Graffiti removal from granite cladding by abrasive water-jet

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Abstract

This study focuses on the assessment of a graffiti removal system based on abrasive water-jet technology (AWJ). Spray paints were applied on samples of an important Italian granite commercially-named as "Rosa Limbara". This granite has been used worldwide as dimension stone for paving and cladding. Two different commercial abrasives have been added in the high-pressure water-jet in order to clean the granite saw-plane surfaces from graffiti. After a check by the naked eye, different criteria have been chosen for assessing the effectiveness of the cleaning process: the similarity in roughness (R_a, R_z, and R_{max}) between the original surface and the one resulted after cleaning, the total colour difference (ΔE) and the depth of material removed by the AWJ action. The tests showed that excellent cleaning results can be achieved with both abrasives by correctly combining the operational parameters of the technology (i.e., water pressure, spacing between passes, stand-off distance, travel speed and abrasive flow-rate) without giving any damage to the stone material. The two abrasives showed good results in total colour difference although one of them gave better results in both roughness difference and material removal. Economic considerations on paint removal with AWJ technology are also offered.

Keywords

Granite; graffiti; spray paints; abrasive water-jet (AWJ); colourimetry; micro-topographic mapping.

1. Introduction

Since ancient times, stone has been widely used in art, urbanisation and construction all over the world: suffice it to think of the multitude of buildings dedicated to worship, monuments, and flooring constructed from natural stones such as marble, travertine, granite, basalt, etc. [1, 2]. The preservation, restoration and cleaning of these artefacts is now a socio-economic factor of great interest which, thanks to up-to-date studies, are making it possible to continuously improve the involved technologies [3, 4].

The cleaning of stone materials is an essential phase of conservation intervention aimed at reducing the effects of degradation phenomena and it represents a critical phase from both a technical and aesthetic point of view, considering the historical-artistic value of the surfaces on which one works [5].

One problem is graffiti. Due to this popular trend, buildings, squares, street furniture and historical monuments are now more an object of vandalism than of artistic expression: writing and drawings of all kinds can be seen everywhere, leading inexorably to a visible degradation of many cities or small urban areas [6, 7] (Fig.1). The removal of such graffiti is not always easy, particularly on natural stones, on which cleaning may cause surface damage and/or alter the colour of the rock [8].

Figure 1. Example of graffiti vandalism on external cladding with Ghiandone granite in Sardinia (photo courtesy of S. Cuccuru).

Many techniques have been studied and applied in graffiti removal. Chemical methods such as solvents and paint strippers are efficient in dissolving or breaking down spray paint [9, 10]; however, they can be used, if they do not further damage the stone substrate. Anti-graffiti coatings can be applied on porous substrates including stone and granite, preventing the penetration of graffiti [11]. Eco-friendly solvents were found to be effective in removing graffiti from sandstones [12]. Sanmartín et al. [13] found good results in graffiti bioremoval from granite using *Comamonas testosterone*. Soft mechanical methods have been used particularly on marbles and limestones. Carvalhão and Dionísio [14] tested dry soft-abrasive blasting media to clean both limestone and marble from graffiti. Careddu and Akkoyun [15] successfully used high-pressure pure water-jet to remove graffiti from Carrara marble. Laser technology has been widely used in the cleaning of graffiti paints made with spray on stone [16-18]. Laser ablation is also enhanced when used in combination of solvents [19] or micro abrasives [20].

Protection from graffiti is provided via coatings which are specially applied to preserve polished stone cladding; in this case, the use of a very thick prevents the spray used by vandals from bonding to the stone surface [8]. In this way, the graffiti can be easily removed from a polished surface. It should be also noted that tagger is tipically attracted to a sound and polished surface rather than to a raw [4]; however, this last is more difficult to be cleaned due to its porosity [21]. Unprocessed raw granite is reportedly used in many different ways - i.e., as outdoor cladding and paving, curbs and street furnishing. In fact, the rustic appearance, non-slip roughness and excellent durability of granite means that such surfaces are preferred for outdoor use. The surface obtained with the traditional pendulum-gangsaw technology, is often applied in works that do not impose tight geometric and dimensional tolerances, such as in paving squares, in pedestrian areas, in artefacts placed at a great viewing distance, or with elements of large size (e.g. outdoor paving) [22]. For these reasons, no preventive anti-graffiti treatment is required for granite raw surfaces.

The aim of this study is the evaluation of the abrasive water-jet (AWJ) technology in the cleaning of stone surfaces and the removal of spray paint from the rough surface of granite. Currently, AWJ technology is used for cutting and surface finishing of stone slabs; definitely, the novelty of this work is to apply the same technology in graffiti cleaning and to prove its feasibility on granite.

