Application of waterjet in stone quarrying and processing

Raimondo Ciccu, University of Cagliari, Italy*

(*) Corresponding Author's Address: University of Cagliari, DICAAR - Dept of Civil and Environmental Engineering, Piazza d'Armi, 09123 Cagliari, Italy, Phone: +39 070 675 5557 , fax: +39 070 675 5523, e-mail: ciccu@unica.it

ABSTRACT

The power of a jet issued at high velocity can be properly exploited for a number of applications in stone engineering. In the quarry the interest is limited to particular situations like the underground extraction of granite block or in sandstone operations, whereas for marble the dominant technologies are those based on diamond tools. Abrasive waterjet is currently used for contour cutting of stone slabs where flexibility and accuracy are of a major concern. Finally waterjet, either plain or abrasive laden, lends itself to surface finishing for which it proved to be superior to other rustic methods like bush hammering and flaming. The paper refers on the contribution to the scientific knowledge and to the development of waterjet technology in the field of stone at the University of Cagliari

Keywords: Stone, Extraction, Cutting, Surface finishing,

1. INTRODUCTION

High Velocity Waterjet can be regarded as one of the major advances in the field of material disintegration. Thanks to its inherent flexibility and efficiency, the application has been rapidly extended to many branches of industry for working almost any kind of materials, from soft to very hard ones.

As regards rock engineering, hydraulic energy was first used for excavating soft rocks using low pressure monitors. With the advent of the high pressure technology also harder rocks have been made amenable to waterjet treatment, opening a new era in mining, quarrying, civil engineering, mineral processing, waste treatment and reclamation.

At present, waterjet lends itself to a variety of operations such as excavation, drilling, slotting, cutting, crushing and cleaning, alone or in suitable combination with mechanical tools. The prospects have been recently enhanced by the development of abrasive jet technology, especially for precision cutting.

2. WATERJET IN THE QUARRY

The only instance of industrial application of waterjet in the quarry concerns sandstone, owing to the very favourable textural characteristics of this kind of rock. In the Rothbach quarry blocks are extracted with a series of orthogonal slots made with a swinging jet lance at a cutting rate of 6.5 m^2/h (Figure 1)

Figure 1. The sandstone quarry at Rothbach (France)

Concerning marble there is no interest in waterjet since diamond tools (diamond wire and rock cutter), are by far superior to any competitor on both technical and economic grounds.

As for granite, blocks are generally extracted in surface quarries according to bench methods using different cutting technologies (diamond wire, explosive splitting and wedge shearing).

In the future, however, the possibility of developing the excavation underground is expected to gain increasing popularity for a number of reasons such as:

- less impact on the environment;
- no need for preliminary overburden removal;
- better overall recovery;
- possibility of working all year round in a protected ambient;
- economic use of left-out stopes.

The access underground would consist of a large gateway tunnel, from which production activity can be developed. The excavation of the gateway is made difficult by the absence of a lateral access, since the only free face available is the front of the advancing tunnel.

All blind slots at the face can be opened with waterjet according to a regular grid, whose geometry is dictated by the size of the blocks to be extracted.

The hidden back face parallel to the front can be redeemed either by using flat hydraulic jacks introduced into the waterjet slots or by cutting with diamond wire with the machine placed at one side of the drift as shown in Figure 2.

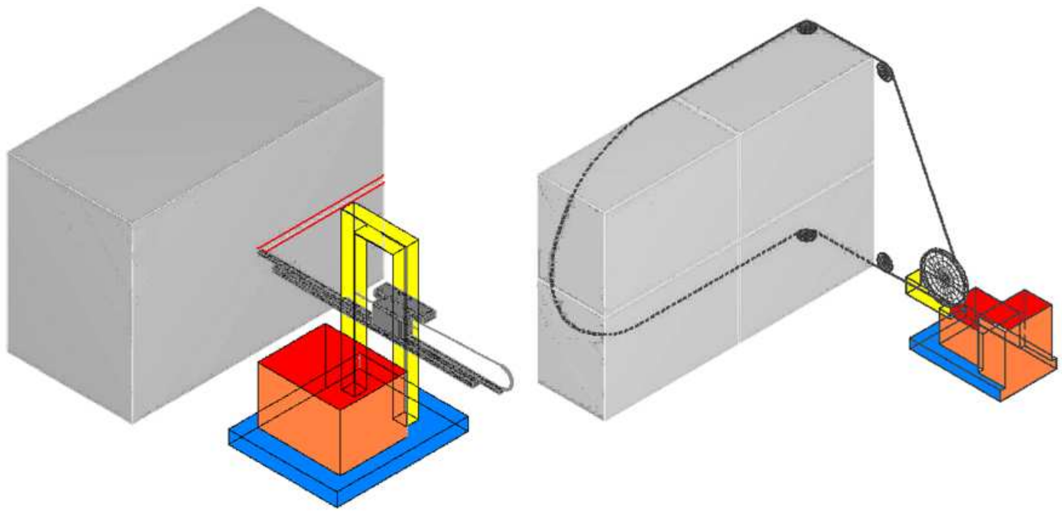

Figure 2. Combination of waterjet and Diamond wire for the tunnel extraction of granite blocks.

