that synthetic, or manufactured. abrasives normally have more constant chemical and physical properties than those of natural minerals.

Field trips to collect rock samples was the first part of the work. Then these samples were shaped according to standard procedures. with conventional diamond blades, prior to the test with the water jet cutting nozzle of the OMAX System. The next phase was the actual test of system. when several rock samples were cut at different transverse speed and with different kinds of abrasives.

Finally, the test results and some general conclusions about the main technological parameters for the optimization of the abrasive water system were established and will be described in the following paragraphs.

Unfortunately. the initial evaluation tests with the synthetic alumina and silicon carbide produced in Brazil by Alcoa. were not satisfactory and the use of these products is not recommended. Thus. the only suitable product for our test program was the imported 80 mesh grain size garnet, from Flow, that was bought in São Paulo.

3 THE ROCK SAMPLES

The three commercial granite quarries selected are the valued Capão Bonito red Granite, the Interlagos silver Granite and the Piracaia black Granite. The mining sequence of the red granite with jet piercing channeling was presented last year at MPES'99 in Dniepopetrovsk, Ukraine (Hennies, W. T. & al., 1999).

The other two are the silver Interlagos Granite that is explored from Parelheiros, a district in São Paulo city, and the black Piracaia Granite, localized north of São Paulo near to Piracaia city, at a distance of about one hundred km from São Paulo city.

The Piracaia black Granite is generally used for funeral arts as cemetery tombstones.

The granite is from Precambrian age and belongs to the crystalline Brazilian shield.

Finally, the marble is a dolomite marble that is partially exploited as dolomite limestone for special white cement production, other part for ground soil corrective purposes, and also marble blocks as dimension stone or also as unpolished, ornamental stone. This marble comes from a bed found in the Precambrian migmatites that occurs near the city of Campos do Jordão in the Mantiqueira Mountains, State of São Paulo.

Figure 1 shows the location of the four quarries in the State of São Paulo..

Table 1. Physical, Mechanical and other technological characteristics of the granite and marble samples.

Property	Capão Bonito red Granite	Interlagos silver-Granite	Piracaia black Granite	Campos do Jordão white Marble
Dry Density	2,625 kg/m^3	2,625 kg/m^3	2,803 kg/m^3	2,816 kg/m^3
Apparent Porosity	0.68 %	0.78 %	0.52 %	0.87 %
Water Absorption	0.26 %	0.28 %	0.19 %	0.31 %
Amsler Wear Test	0.60 mm	0.64 mm	0.68 mm	3.84 mm
Impact Strength Test	0.51 m		0.38 m	0.22 m
Linear Thermal Expansion	8.9 mm/m °C x 10^{-3}		9.3 mm/m °C x 10^{-3}	11 mm/m °C x 10^{-3}
Compression Breaking Load at Natural State	133 MPa	179 MPa	170.0 MPa	77 MPa
Compression Breaking Load after Freezing/Thrawing	134 MPa			
Modulus of Rupture	9.2 MPa			
Bending Test	13.2 MPa	14.1 MPa	17.8 MPa	6.0 MPa
Static Deformability Modulus	56.1 GPa		32.963 GPa	55.277 GPa
Knoop Micro hardness	6789 MPa			
Ultrasonic Pulse Velocity	5380 m/s			
Ammonium Hydroxide (NH_4OH)	Unaltered aspect			
Sodium Hypochloride ($NaClO_5H_2O$)	Unaltered aspect			

4 THE TECNOLOGICAL CHARACTERISTICS

Some of the major technological characteristics of the collected rocks are presented in table 1. This data were in part collected from sources of the following papers: Capão Bonito red Granite (Hennies et al., 1999); Interlagos silver Granite (Born et al. 1996); Piracaia black Granite and Campos do Jordão dolomite Marble in the work of Ornamental Stones of State of São Paulo published by IPT the São Paulo Research Institute (Caruso et al, 1990).

Other data as mineralogical description and photographs of the polished rocks of three of the samples appears in the last work of Caruso et al, 1990.

5 SAMPLE PREPARATION

After a field trip to collect the rocks, test samples were prepared according to a specific shape for the new cutting system.