To this end, surface cleaning tests were carried out to assess the operating parameters of AWJ technology that could guarantee both the effectiveness of the paint removal process and the preservation of the original condition of the stone material.

2. Materials and equipment

2.1 Stone material

The stone material used in this study is commercially known as Rosa Limbara, belonging to the family of Ghiandone granite (Fig. 2a). This stone has been chosen because of its easy availability and worldwide use; there are countless examples of use of Ghiandone granite throughout the whole world [23]: see for instance the stairs of the Presidential Palace in Turkmenistan and the cladding of some skyscrapers in Perth (Australia) as well as the many buildings, street paving and urban furnishing in the towns of North Sardinia. Ghiandone granite represents a typical example of stone relative to the vernacular architecture in Sardinia. Finally, the slabs of Ghiandone are sold with almost all types of surface finishing.

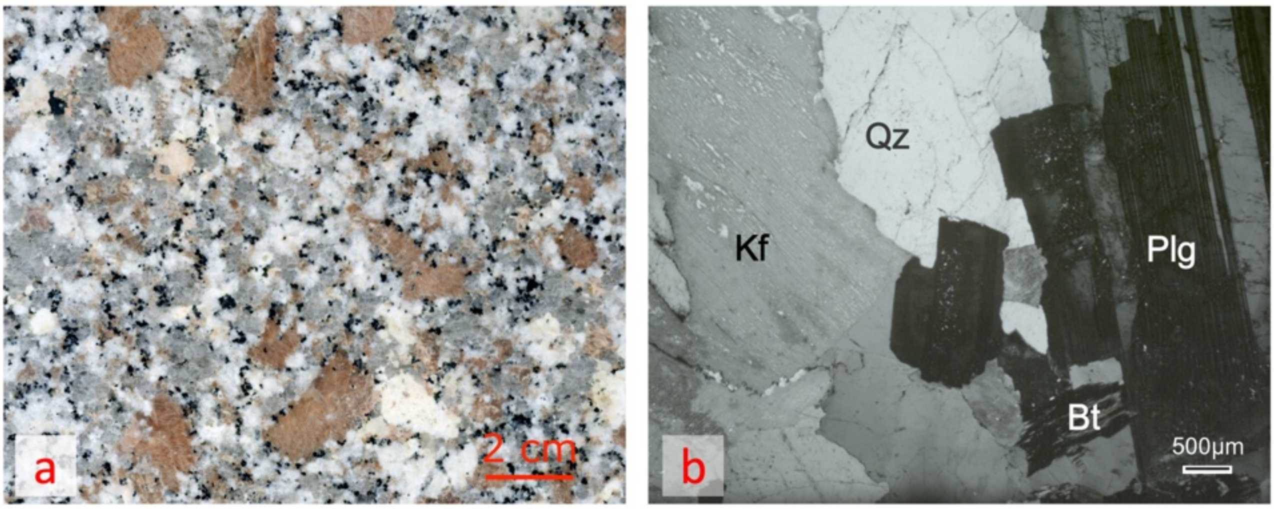
Ghiandone granite is quarried nearby the town of Priatu in northern Sardinia, Italy. The slabs from which the specimens were taken, have been produced by traditional pendulum-gangsaw sawing.

By the naked eye, the stone appears to have the characteristics of a medium to coarse grained granitoid with the presence of “acorn-shaped”. These are referred to as both automorphic and xenomorphic mega-crystals of K-feldspar. The size of these crystals varies from 1 cm to some exceptional case of 8 cm. The most frequent size is around 2 cm.

Macro-crystals of plagioclase (from 0.5 to 2 cm) and quartz (from 0.5 to 3 cm) are well visible by the naked eye, in addition to biotite agglomerates and opaques. Biotite crystals are from 0.2 to 1 cm in size.

In the 30 μm thin section (Fig. 2b) and according to the QAPF classification, the rock is petrographically classified as Monzogranite with the following percentages of components Q = 33 %, A = 27 % and P = 40 %. In addition to the QAPF phases, the rock has a biotite percentage of about 6% and an opaque percentage of 2%.

The rock’s ensemble of macro and microscopic traits are recognized as “Lovia Avra” lithotype of the monzogranites from the area of Gallura [24].



Figures 2. a: Rosa Limbara granite (polished). b: thin section (crossed nicols) from Rosa Limbara granite. Legend: Qz = Quartz, Kf = K-feldspar, Plg = plagioclase, Bt = Biotite.

Some of the physical and mechanical properties of Rosa Limbara granite given in Table 1. The physical and mechanical properties were determined by a whole range of laboratory tests, which were carried out in accordance with both UNI-EN and ASTM standards.