The association of waterjet with diamond wire offers a very interesting solution for mechanised quarrying, since both are able to work in a completely automated fashion.

3. CONTOUR CUTTING WITH ABRASIVE WATERJET

AWJ technology is being increasingly used for contour cutting of slabs in stone processing plants, whereas for straight linear cutting diamond circular blade is faster and cheaper, especially in the case of thick slabs. A typical equipment for contour cutting with abrasive waterjet is shown in figure 3.

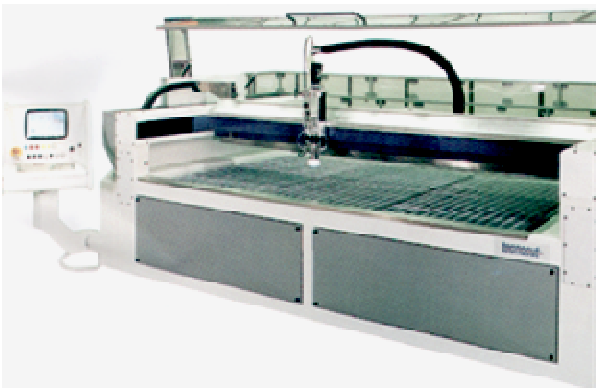

Figure 3. Waterjet cutting table at the DICAAR laboratories, University of Cagliari

3.1. Conventional separation cutting

In separation cutting the jet cuts through a given slab thickness with only one pass.

For a given machine setting (pressure, nozzle diameter), experimental evidence has shown that maximum specific erosion, i.e. the surface cut by the unit mass of abrasive (cm^2/g) achievable at optimum traverse speed of the nozzle is affected by some relevant characteristics of the abrasive used, such as micro-hardness, particle size and shape, density, as well as by the relative proportion by volume of solids in water. On the other hand, specific erosion is also chiefly influenced by the hardness of the rock, depending on the operational conditions.

It is worth underlining that the quality of the cut depends on the traverse velocity of the nozzle that must be kept slow enough in order to limit the roughness and waviness due to spreading and instability of the abrasive flow.

The results of the investigation carried out at the University of Cagliari show that peak specific erosion E_s (cm^2/g) can be expressed as a function of a global parameter P_m accounting for the different characteristics of the abrasive as shown in figure 4 for different materials taken into consideration, including some rocks.

The structure of P_m is of the general form:

$$P_m = (H_m)^a \cdot (S)^b \cdot (\rho)^c \cdot (D)^d \cdot (P)^e$$

where:

- H_m is the Knoop hardness [GPa]
- S is the shape factor of the abrasive particles (dimensionless)
- ρ is the volumic mass of the abrasive [g/cm^3]
- D is the average particle size [mm]
- P is the proportion of solids in water by volume [‰]

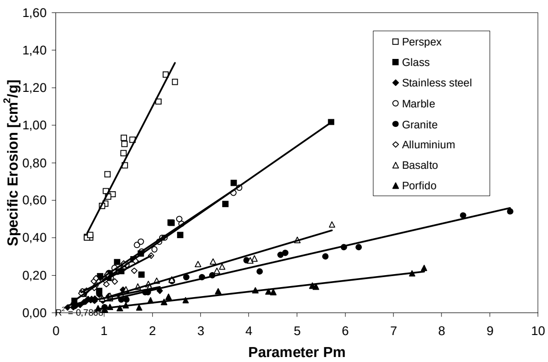

Figure 4 . Correlation lines of specific erosion as a function of parameter P_m .

Exponents in the mathematical expression of P_m have been calculated through a statistical processing of experimental data by maximising the correlation coefficient of the linear relationship:

$$E_s = K \cdot P_m$$

Where K is a constant typical of each material, obtained through the same computer procedure.

It was found that:

- exponent "c" and "e" are constant, irrespective of the material;
- exponent "d" is constant equal to 0.3 except for ductile materials;
- exponents "a" and "b" and coefficient K are variable for the different materials.