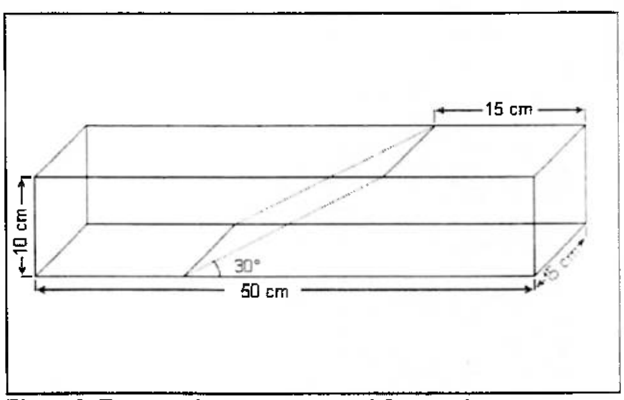

Figure 2. Test samples geometry cuted from rocks.

A regular 10 cm x 15 cm x 50 cm parallelepiped prism was first cut with a diamond saw blade with and then split in two at a 30° angle at the middle of the shortest distance to provide two samples for assay.

Figure 2 shows these rock samples for the abrasive water jet system cutting test.

These samples of the four selected rocks were then cut to determine some of the kerf's topographical features.

6 LABORATORY ASSAYING

Two different laboratory assays of the four rocks were performed, a linear cut with greater traverse velocity and a circular cut with lower traverse velocity to test the performance of the resulting kerf. The employed jewel had a 0.3556 mm (0.014") diameter and pressure of 290 MPa (42,000 psi). The mixing tube of the equipment had 0.762 mm (0.03") diameter. The distance of the nozzle to the rock surface was about 5 mm. The abrasive used in the test was the imported garnet sample from Flow, 80 Tyler mesh and 0.180 µm mean grain diameter.

To characterize the various topographic entities of the kerf the following parameters were measured:

1 top width of the cut (b_T)
2 bottom width of the cut (b_B)
3 taper of the cut (T_R)

Additionally, there were two distinct cut regions, an upper, smooth finished kerf zone, and a lower, wavy kerf zone on the samples. These data are:

4 high of the smooth kerf
5 high of the wavy kerf
6 total kerf high.

All the above mentioned topographic measures are illustrated in figure 3, from the papers of N. S.

Guo, 1994 and D. Arola & M. Rumulu, 1993 in (apud: Momber & Kovacevic, 1998).

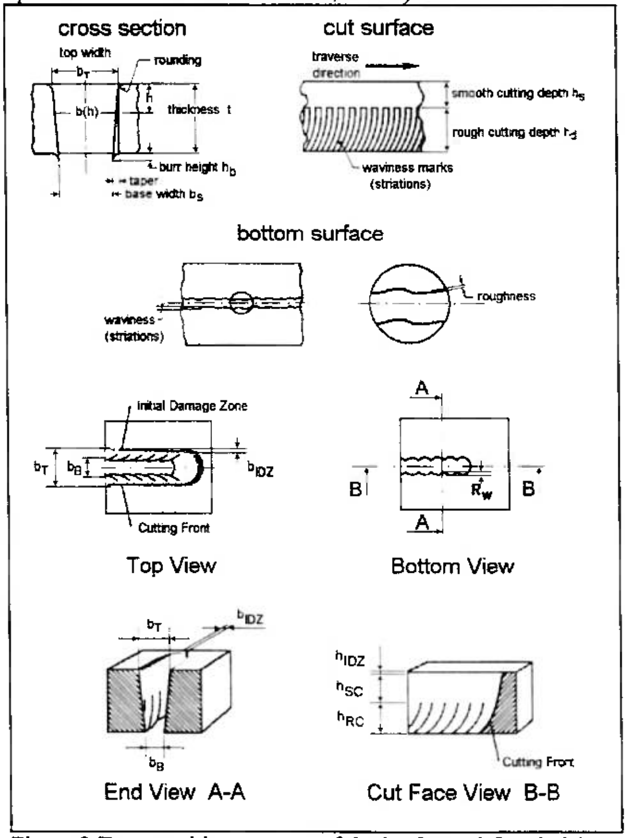

Figure 3 Topographic measures of the kerf (apud Guo in Momber & Kovacevic, 1988)

7 ASSAYING RESULTS

The first series of assays were straight cuts in the rock samples using default values for granite and marble machining, and considering a 5 cm theoretical thickness of the target material. The systems's machining control software provides 5 quality settings with corresponding mean traverse speed in mm per second, according to table 2.