Table 1. Stone properties of Rosa Limbara granite according to UE and ASTM standards.

Stone Properties - UE STANDARDS	**UNIT**	**STONE**
Denomination - UNI EN 12440:2008		Ghiandone Rosa Limbara
Petrographic denomination - UNI EN 12407:2007		Granite
Real density – UNI EN 1936:2007	kg/m^3	2,658
Apparent density – UNI EN 1936:2007	kg/m^3	2,626
Total porosity – UNI EN 1936:2007	%	1.20
Open porosity – UNI EN 1936:2007	%	0.90
Water absorption at atmospheric pressure - UNI EN 13755:2008	%	0.30
Flexural strength under concentrated load – UNI EN 12372:2007	MPa	15.10
Flexural strength under concentrated load (after 48 freeze-thaw cycles) – UNI EN 12372:2007 + UNI EN 12371:2003	MPa	15.20
Compressive strength – UNI EN 1926:2007	MPa	226
Compressive strength (after 48 freeze-thaw cycles) – UNI EN 1926:2007 + UNI EN 12371:2003	MPa	228
Resistance to ageing by thermal shock – UNI EN 14066:2004 + UNI EN 14146:2005	%	Δm = 0.04 ΔE_d = - 17.70
Abrasion resistance – UNI EN 14157:2005	mm	15.50
Slip resistance by means of the pendulum tester – UNI EN 14231:2004		47 (polished and dry sample) 11 (polished and wet sample)
Linear thermal expansion coefficient – UNI EN 14581:2005	μm/m/°C	9.48
Breaking load at dowel hole – UNI EN 13364:2003	mm (d_1, b_A) kN (F)	d_1 = 9.10 b_A = 43 F = 1.78
Knoop hardness – UNI EN 14205:2004	MPa	HK25 = 5,536; H50 = 7,259; HK75 = 8.898
Stone Properties - ASTM STANDARDS	**UNIT**	**STONE**
Bulk specific gravity - C 97 - 02	kg/dm^3	2.63
Absorption – C 97 - 02	%	0.20
Modulus of rupture – C 99 - 00	MPa	R = 16.30
Flexural strength – C 880 - 98	MPa	σ = 13
Compressive strength – C 170 - 99	MPa	C = 172
Abrasion resistance of stone subjected to foot traffic – C 241 - 97		H_a = 38.27

2.2 Abrasive water-jet equipment

The equipment used for the cleaning test is the model Waterline 1620, which is a numerical control water-jet cutting robot (Fig. 3).

The high-pressure system includes the pump, cutting head and plumbing. The pump is equipped with three linear intensifiers with 35 kW installed power, which supplies a working water pressure ranging from 100 to 380 MPa at a flow rate of 7 L⁄min.

The cutting head is provided with a 0.3 mm diameter sapphire nozzle and a 7.6 cm long focusing tube, made of tungsten carbide, with an internal diameter of 1 mm. The cutting head can be moved along its X and Y axis (numerically controlled) on the working area (1.6 m x 2.0 m). The Z-axis is manually moved. In order to carry out the cleaning tests, the cutting head has been modified to allow a change of the angle of the jet inclination.

The control module, which governs the whole system, is interfaced to the machine via an automatic programming system CAD-CAM. The abrasive particles are sucked in dry by the Venturi effect into the mixing chamber (through a dosing device), in which they are introduced into a primary jet issuing from a nozzle. The water-jet has the function of accelerating and transporting the abrasive particles which work on the stone [25, 26].