Attempts have been made to express exponents "a", "b" and "d" and coefficient K as a function of hardness that is believed to be the most important material parameter capable of describing its behaviour under the action of abrasive waterjet.

The following remarks deserve some consideration:

- An increase in abrasive hardness is always beneficial, the more for harder materials, whereas the advantage becomes less important or even insignificant for softer ones;
- also the shape factor is favourable, except for the very hard porphyry rock, but the best advantages of irregular particle shapes are now for softer materials while for rocks the gain is very poor, if any;
- regarding particle size, coarser particles produce a better performance, although with a decreasing marginal benefit;
- as for density, heavier abrasives are increasingly detrimental for all the materials;
- finally, the influence of increasing the abrasive load into a given volume of water is always negative concerning the abrasive efficiency, since specific erosion is inversely proportional to the square root of the solids/water ratio in the jet.

Therefore, although the most used abrasive is garnet, cheaper and more efficient abrasives should be preferred in particular cases like for instance copper slag for soft marble.

3.2. Multiple pass strategy

In flat-bed contour cutting with abrasive waterjet, a separation cut through a thick slab can be made with multiple passes of the nozzle along the planned profile at relatively high traverse velocity. Since the relationship between depth of kerf and traverse velocity is not a straight linear one due to a gradual loss of efficiency of the jet, it turns out that the overall time needed per metre of cut and thus the unit cost of cutting can be minimised by resorting to multiple passes. Of course the quality of the cut surface is also affected, either favourably or adversely according to the particular conditions (figure 5).

Results of cutting tests with abrasive waterjet on a variety of materials clearly demonstrate the advantages of using multiple passes at high traverse velocity, consisting in:

- Reduced waviness except for heterogeneous materials;
- constant cut quality over the entire area at suitable conditions;
- almost zero trail-back;
- no significant taper;
- good separation cuts on either sides in case of curved or angled section of the contour profile;
- slow decrease in the incremental depth per pass irrespective of the thickness of the workpiece.

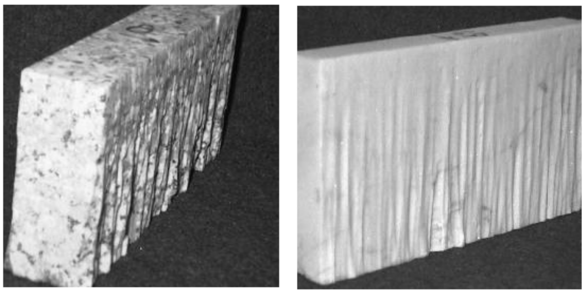

Figure 5. Features of surfaces cut with multi-pass strategy on Granite (left) and marble (right)

The benefits offered by the concept of multiple passes are much more important in the case of complex profiles consisting of curved sections and including angles, for which a deceleration of traverse velocity is required in order to avoid the problems related to trail-back, whereas this measure is not needed in the case of multiple passes. Moreover blind cuts can be made without the need to pierce a starting hole which is a time consuming operation.
Multi-pass strategy has proved to be an efficient solution from both the technical and economical point of view.

3.3. Improvement with additives

The concept of efficiency entails not only an increase in cutting rate (higher power available at the nozzle for a given power at the prime motor) but also a better accuracy in the cut quality (more jet coherence, even distribution of the abrasive in the jet core).
The technical and economic performance of an abrasive jet can be expressed in terms of specific erosion, which represents the cut surface generated by the unit mass of abrasive. The other conditions being the same, this parameter is chiefly influenced by the kinetic energy carried by the abrasive particles incorporated in the jet at the moment of their impact on the target material.
This implies that:

- friction losses along the hose and the nozzle are reduced, thus maximising the velocity of the carrier fluid;
- favourable conditions are created for the transportation of suspended solids;
- particle acceleration in the nozzle is as high as possible, thus maximising the transfer of energy to the solid particles;
- the jet maintains its coherence over longer distances from the nozzle.

Experimental evidence shows that he use of additives can improve significantly the efficiency and the cut quality of ASJ.
In fact:

- the depth of cut increases with the concentration of additive in water especially at higher traverse velocities;
- the width of cut decreases owing to a better coherence of the jet;
- roughness parameters are generally improved;
- the use of additives can be economically advantageous since the additional cost is outbalanced by a higher performance;
- conditions at the working site (noise) are slightly better;
- side effects (foam generation) may be important but can be controlled with suitable measures (addition of salts in the vessel, working under a shallow liquid seal);
- the use of additives is beneficial also under submerged conditions, especially at slow traverse velocity and at short stand-off distance;
- according to the results of preliminary field tests, the additives proved to be beneficial also in the case of plain waterjet for cutting soft materials (thick polystyrol plates, plywood) as well as for cutting hard materials (glass, stainless steel, rocks) using the abrasive injection jet.