Table 2 Linear traverse speed of nozzle in straight cut

Rock	granite (mm/s)	marble (mm/s)
Quality 1	3.376	6.054
Quality 2	2.097	3.761
Quality 3	1.316	2.359
Quality 4	0.945	1.695
Quality 5	0.731	1.311

The laboratory test results for this characteristics with default transverse cutting speed for granite and marble, and 80# garnet is presented in table 3.

In this table 3 the results values for straight linear cut ranging from quality levels 1 to 5 are presented as Q1 to Q5.

Table 3. Results of the laboratory assaying.

Rock		granites			marble
		red	silver	black	white
b_T	Q1	1.3	1.4	1.4	1.3
b_B		0.5	0.6	0.9	1.0
T_R		2.6	2.3	1.6	1.3
smooth kerf		18.9	25.3	18.6	13.7
wavy kerf		21.4	13.9	22.8	22.7
total kerf high		40.3	40.3	41.4	36.4
b_T	Q2	1.3	1.4	1.4	1.3
b_B		0.3	0.5	0.6	0.7
T_R		4.3	2.8	2.3	1.9
smooth kerf		22.5	25.5	23.9	19.0
wavy kerf		19.5	20.0	29.3	23.6
total kerf high		42.0	45.5	53.2	42.6
b_T	Q3	1.3	1.4	1.4.	1.3
b_B		0.4	0.5	0.5	0.5
T_R		3.3	2.8	2.8	2.6
smooth kerf		25.8	29.5	31.4	22.6
wavy kerf		22.8	23.7	34.2	31.7
total kerf high		48.6	53.2	65.6	54.3
b_T	Q4	1.3	1.4	1.4	1.3
b_B		0.3	0.4	0.5	0.5
T_R		4.3	3.5	2.8	2.6
smooth kerf		34.6	38.4	32.6	23.6
wavy kerf		32.4	25.9	>36.4	>45.4
total kerf high		67.0	64.3	> 69	>69
b_T	Q5	1.3	1.4	1.4	1.3
b_B		0.3	0.4	0.5	0.5
T_R		4.3	3.5	2.8	2.6
smooth kerf		36.7	38.6	37.9	31.1
wavy kerf		>32.3	>30.4	>31.1	>37.9
total kerf high		>69.0	>69.0	>69.0	>69.0

Figure 4 exhibits the bottom view of the cut in the black Piracaia granite and white Campos do Jordão dolomite marble, whose slab thickness is approximately 70 mm.

The samples' bottom view indicate full cut length for quality 5 setting.

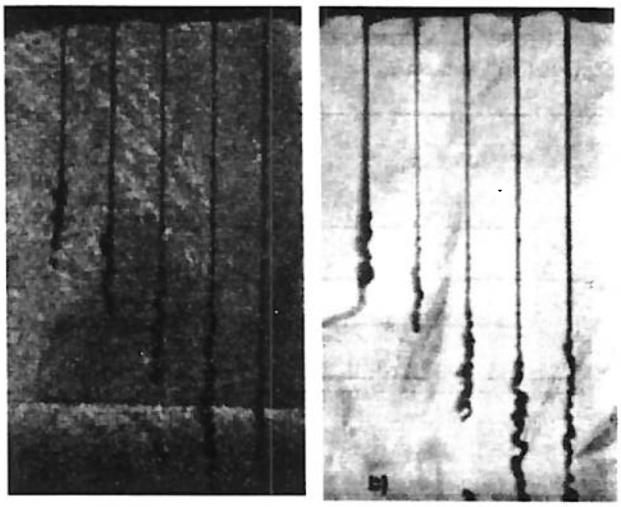

Figure 4. Botton view of straight cut in: a) black Piracaia granite and b) white Campos do Jordão dolomitic marble.

This figure also indicates that at the bottom view, for any quality setting from 1 to 5, there is a maximum of smooth kerf height. In the higher quality settings 4 and 5, the sample was completely cut, not as a straight kerf, but in the wavy kerf zone.

If we look at next quality setting (3) the sample was not completely cut, and the same happens with quality settings 2 and 1.