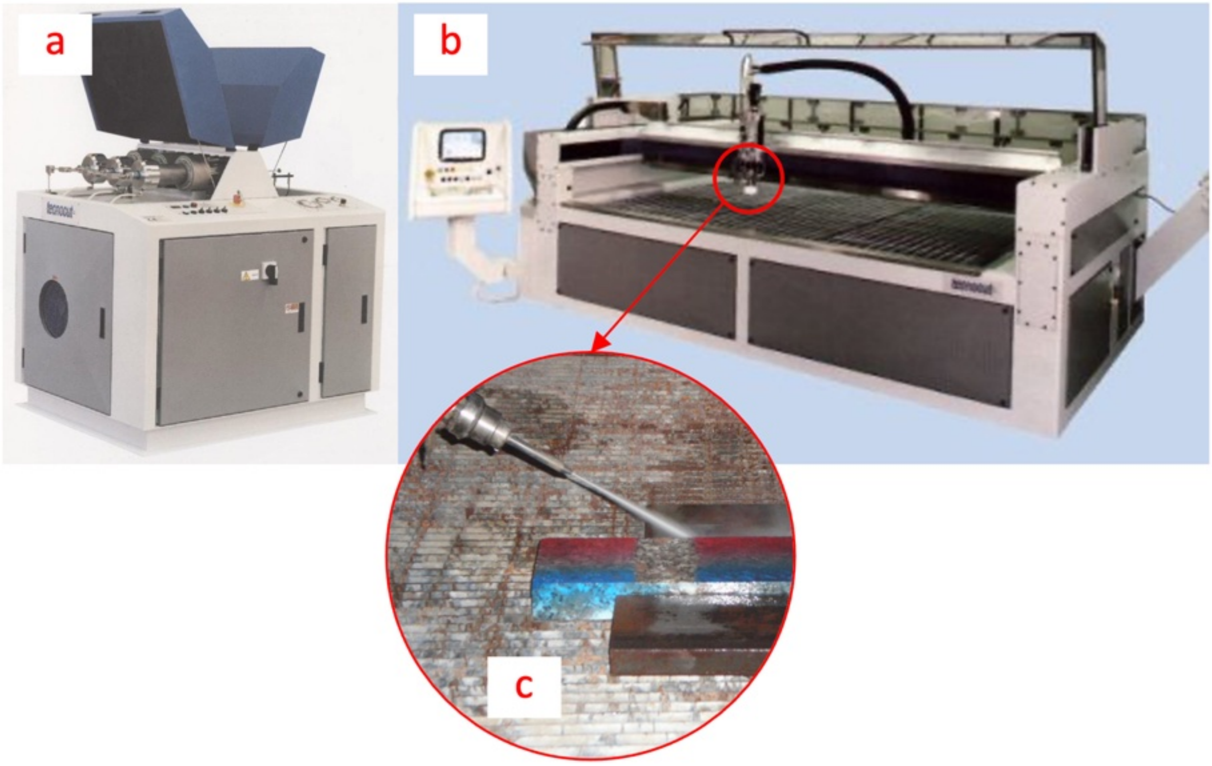


Figure 3. Abrasive water-jet equipment. a: pressure intensifier; b: CNC-controlled working area; c: cutting head.

2.3 Abrasives

Two abrasives (hereafter called A and B) have been used in the experimental tests; both have been chosen because they are the most used abrasives in the stone-cutting industry. Abrasive A consisted of almandine garnet, while abrasive B came from metal slag deriving from copper metallurgic process. Due to the distribution of the grain size of this latter product (Fig. 3) - which ranged 45 µm < B < 1 mm -, it was necessary to cut the particle size distribution by screening to bring the abrasive B to the same class of abrasive A: 105 µm < A < 300 µm. Figures 5a and 5b show the results of X-ray diffractometer tests on the two abrasives.

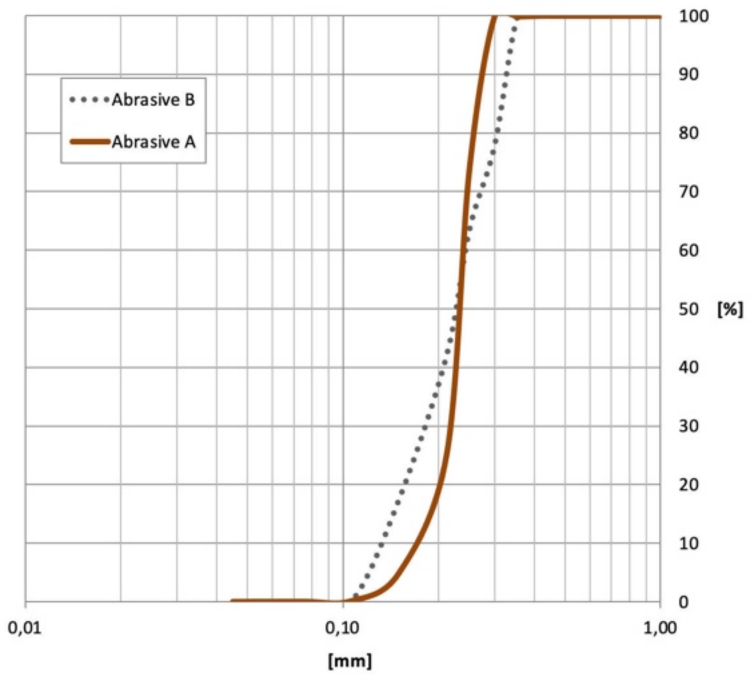
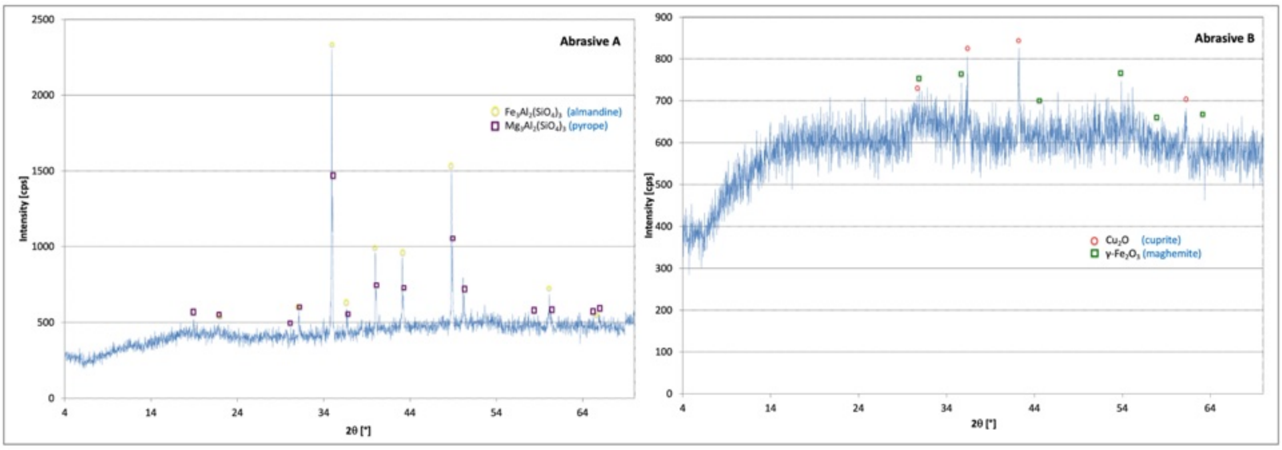


