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WATERJET ROUGH FINISHING OF STONE SURFACE

Raimondo Ciccu, Giorgio Costa

Original scientific paper

The paper deals with the assessment of the potential application of plain waterjet for surface treatment of stone materials as an alternative to technologies traditionally employed for this task, like bush-hammering, sand-blasting and flaming. Waterjetting has been already proposed in the market for rough finishing of surfaces making use of a fast rotating head provided with multiple nozzles. At the University of Cagliari considerable research has already been carried out using either abrasive or plain waterjet, stationary or pulsed, generated through a fan-type nozzle aiming at obtaining an evenly treated surface. A particular goal of the tests described in the paper is that of developing a technique enabling to make engravings on the stone in order to achieve special aesthetic effects. The experimental results obtained on a broad set of rocks show that the technology is viable on both technical and economic grounds, allowing to obtain excellent results at a relatively low processing cost by resorting to multiple line nozzles.

Keywords: *stone, surface finishing, water jet*

Gruba završna obrada površine kamena vodenim mlazom

Izvorni znanstveni članak

Rad se bavi procjenom potencijalne primjene otvorenog vodenog mlaza za površinsku obradu kamenog materijala, kao alternativa tehnologijama koje se tradicionalno upotrebljavaju za ovaj zadatak, kao što su rovašenje dlijetom, pjeskarenje i žarenje. Obrada vodenim mlazom već je predložena na tržištu za grubu završnu obradu površine uporabom brzo rotirajuće glave opskrbljene s više mlaznica. Na Sveučilištu u Cagliariju već su provedena značajna istraživanja uporabom abrazivnog ili otvorenog vodenog mlaza, stacionarnog ili pulzirajućeg, nastalog kroz ventilatorski tip sapnica s ciljem dobivanja ravnomjerno obrađene površine. Posebni cilj u članku opisanih ispitivanja je razvijanje tehnike koja omogućuje gravuru na kamenu kako bi se postigli posebni estetski učinci. Postignuti eksperimentalni rezultati na širokom asortimanu kamena pokazuju da je tehnologija isplativa i iz tehničkih i iz ekonomskih razloga, što omogućuje dobivanje odličnih rezultata uz relativno nisku cijenu obrade kod primjene višestruke frontalne sapnice.

Ključne riječi: *kamen, mlaz vode, završna obrada površine*

1 Introduction

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.

1.1 Smoothing and polishing

They represent the most common method of surface finishing of stone elements used for interior decoration where the aesthetic quality is of a major concern. Smoothing is the first step of the process for eliminating the imperfections of sawing before the subsequent polishing that gives the final brilliance.

At present the operation is carried out with a variety of bridge or belt machines using revolving tools mounted on a series of rotating mandrels where abrasive particles with decreasing size are incorporated. Modern machines are characterised by high production rates thanks to the degree of automation.

Polishing enables to put into full evidence the chromatic and textural appearance of the material, posing however some safety problems when the stone elements are applied in floors and stairs, due to possible sliding risk.

1.2 Bush hammering

The machines are composed of a metal structural beam carrying a trolley equipped with one or more pneumatic hammers with different shapes. Roughness patterns can be varied by simply changing the tool. Smaller hand-held machines are used for special works or for a light scarification of floors. Treatment rate in marble can be around 50 m^2 per shift.

However, soft and coarse-grained materials may be broken by the impacts, especially if their texture is unfavourable. This drawback can be overcome only by increasing the thickness of the slabs and/or by limiting the impact force and reducing the depth of removal. The material can often be damaged or weakened at the smaller scale (less than 1 mm) as the consequence of micro-cracks, in addition to the natural porosity, causing a faster deterioration and a deeper development of the weathering process.

Bush hammering gives a very rough finishing resulting in a considerable modification of the natural colours and of the fabric itself. On the other hand the surface provides a marked, slide-preventing grip. This technique is seldom applied on granite for which flaming is generally preferred. Marble elements treated in this way are therefore suitable chiefly for exterior applications like sculptures, stairways, paving, curbs and items having a non-planar shape.