Figure 5 (a) and (b) illustrate the same straight cuts from the samples top view for the black Piracaia granite and the white Campos do Jordão dolomite marble. In this figure it is possible to notice the effect of the garnet's impact on the kerfs' edges, as the kerfs are wider and with round instead of straight edges.

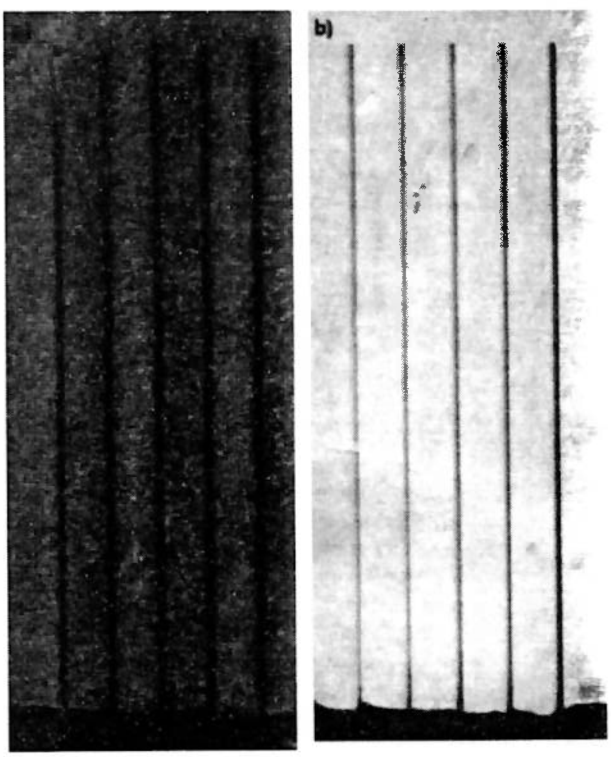

Figure 5. Top straight cut in a) black Piracaia graniteand white Campos do Jordão dolomitic marble.

The second series of tests consisted of cutting two concentric circles with 25 mm diameter and 50 mm diameter, respectively, on 50 mm thick samples at quality settings ranging from 3 (average) to 5 (high). Table 4 displays the system's average cut speed.

Table 4 Traverse speed of nozzle in curved cut

Rock	granite (mm/s)	marble (mm/s)
Quality 3		
(25 mm) circle	0.773	1.356
(50 mm) circle	1.156	2.036
Quality 5		
(25 mm) circle	0.189	0.274
(50 mm) circle	0.282	0.503

Figure 6 illustrates the top view of the cylindrical cut with 25 mm and 50 mm diameter respectively. Slab thickness was 50 mm, and just two test settings were performed, quality 3 and quality 5. Figure 6 (a) illustrates the red Capão Bonito granite and 6 (b) depicts the white Campos do Jordão dolomite marble. As mentioned above, these cut tests were performed at quality 3 on right side and quality 5 on the left.

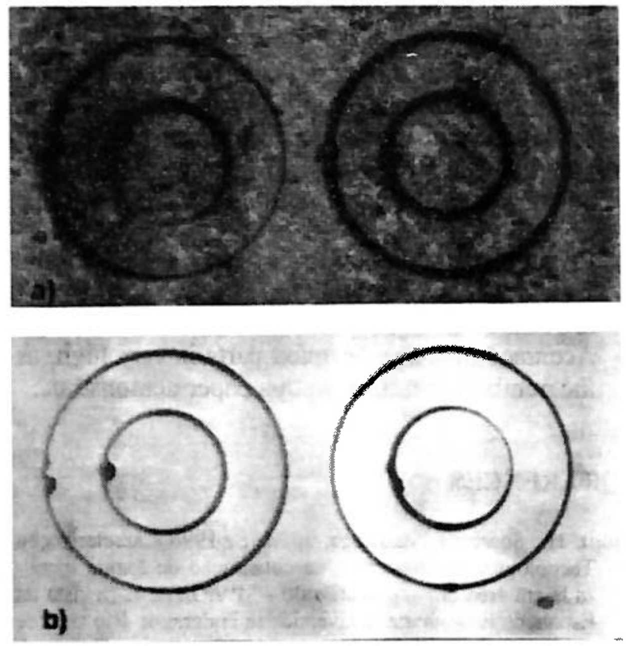

Figure 6. Top view of circular cut on: a) red Capão Bonito granite and, b) white Campos do Jordão dolomitic marble.