Figure 4. Particle-size distribution curves of abrasives A and B.



Figures 5. XRD analysis of the two abrasives

3. Methods

The aim of the experimental tests was to remove graffiti from the stone by limiting variations in the technical and aesthetic characteristics of the treated surface as much as possible. The method applied in this study is given in Fig. 6 and it is explained in the next sub-sections.

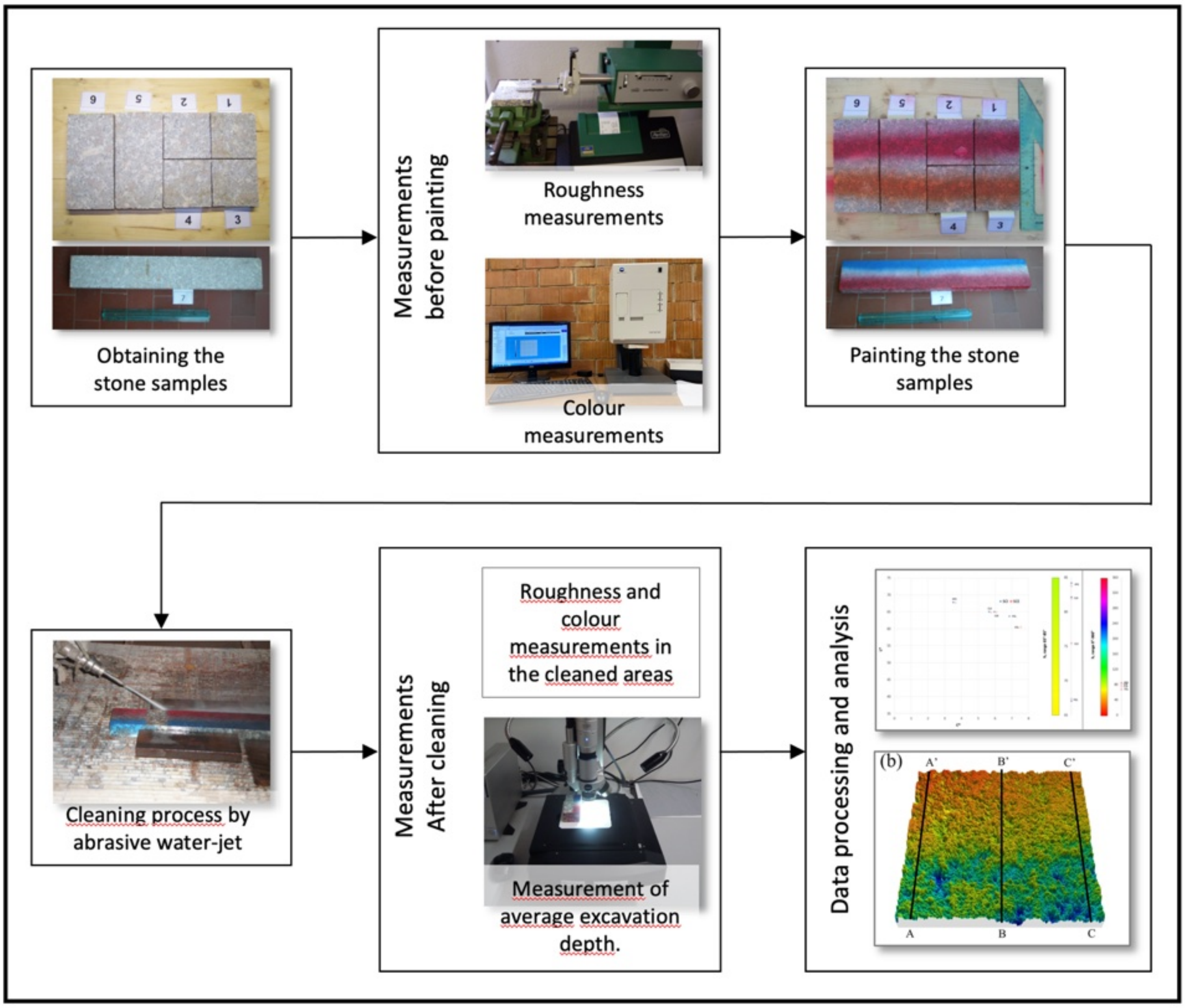


Figure 6. The methodology followed in this study.

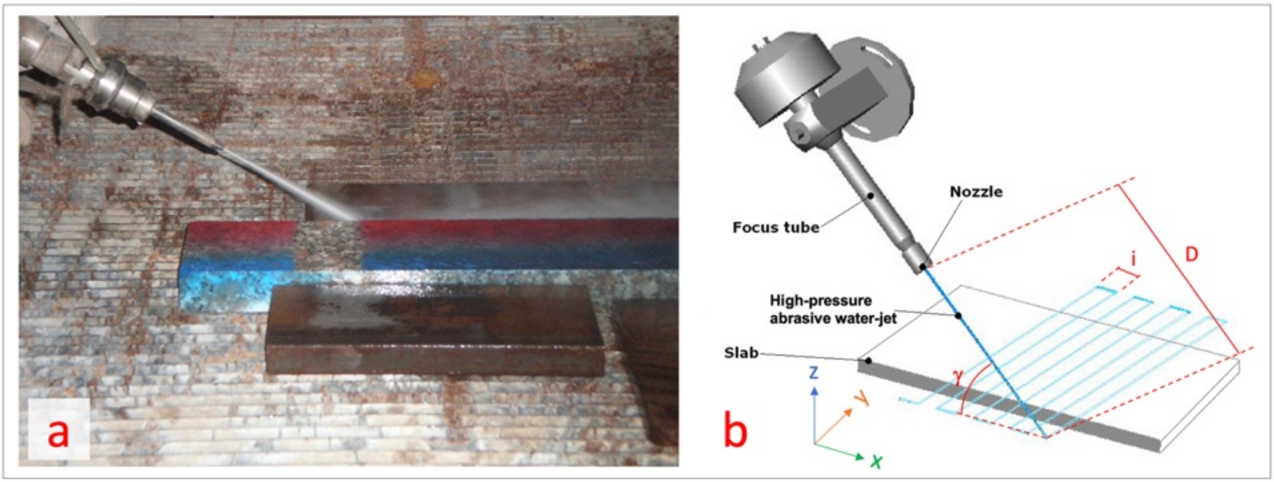
To reproduce the granite surface that is commonly used in paving, cladding or other urban furnishing, the saw-plane surface of the specimen has been considered as the original surface. The granite specimens were painted by using spray paints in red (acrylic paint), orange and blue (synthetic paints). A piece of confectionery chewing gum was applied on one of the specimens, and they were left to weather for seven days. This time allowed for complete absorption of the paint and drying of the chewing gum. The idea behind this experiment originated from the consideration that littered chewing-gum is typically a frequent environmental problem in many countries.

3.1. Cleaning test

During the study, several different operation conditions of the abrasive water-jet plant were set to use it as a cleaner tool onto the different painted parts of stone surfaces. The different operational condition features of the water-jet plant are given in Table 2; twenty different combinations have been tested in the study.

Fig. 7a shows the process of paint removal by abrasive water-jet. Based on the results obtained from earlier investigations [27, 28], a finishing program for parallel rectilinear passes of the jet was adopted. The operating parameters as the nozzle diameter ϕ (0.3 mm) and water-jet inclination γ (30° with respect to the horizontal plane) were kept constant. The stand-off distance *D*, the inter-distance between passes *i* (spacing), travel speed v_t, water pressure *P* and abrasive flow-rate Q_a were varied as listed in Table 2.

Figure 7b can help to summarize the geometrical operating parameters.