1.3 Sand blasting

In the factory, sand blasting is performed with machines quite similar to bush-hammers. Abrasive particles (silica sand, carbide grit or other hard materials like spherical glass shot) are blasted against the surface using compressed air as the driving fluid. The nozzles are aligned on the beam above the stone slab placed onto a traversing roller-belt. The latest models of machine are equipped with abrasive circulation system for the sake of cost savings. The typical production rate in marble is 150 m^2 per shift.

The surface is faintly rough having a silky appearance without coarse or sharp protrusions, which is highly desirable in many materials. When the thickness of removed layer is a problem, like in the case of art restoration, the control of the operation becomes critical.

Sand blasting is also used for carving, drawings and writings, especially in funeral art.

1.4 Flaming

The flaming torch fed by oxygen and propane can be applied to the same structural frame of the bush-hammering machine. If accompanied by water cooling, flaming provokes a thermal shock resulting in a breakage or vitrifying of the component minerals, revealing the appearance of their crystal structure.

Quartz is particularly sensitive to thermal treatments owing to the allotropic transformations of its crystal lattice as temperature increases, whereas feldspar tends to melt while micas behave as refractory.

Flamed granite slabs are used primarily for flooring and external facing as an alternative to bush-hammering. It has been found that in some cases flaming improves the durability of the stone, especially the resistance to chemical agents.

The aspect of the surface is rather soft with attenuated chromatic contrast. In some cases the flaws of the material, clearly evident in polished surfaces, can be somewhat masked by flaming, resulting in a considerable economic benefit.

1.5 Laser beam

Laser technology is sometimes used for printing, drawing and in general for high- accuracy engraving of stone surface. Not all the rocks are amenable to this kind of treatment which is restricted to white carbonate materials.

In principle, all the above methods are technically viable for surface finishing of dimension stone, taking into account the need to preserve the ornamental features of the material.

However their practical applicability can be restricted by a number of factors concerning the characteristics of the material and the end use of the stone element in presence of external constraints, with particular reference to climatic conditions.

2 Goals of the research

Aiming at matching safety, durability and artistic values of stone elements applied in buildings very interesting opportunities are offered by waterjet.

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 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.

A particular goal of the research illustrated in this paper is the development of a technique enabling to make engravings on the stone surface in order to achieve special aesthetic effects.

The task underlying the test program was that of studying the effect on the stone surface obtained by changing the various parameters of relevant importance in the treatment using plain waterjet.

3 Experiments

3.1 Target materials

In order to prove the general applicability of waterjet in surface treatment of geologic materials a variety of samples

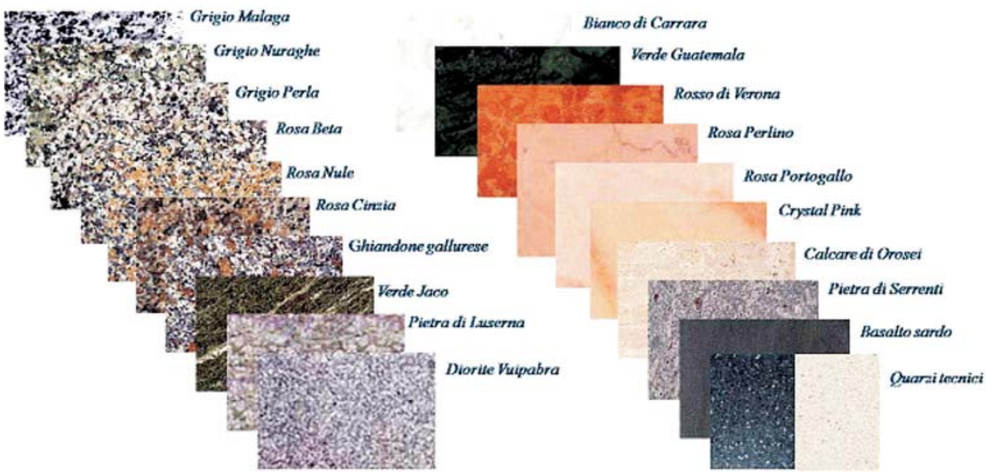


Figure 1 Variety of stone materials with their commercial denomination included in the experimental plan

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 Fig. 1.

Each sample was cut with a diamond blade sawing machine into 2 cm thick stripes about 40 cm long and 10 cm wide.