4. SURFACE FINISHING WITH WATERJET

Surface finishing is the last stage of stone processing. This operation must be carried out with particular care since the aesthetic features, the technical performance and the durability of the building elements strongly depend on the appropriateness of the technology employed as a function of the characteristics of the material.
A number of technologies are available for the task.
They differ essentially for the kind of action applied to the stone by the active tool, with the consequence that the resulting quality of the surface treated, which is suggested by the end use of the element (for interior or exterior paving, face cladding, artwork, premium types of workmanship), is also somewhat affected.
Aiming at matching safety, durability and artistic values of stone elements applied in buildings very interesting opportunities are offered by waterjet.
In this field, considerable research has been carried out at the University of Cagliari using either abrasive or plain waterjet, stationary or pulsed, generated through a fan-type nozzle aiming at obtaining an evenly treated surface.

4.1 Using plain stationary jets

Plain waterjet has been already proposed as an alternative to flaming for obtaining a rough finishing of granite slabs. Some commercial machines are offered in the market but the acceptance has not yet been very enthusiastic due to the higher cost of processing with respect to competitor technologies.
On the other hand the quality of the treated surface is very good owing to the selective action of waterjet that develops along the existing cleavage planes giving the material a natural appearance by preserving the original colours and the textural features of the stone.
In order to prove the general applicability of waterjet in surface treatment of geologic materials a variety of samples have been selected, representative of the different lythological classes, i.e. marble (including limestone), granite (comprehensive of all intrusive and volcanic rocks) and stone (embracing all the materials not amenable to polishing).
Travertine was excluded since rough finishing would be aesthetically unsuitable.
The set of samples considered for the experiments is shown in Figure 6.

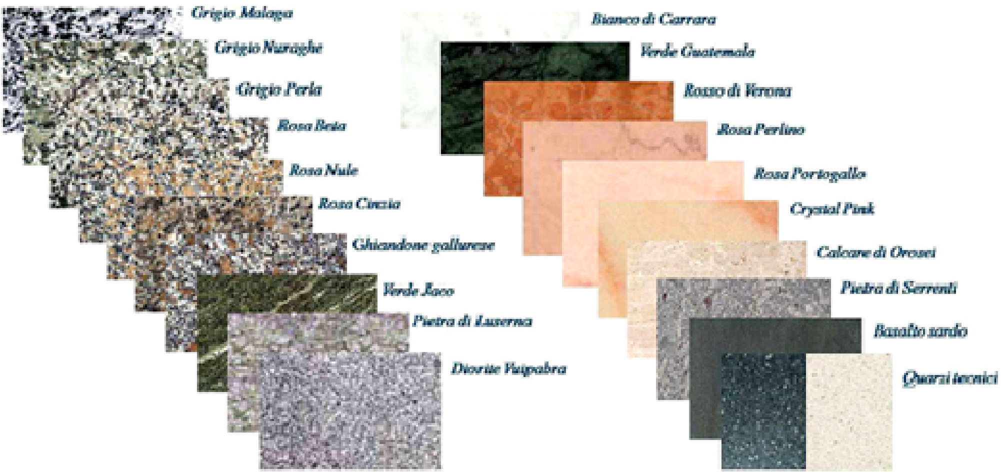

Figure 6.Rock samples included in the surface finishing tests

Tests have been carried out by changing the setting parameters independently within the following ranges:

- Pressure: 100 up to 300 MPa,
- Traverse velocity: 1.0, 6.0 and 10.0 m.min^{-1}
- Stand-off distance: 50, 100 and 150 mm
- Lance inclination angle: 30, 45, 60 and 90°

Nozzle diameter was kept constant (0.3 mm) far all tests as suggested by a series of preliminary experiments.

The repeated passages of the jet across the sample at a given traverse velocity produced a sequence of linear grooves parallel to or crossing each other according to the particular strategy adopted in the experimental plan.
The strategy can be defined by:

- the forwards or backwards motion of the nozzle with respect to the inclination of the lance while traversed sideways (Fig. 7),
- the pattern of grooves (parallel or intersecting)
- the distance between lines.