Figures 7. a: view from the cleaning process by abrasive water-jet plant in the test laboratory. b: example of cleaning program for parallel passes indicating spacing (*i*) between passes, stand-off distance (*D*) and water-jet inclination (γ).

Table 2. The operating parameter ranges of the abrasive water-jet machine.

Abrasive type	**Spacing *i* [mm]**	**Stand-off distance *D* [mm]**	**Water pressure *P* [MPa]**	**Travel speed v_t [m/min]**	**Abrasive flow-rate Q_a [g/min]**
A	10, 14, 20	100, 120	200, 300	20, 35, 40	90, 195, 202
B	10	100	200, 300	10, 20, 21, 30, 35, 40	58.6, 63, 146, 211

3.2. Colour measurements

Since the objective of the experimental tests is to restore the stone surface to the appearance it had before being vandalized, the color of the specimen had to be assessed, so as to compare the stone surface before painting and after cleaning. The colour of the specimen was measured with a bench-top spectrophotometer CM-3610A provided by Konica-Minolta and equipped with Spectra Magic NX PRO software. The measuring conditions set in the device were: illuminant D65, and observer 2° [29] with a d=8° illumination viewing geometry (following [30]). The diameter of the target mask has been set at 25.4 mm diameter in order to allow an average of the stone colour to be measured, simulating viewing from a distance [31]. Fig. 8 shows the target masks on the cleaned area of a texted sample.

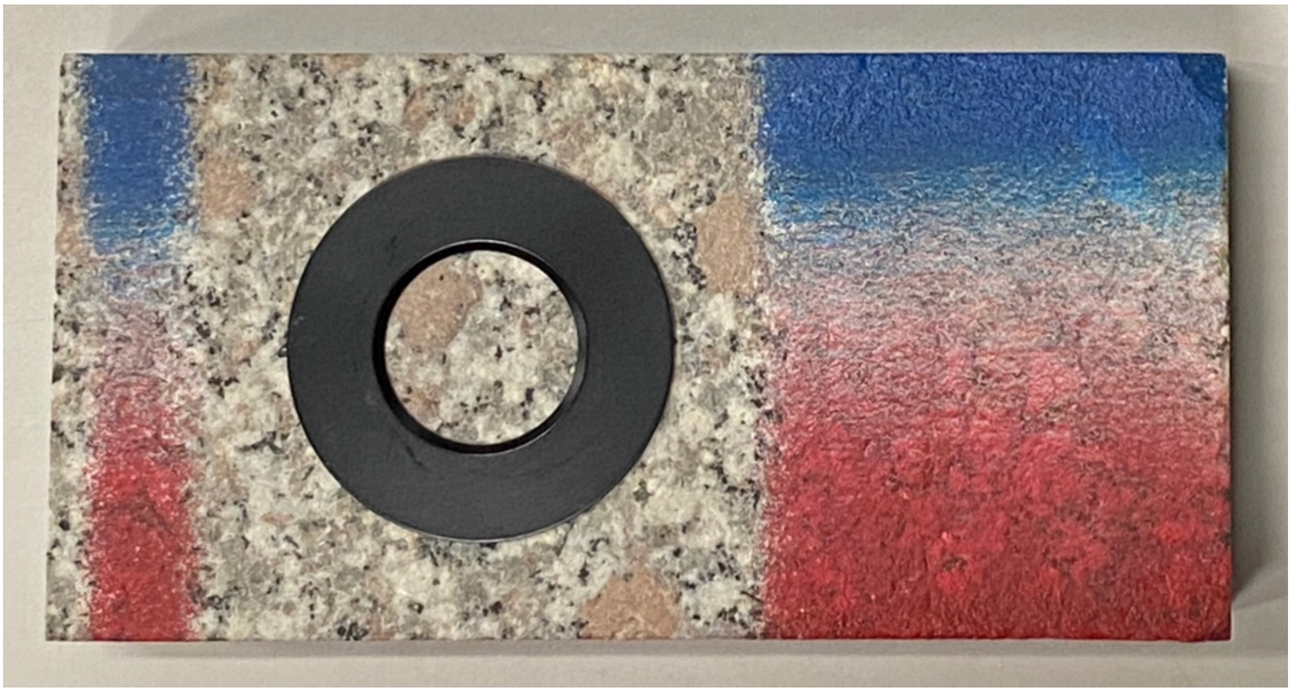


Figure 8. The 25.4 mm diameter target masks used in this study.

Colour was assessed by taking 9 random readings on some zones of the surface for each one of the specimens both before painting (original stone surface) and after the cleaning process.

Due to the fact that the surface of the samples is not entirely reflective or matte, inclusion or exclusion of the specular component may be important for colour measurements [32].