Therefore the surface to be treated with waterjet was characterised by a saw-plane roughness as in the case of industrial processing.

The relevant properties of each stone (mineral composition, grain/crystal size, Knoop hardness, and so on) were studied aiming at obtaining suitable correlations with the results of waterjet action (roughness parameters, removal rate, etc.).

3.2 Equipment used

The equipment used for the tests is a computer controlled X-Y cutting system completed with a pump consisting of three electronically controlled one-way pressure intensifiers giving the following performance:

- Installed power (three intensifiers) 37,5 kW
- Maximum pressure 400 MPa
- Working pressure 300÷380 MPa
- Water flow rate at 400 MPa 3,2 l/min.

The nozzle head shown in Fig. 2 can be inclined with an angle variable from 15 to 90° with respect to the horizontal plane by adjusting a rotating supporting disc (Fig. 3).

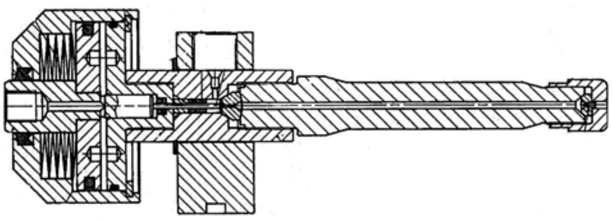


Figure 2 Details of the cutting head used for the experiments

Figure 3 Picture of a typical test showing the features of the jet hitting the rock sample

3.3 Experimental plan

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

- Pressure: 100 up to 300 MPa,
- Traverse velocity: 1, 6 and 10 m/min
- Stand-off distance: 50, 100 and 150 mm
- Inclination angle of the lance: 30°, 45°, 60° and 90°.

Nozzle diameter was kept constant (0,3 mm) for 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. 4),
- the pattern of grooves (parallel or intersecting) as shown in Fig. 5,
- the distance between lines.

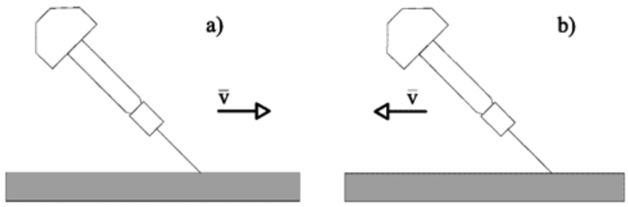


Figure 4 Alternate motion of the nozzle across the sample

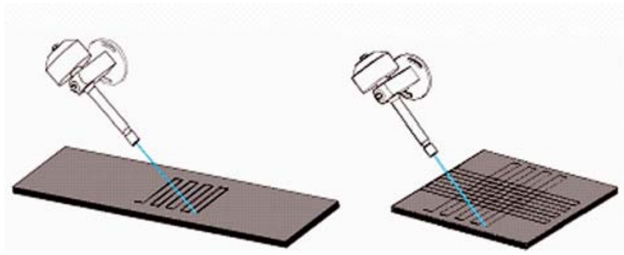


Figure 5 Pattern of grooves obtained with the sequence of passages of the nozzle

The results of waterjet finishing depend also on the quality of the original surface of the rock sample.

Actually the results are not satisfactory if the original surface is polished since in this case the jet tends to be simply reflected with poor material removal as sketched in Fig. 6, right side.

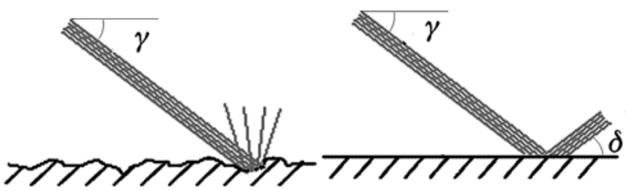


Figure 6 Different action of the jet on a rough or polished surface

In order to reduce the number of meaningful tests, the range of variation of the parameters was restricted for each kind of rock with some exploratory tests enabling to single out the area of optimum results from the aesthetic point of view.

The completion of the experimental plan involved about 350 tests (about 20 for each kind of material) enabling to draw some interesting conclusions concerning the influence of experimental conditions on the treatment results on both aesthetic and economic grounds.