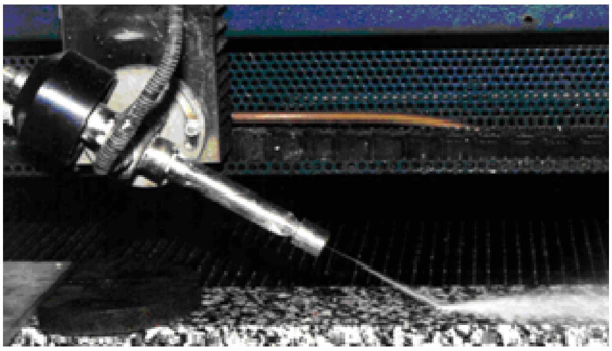

Figure 7 Waterjet nozzle in surface finishing tests

4.1.1. Influence of variables

a) Lance inclination angle. As expected, it has been found that as inclination angle becomes progressively shallower the depth of grooves decreases while its width increases. Accordingly, although material removal rate diminishes, being the highest when the inclination angle approaches 90°, the productivity of surface treatment is favoured since the distance of the grooves can be increased, thus reducing the time needed for processing the unit area of stone. A side effect can be a certain reduction in the selective removal of particular mineral components (biotite contained in some granites, for instance).

b) Stand-off distance. (jet path in air from nozzle to target). The effect of this variable is clearly evident: as the nozzle is moved farther away, the depth of groove decreases and less material is removed due to power losses and to the spreading of the jet impacting over a larger area. Accordingly, the grooves become less evident, thus making the treated surface more homogeneous.

c) Pressure (jet power). In the course of the experiments it was observed that pressure below 100 MPa always produced negligible effects on all the stones tested (either carbonate or silicate). Therefore systematic tests were limited to 200 and 300 MPa. The use of high pressure can be more profitable in the industrial application of the technology. In fact, in spite of a higher power involved, the consumption of energy per unit area treated can be lower due to faster operation. On the other hand the grooves become more evident as the pressure increases to the detriment of the uniformity of surface appearance.

d) Traverse velocity. The influence of this variable was found to be consistent with the findings of previous experiments: the faster the nozzle is moved, the smaller is the depth of groove. Concerning the appearance of the treated surface, the effect of traverse velocity depends very much on the features of the particular stone, especially in the case of heterogeneous materials (coarse granites and some kinds of fossil-bearing limestone). Generally speaking, the quality of the treated surface worsen at too high traverse rates, due to insufficient impingement time that leaves almost intact the components more refractory to the action of the jet (not the harder ones!). As shown in Figure 8 grooves are regular (with constant depth and width of cut) in homogeneous stone like the sample of Rosa Portugal marble, whereas they are clearly unequal in poly-mineral rocks (granites) or in limestone crossed by veins of harder material, that are left protruding. In the case of granites the more reluctant component to the action of the jet is represented by feldspar that is not the harder component and thus less fragile to impact than quartz.

e) Advance step. The effect of groove spacing is purely geometric. Increasing it allows to obtain a striation pattern that can be exploited by architects (incision of the stone according to a desired outline). When spacing approaches the width of grooves the surface becomes even and striation disappears as shown in the photo of Figure 9).

For each test the conventional roughness parameters were measured according to a suitable grid of lines intersecting each other at right angle, using a mechanical roughness meter. The knowledge of the profile shape is important for carving and drawing purposes.

Roughness profiles with waterjet were then compared with those obtained with competitor technologies, in particular polishing, bush-hammering and flaming.

Figure 8. Results of surface finishing with plain waterjet on some granite and marble samples

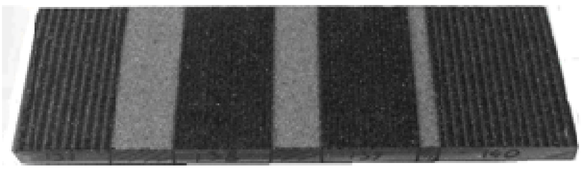

Figure 9. Results of surface finishing with plain waterjet on basalt with different advance steps

4.1.2. Elaboration of images

With the purpose of putting into better evidence the difference in features of treated stone surfaces, their images were processed using some commercial techniques like Adobe Photoshop.

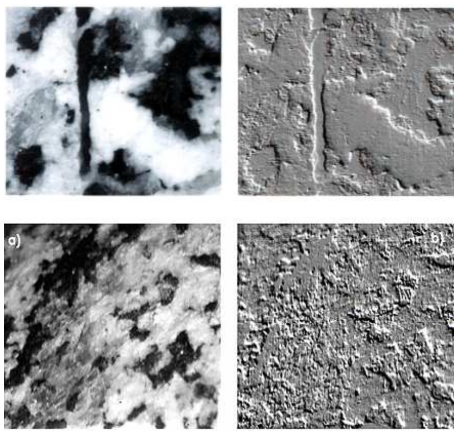

Fig. 10. Elaboration of the image of a Grigio Malaga granite sample treated with waterjet (above) and with flame torch (bottom)

It was observed that waterjet, compared with flame torching and especially with bush hammering enables to put into better evidence the peculiar features of the material thanks to a greater sensitivity to waterjet of each mineral component (Figure 10).