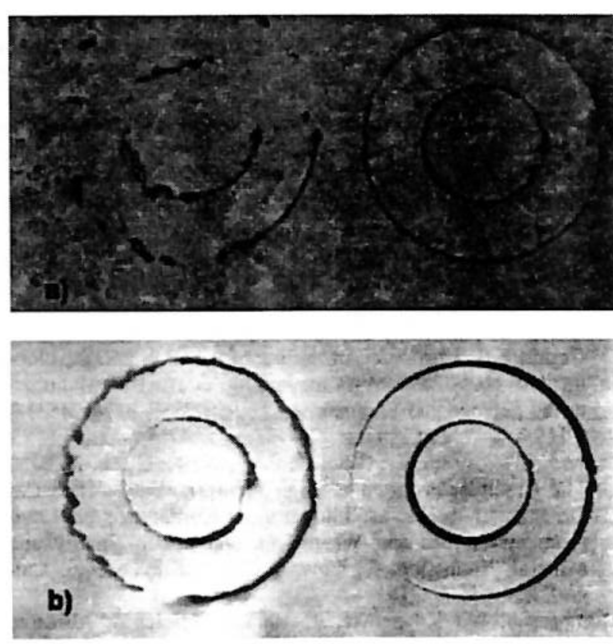

Figure 7 illustrates the bottom view of the same circular cut tests from the previous figure. It is noticeable that while quality 3 setting for the granite (left side) only accidentally cut through the full sample thickness. The marble sample was completely cut, but in the wavy zone of the kerf. Otherwise, quality 5 settings at lower speed provided good results (right side on Figures 5 and 6) for marble and granite.

8 SOME INITIAL CONCLUSIONS

After the series of laboratory test performed on Brazilian granite and marble, the following initial main conclusion are:

1 The OMAX machining system works well for cutting marble and granite slabs up to 50 mm thickness, with good finish surfaces. As tile or plate thickness dimensions range from 10 mm to 30 mm even the most complex designs will be easily cut.
2 Parts with straight cuts are faster to make, but the system also works well for circular cuts, but at lower speeds.
3 Accuracy of CAD designed parts is very high. as the numbers presented in this paper demonstrate.

REFERENCES

Born, H.; Soares, L. & Braga, J. M. S. 1996 Caracterização Tecnológica dos Materiais de construção de Jazida localizada em área urbana, São Paulo - SP *EGATEA*: Revista da Escola de Engenharia. Universidade Federal do Rio Grande do Sul, n. esp., p.323-31, nov. 1996./Apresentado ao 4. Congresso Ítalo Brasileiro de Engenharia de Minas, Canela, 1996/

Caruso, L.G. et al 1990 Catalog of Dimension Stones of the State of São Paulo Secretaria da Ciência, Tecnologia e Desenvolvimento Econômico - SCTDE - PRÓ-MINÉRIO IPT Instituto de Pesquisas Tecnológicas do Estado de São Paulo, Publicação IPT 1820 122 pp.

Hennies, W. T.; Stellin Jr. A.; Cretelli, C. 1999 Jet piercing application for red granite block mining in São Paulo, Brazil. In: International Symposium on Mine Planning and Equipment Selection, 8/The International Symposium on Mine Environmental and Economical Issues. Proceedings Dnipropetrovsk : National Mining University of Ukraine, 1999. *Proceedings*. National Mining University of Ukraine, 1999.p.21-26.

Kovacevic R.; Hashish M.; Mohan R.; Ramulu.; Kim T.J.; Geskin E.S. 1997 State of the art of research and development in abrasive waterjet machining. Journal of Manufacturing Science and Engineering, *Transactions of the ASME*. v 119 n 4(B) Nov 1997, p 776-785.

Lauand, C.T.; Martin C., G.R.; Hennies, W. T.; Ciccu, R. 2000 The Brazilian Program of High Pressure Water Jet to Cut Ornamental Rocks. In: International Conference on Environmental Issues and Waste Management in Energy and Mineral Production, 6., Calgary, 2000. *Proceedings*. Calgari, 2000. p. 711-16.

Momber, A. W.; Kovacevic, R. 1998 Principles of Abrasive Water Jet Machining Springer Verlag London Limited 394 pp.