4 Results obtained

4.1 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 Fig. 7 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.

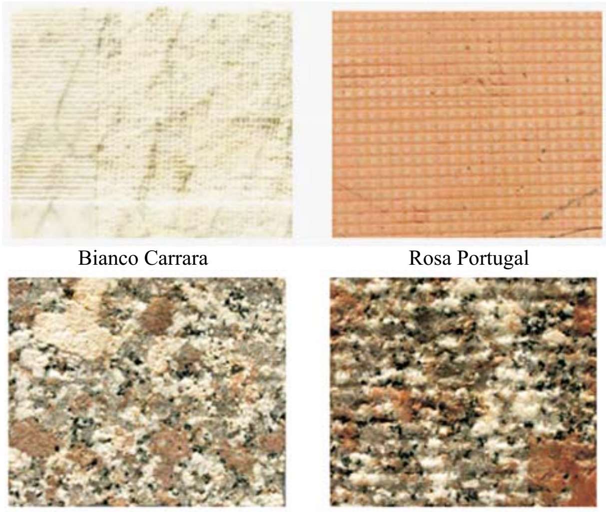


Figure 7 Influence of rock features on the results of waterjet treatment under different experimental conditions

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 Fig. 8).

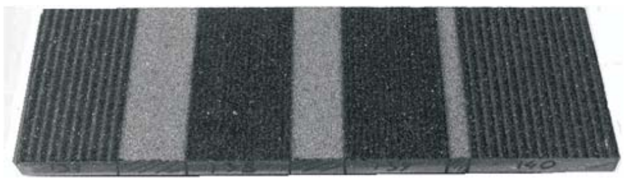


Figure 8 Different striation pattern on basalt (the pale grey parts correspond to the original blade sawing surface)

5 Roughness profiles

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.

6 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.

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 (Fig. 9).

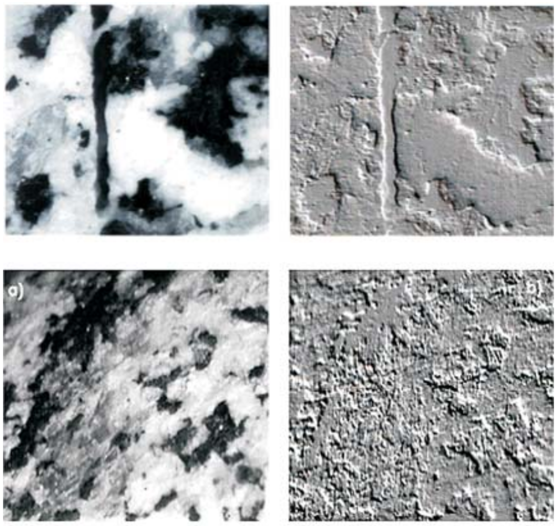


Figure 9 Elaboration of the image of a Grigio Malaga granite sample treated with waterjet (above) and with flame torch (bottom)

7 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.

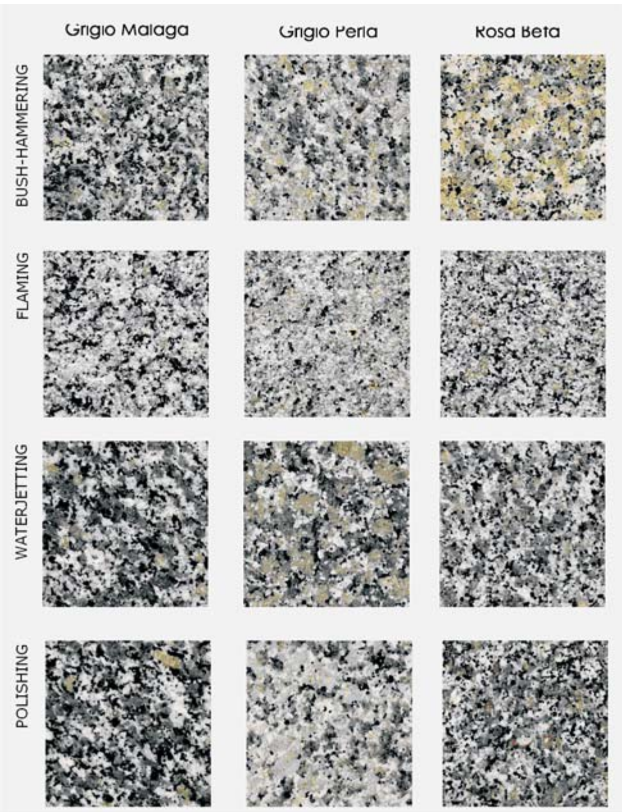


Figure 10 Appearance of some granite surfaces treated with different technologies

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, as shown by the images of Fig. 10, 11 and 12.