4.1.3.Comparison with competitor technologies

The aesthetic features of stone surfaces can be considerably different according to the finishing technology used.

Whereas the visual appearance of surfaces treated with bush-hammering and flaming is thoroughly changed since the mechanical or thermal treatment induce major modifications in the topmost layer of exposed material (plasticization or vitrifying), this is not the case of waterjet that substantially preserves the crystal structure of the material, owing to the fact that removal process develops by exploiting the natural cleavage planes present in the rock.

Therefore the colour does not fade away and brilliance is maintained or even enhanced. Especially for marble and more generally for homogeneous materials, the effect of waterjet is surprisingly similar to that of polishing, even in spite of a rough finishing.

Moreover, the striated surfaces obtained with waterjet, if observed from a far distance may assume a variable shade according to the angle of incidence of light with respect to the stone surface and to the direction of the grooves.

This offers the architect a large variety of opportunities in the design of the stone veneer of a building.

Concerning granites, waterjet resulted to be more effective on laminar biotite (easy to split) and on quartz (the most fragile mineral). In particular biotite removal was very sensitive to the nozzle inclination angle (increasing with it).

Also flaming produces a selective action on granites but, contrary to waterjet, biotite is now hard to remove being very refractory to heat so that the stone surface is characterised by protruding black points, whereas quartz is deeply excavated due to its peculiar behaviour at increasing temperature (expansion of crystal lattice due to allotropic transformations) and feldspars undergo vitrifying.

Bush-hammering is not selective at all since the percussive action produces the same effect irrespective of the particular minerals, resulting in a general flattening of chromatic contrast.

4.2 Using pulsed waterjet

The application of pulsed water jets in ornamental stone surface treatment has the potential to improve the productivity and reduce costs of water jet technology.
This is due to the fact that pulsed water jet produces a dynamic stress action on the target material by the short high-pressure transients generated by repeated impacts of high-velocity liquid mass on the rock surface. The impact pressure generated in the area by the pulsating jet is about ten times higher than the corresponding stagnation pressure. The concept of pulsed jet is depicted in Figure 11.

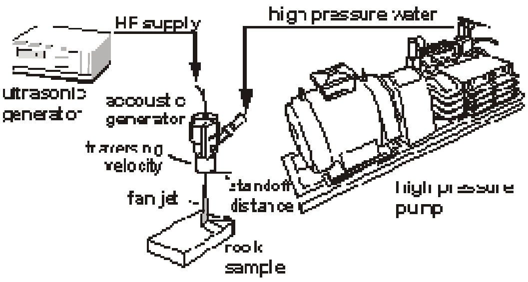

Figure 11. Scheme of the pulsed waterjet system

Surfaces created by the flat pulsating jet issued through a fan-jet nozzle were evaluated in terms of preserving of the aesthetical appearance of the stone and compared to those created by polishing, soft and hard bush hammering, flaming, and by high-speed continuous water jets.
Three different types of rocks (granite, basalt, and marble) were exposed to flat pulsating water jets during the tests.
The characteristics of rock surfaces created by acting of pulsating water jets were compared to those created by traditional methods, namely polishing, bush hammering and flaming.
Results so far obtained indicate that the application of pulsating water jets in surface treatment of ornamental stones can reduce (or even eliminate) some of the disadvantages of traditional techniques because it creates a surface with required roughness while preserving the peculiar aesthetical appearance of the material.
On economic grounds, the great advantage of the technology is represented by the use of relatively low operating pressure.
As previously mentioned, the results of the process are represented by the surface roughness and aesthetic appearance obtained.
It is to be outlined that the flexibility of the technology, due to the number of operative parameters that can be differently adjusted, can lead to a desired surface roughness meeting the end users requirements.
This fact represents a substantial advantage considering that the production rate can be consequently modified and kept at the requested industrial level.