Moreover, the striated surfaces obtained with waterjet observed from a far distance 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.

The different effect obtained using the various finishing technologies, corroborated by microscope analysis, is put into evidence also by the roughness parameters.

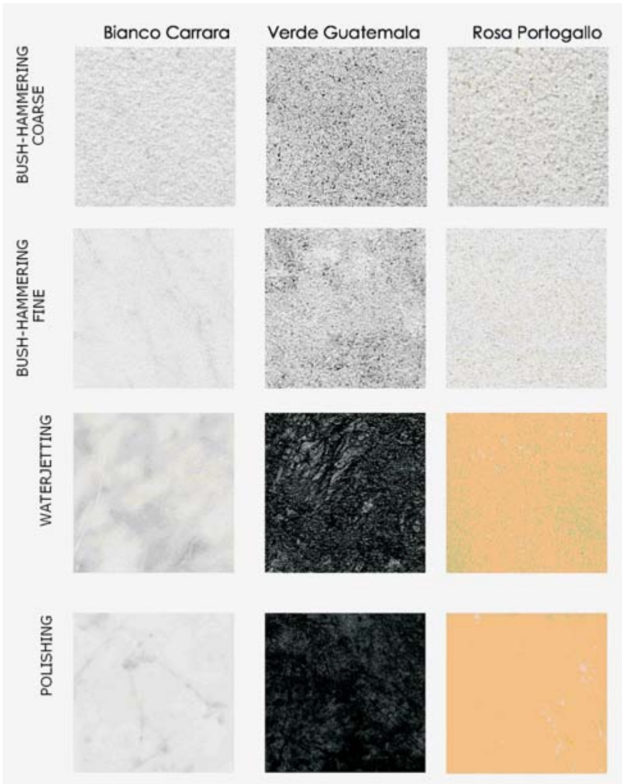


Figure 11 Appearance of some marble surfaces treated with different technologies

Flaming produces low levels (mean and maximum values) for both roughness and waviness, resulting in a rather smooth and uniform surface, whereas heavy bush-hammering is characterised by higher values of those parameters. Waterjet lays between the two, very close to light bush-hammering as shown in Fig. 13 for the case of

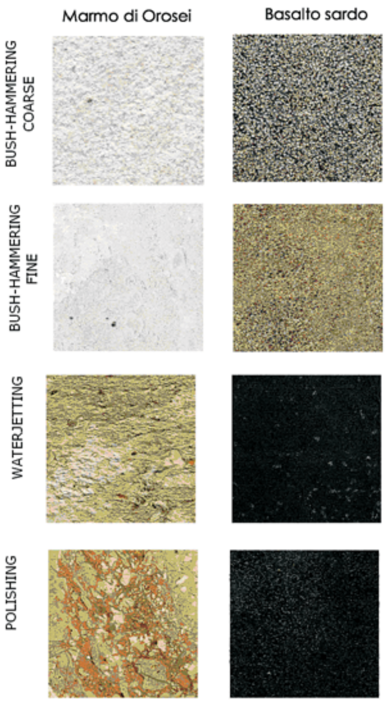
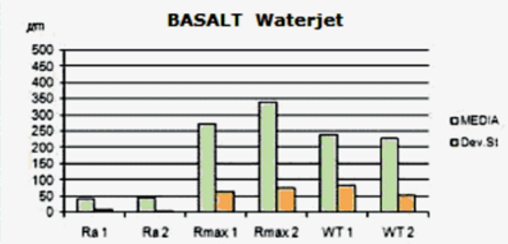
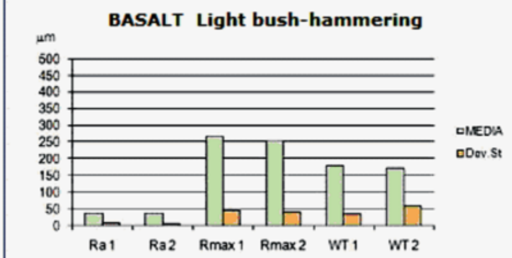


Figure 12 Appearance of limestone and basalt surfaces treated with different technologies

WJ (LS316)	Ra 1	Ra 2	Rmax 1	Rmax 2	WT 1	WT 2
MEDIA	40.9	45.4	274.5	340.7	238.1	228.2
Dev.St	7.6	5.6	64.9	75.9	82.7	54.6



Bas B1	Ra 1	Ra 2	Rmax 1	Rmax 2	WT 1	WT 2
MEDIA	38.5	38.6	268.5	254.0	180.9	173.3
Dev.St	8.7	6.0	46.8	40.6	35.1	58.4



Bas B2	Ra 1	Ra 2	Rmax 1	Rmax 2	WT 1	WT 2
MEDIA	42.2	53.1	277.9	364.2	476.0	463.1
Dev.St	6.6	9.0	20.2	46.7	280.8	102.5

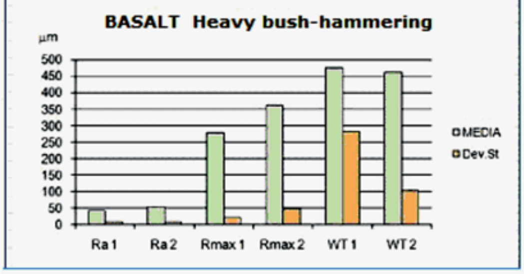


Figure 13 Roughness parameters of basalt surfaces treated with waterjet and bush-hammering

basalt surfaces.

Maybe more significant is the comparison of the finishing technologies on the basis of the tone, measured according to the RGB model as described the CIE (Commission Internationale de l'Eclairage) based on the combination of three fundamental colours: Red, Green and Blue.

With reference to these methods of artificial visualisation and image analysis, which are gaining increasing application especially for product quality control, a simple and reliable procedure has been adopted, consisting in the extraction of a 10×10 cm^2 central square from a larger digital image of the stone surface obtained through a high resolution scanning.

Further data processing with MatLab code allowed to obtain the RGB diagrams and the variance for each channel. In this way an objective and unbiased information could be obtained concerning the aesthetic evaluation of the results of surface treatment.

It came out that waterjet preserves the darker colours of all the stone samples tested (RGB values close to zero in the range 0÷255, particularly evident in some materials like Guatemala Green and Sardinian Basalt, on which bush-hammering produces a bleaching effect due to fine crushing of the near-surface layer (Fig. 14). Worth noting is that waterjet response is close to that of polishing.

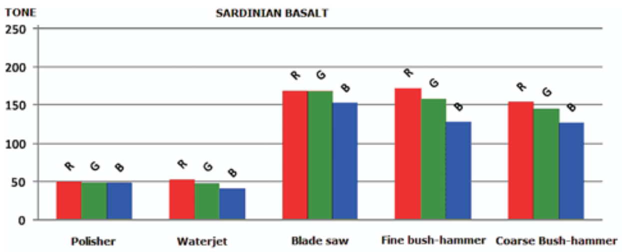


Figure 14 Red, Green and Blue Tone levels for the different finishing technologies of basalt surfaces

8 Conclusions

The experimental results obtained 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 is unsuitable.

Quid magis est saxo durum, quid mollius unda?
Dura tamen molli saxa
cavantur aqua.

Publio Ovidio Nasone (43 a.C. – 18 d.C.)
Ars Amatoria Liber

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Authors' addresses

Raimondo Ciccu
DIGITA - Department of Geo-engineering and Environmental Technologies University of Cagliari
Piazza d'Armi
Cagliari 09123, Italy
ciccu@unica.it

Giorgio Costa
DIGITA - Department of Geo-engineering and Environmental Technologies University of Cagliari
Piazza d'Armi
Cagliari 09123, Italy