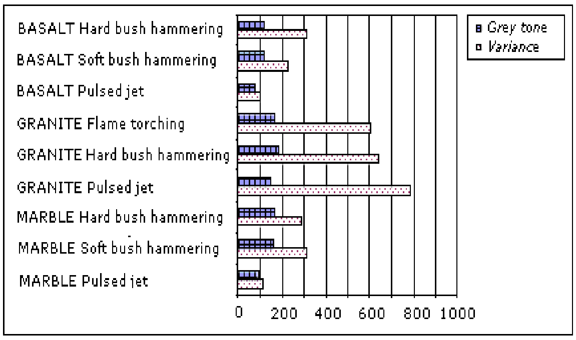

Figure 12. Gray tone and its medium variance for different treatment technologies applied to basalt, granite and marble

The same kind of results were obtained for granite, while in the case of marble the application of the new technology is compatible only for low values of roughness. In fact, for rougher treatments the marble surface suffers a reduction of the aesthetical appearance.
In Figure 12 the gray tone and its medium variance are reported for different treatment technologies applied to basalt, granite and marble. The data reported in that graph should be read differently according to the rock characteristics.
In the case of basalt and marble, the natural structure of the rock, from the chromatic point of view, is quite uniform and if the preservation of that structure is considered a positive result, the performance of an effective treatment should lead to a low value of the medium variance.
In compliance with this, the pulsating jet technology treatment produces a surface which is to be considered better than the surface obtained with the other technologies (soft and hard bush hammering) as the results reported in Figure 12 show for both basalt and marble.
In case of granite the situation is opposite. The natural chromatic structure is not-homogeneous and an efficient treatment should lead to a high value of the mean variance, witness of unchanged

conditions. Again from this point of view the pulsating jet technology is more efficient than bush hammering and flaming.
It is to be underlined that waterjet treatment preserves the aesthetical features of the stone, contrary to bush hammering and flaming as shown in Figure 13.

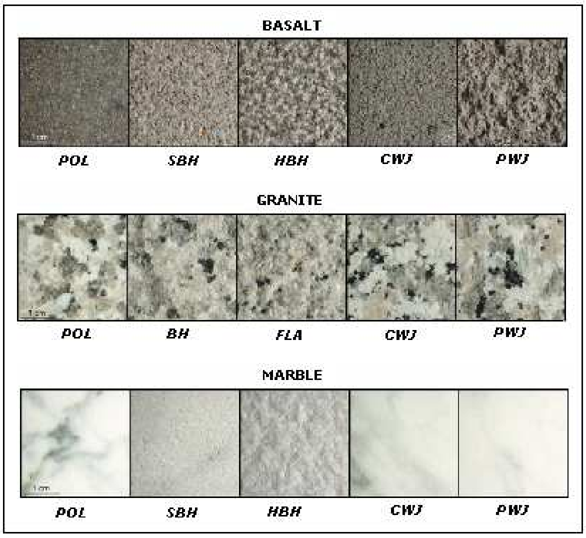

Figure 13 Feature of basalt, granite and marble surfaces treated with different technologies

POL = Polishing; SBH = Soft Bush Hammering; HBH = Hard Bush Hammering; BH = Medium Bush Hammering; FLA = Flaming; CWJ = Continuous Water Jet; PWJ = Pulsed Water Jet

The experimental results have shown that the pulsating jet technology is competitive even when the productive aspects are considered.
In fact the production rate obtained for the different rocks during the tests are comparable to that obtained in the industrial application of traditional technologies.

4.3 Using abrasive waterjet

Problems may arise especially for interior floors where the preservation of the aesthetic values must be matched to safety. A possible solution can be found in a combination of conventional polishing (for enhancing the textural and chromatic features of the material) with a light erosive action intended to produce a pattern of micro-craters capable of improving the grip without impairing the durability.
To this end a very interesting opportunity is offered by abrasive waterjet

The database obtained and the model proposed as the result of the experimental plan enable to predict the effect of abrasive waterjet on a given stone surface as a function of setting conditions of the operational parameters (especially pressure, nozzle geometry, abrasive mass flowrate, traverse velocity and stand-off distance).

Figure 14. Close view of a AWJ kerf on marble

Therefore it is possible to make the best use of the technology for fulfilling the desired tasks: surface treatment as a substitute to sand blasting, in addition to carving, drawing (Figure 14).
Concerning safety, micro-craters produced as a result of the impacts of abrasive particles on the polished surface of stone render the floor and stairs less slippery with minor modification of the visual appearance of the material.

5. CONCLUSIONS

Waterjet offers new opportunities in the field of dimension stone thanks to its flexibility and efficiency.
In quarrying operations, due to the development of diamond tools the prospects of waterjet are limited to the extraction of sandstone blocks and maybe, in the future to underground excavation of granite.
The abrasive waterjet technology is already extensively used for contour cutting of stone slabs and has been proposed also for carving.
The new applications concern the rustic finishing of slab surface using stationary or pulsed jets. The experimental results obtained at the University of Cagliari on a broad set of rocks show that waterjet technology is viable on both technical and economic grounds, allowing to obtain excellent results with very interesting aesthetic features at relatively low processing cost by resorting to multiple line nozzles.
It is worth underlining that waterjet, owing to a gentler action on the material allows to obtain rough surfaces even on very thin slabs that would

easily break with bush-hammering or flaming, as demonstrated by a recent research.

This makes waterjet applicable also to the preparation of light stone panels having a sandwich structure, for which the competitor technology are unsuitable.

REFERENCES

Ciccu R., Bortolussi A.: Waterjet in dimensional stone quarrying, in: *Waterjet applications in construction engineering* (A:W: Momber Ed.) Balkema, Rotterdam, 1998 pp. 289-305

Ciccu R. and Fiamminghi A.: Quarrying granite underground is now feasible with waterjet, *Proc. 13th Int. Conf. on Jetting Technology*, Cagliari, October 1996

Agus, M., Bortolussi, A., Careddu, N., Ciccu, R., Grosso, B., Marras, G.: Multi-pass abrasive waterjet cutting strategy *16th International Conference on Water Jetting, Edited by Paul Lake, Published by BHR Group Limited, The Fluid Engineering Centre, Cranfield, UK (C) BHR Group 2002*, pp 243-257 ISBN: 1 85598 042 8

Bortolussi, A., Careddu, N., Ciccu, R., Manca, M.G., Olla, S.: Surface finishing of marble with abrasive *waterjet 16th International Conference on Water Jetting, Edited by Paul Lake, Published by BHR Group Limited, The Fluid Engineering Centre, Cranfield, UK (C) BHR Group 2002*, pp 425-435 ISBN: 1 85598 042 8

Guo N.S., Louis H. and Meier G.: Surface structure and kerf geometry in abrasive water jet cutting, *Proc. 7th American Water Jet Conf.*, Seattle USA 1993, pp. 1-25

Agus M., Bortolussi A., Ciccu R., Kim W.M., Vargiu A.: Abrasive performance in rock cutting with AWJ and ASJ, *Proc. 8th American Waterjet Conference*, T. Labus ed., 1995, pp. 31-47

Bortolussi A., Ciccu R.: Contour cutting of thick steel plate, *14th International Conference on Jetting Technology* - BHR Group Conference Series, Publication No. 32, edited by H. Louis, pp. 273-284, 1998.

Hashish M.: On the modelling of surface waviness produced by abrasive-waterjets, in: "*Jet Cutting Technology*", Proc. 11th Int. Conf. on Jetting technology, BHRg, St. Andrews 1992, pp. 17-34

Agus M., Bortolussi A., Careddu N., Ciccu R., Grosso B.: Optimisation of abrasive-workpiece matching *Proc. 15th Int. Conf. On Jetting Technology* Ronneby Sept. 2000, pp.171-180

Bortolussi A., Ciccu R. and Grosso B.**:** Improvement of abrasive jet efficiency in cutting operations, *Proc. 18 th International Conference of Water Jetting* – Gdansk, Poland, September 2006 - Peter Longman Ed. BHR group Cranfield UK ISBN 1 85598 080-0

Final report of cooperative Research Project BE-S2-2649 Contract No. BRST-CT98-5261 Improvement of Efficiency, Availabilitty and Quality of Abrasive Water Suspension Jets

Niu M.S., Kobayashi R.,Yamaguchi T.: Kerf width in abrasive waterjet machining, *Proc. WJ Technology*, Shimizu, Japan, 1995

Ciccu R., Costa G.: Waterjet rough finishing of stone surface , *Proc. Water Jet 2011*, Libor Sitek & Michal Zelenak Ed., Ustav Geoniki AV CR, OFTIS Ostrava, Ostravice October 3-5 2011 pp. 85-98 ISBN 978 80 86407 23 4 (2011)

Ozcelik Y., Gursel M., Ciccu R., Costa G., Bortolussi A.: Optimization of working parameters of water jet cutting in terms of depth and width of cut, *Proceedings of the Institution of Mechanical Engineers, Part E, Journal of Process Mechanical Engineering*, Volume 225, Number 1 / 2011

Ciccu, R., Bortolussi, A.: stone surface finishing by pulsed water jets, *Proc. Global Stone Conf. 2010*, Alicante, february 2010. ISBN: 978-84-614-1147-4