The technique of colour measurement, which excludes the specular reflectance, is named SCE (Specular Component Excluded). When the specular reflectance is included in the colour measurement by completing the sphere with a specular plug, we refer to it as SCI (Specular Component Included). In SCE mode, the specular reflectance is excluded from the measurement and only the scattered reflectance is measured. This gives a colour evaluation which correlates to the way the observer perceives the colour of an object. Stone surfaces characterized by matte colour and irregularities induce the light diffusion in many directions, thus reducing the SCE [32]: for this reason, measurements have been carried out in SCE mode. When using the SCI mode, the specular reflectance is included with the scattered reflectance during the measurement process. This type of colour assessment measures the entire appearance in spite of the surface condition.

For these reasons, the measurements were carried out in both SCI and SCE modes.

Regarding the choice of CIE colour space, the CIE L*a*b* coordinates are recommended for achromatic colours, whereas the CIE L*C*h* coordinates are preferred for stronger colours [33]. Because the objective of this study was to try to assess the possible difference in the colour of the stone before painting and after cleaning, both sets of colour space coordinates were used.

To better assess the colour differences between the original surface and the ones obtained after graffiti removal, the classical CIEL*a*b* formulation (1) [34] was used, as supported by Prieto et al. [35] especially when textured surfaces are to be studied:

$$\Delta E_{ab} = \sqrt[2]{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

3.3. Roughness test

The data which have been obtained with the spectrophotometer analysis have to be updated with the information about roughness. In fact, a cleaned surface, which shows similar colours compared to an unpainted surface, it may have completely different roughness features, due to an excessive excavation caused by the water-jet during the cleaning process.

The purpose of roughness measurements is to determine which one of the treated surfaces has similar roughness to the original surface. For this reason, the roughness profile of the cleaned samples was carefully analysed using a mechanical comparator. Parameters R_a (mean roughness), R_Z (average distance between the highest peak and lowest valley in each sampling length) and R_{max} (maximum roughness depth) were determined in accordance with EN ISO 21920-3 [36].

3.4. Measurement of average excavation depth

It is very important to assess how much stone material was removed during the cleaning operation. This was calculated according to three cross sections of stone surface perpendicular to the transition line between the painted area and the area subjected to the water-jet.

A 3D micro-topographic map (3x3 cm) has been performed by an HIROX-01 microscope equipped with a nano point scanner (NPS-NP3, working range $0 < R < 1400$ μm). The 3D micro-topographic map consists of 200 scanning lines realized through a speed of 3000 μm/s.

The crossing section profiles have been extracted by the 3D micro-topographic map with the help of the software Mountain Map Imaging topographic version 7.4

In any cross section, the difference (ΔY) between the average elevation in the painted area and average elevation in the area subject to water-jet was measured by means of the processing software. The average amount of material removed during the cleaning operation is then calculated as the arithmetic average of the ΔYs of each of the three profiles.

4. Results and discussion

After the cleaning process and before the colorimetric study, the granite samples were checked by the naked eye for macroscopic control. Graffiti removal was observed on all samples subjected to the cleaning process. However, some tests were excluded from subsequent measurements because the jet removed an excessive amount of material, which was not ideal.

The cleaning tests that passed this initial screening were subjected to the subsequent measurements.

As general considerations, we can say that the best results, from a technical point of view, are obtained with the following combinations of water-jet operating parameters:

- When using abrasive A:
  - P = 300 MPa, v_t = 40 m/s, i = 10 mm, D = 100 mm, Q_a = 202,1 g/min
- When using abrasive B:
  - P = 300 MPa, v_t = 20 m/s, i = 10 mm, D = 100 mm, Q_a = 211,2 g/min
  - P = 200 MPa, v_t = 35 m/s, i = 10 mm, D = 100 mm, Q_a = 58,6 g/min (chewing-gum test)

In fact, the tests which was carried out with these combinations resulted in perfectly clean specimens, with a surface similar to the original one (before painting).

The high-pressure water-jet causes the removal of layers of variable thickness on the stone. In monomineralic stones, water-jet abrasion capacity depends on the porosity of the rock especially in the pore range $0.01 < \phi < 1$ μm [37].

In multi-mineralogic rocks, as Ghiandone granite, surface removal takes place according to differential erosion. By the latter, minerals with higher hardness and absence of microfractures or layers of inclusions resist the action of the water-jet better. Conversely, softer or micro-fractured minerals will exhibit low strength.

In our test, removal craters were often deeper and thinner when the water-jet was directed parallel to micropertitic layers [38].

Following our test and based on bibliographic observations, the removal craters on macrocrystals of K-feldspar are deeper than plagioclase.

Additionally in this latter, it has been statistically observed that the volume of the erosion crater is not proportional to the pressure of the water-jet flow but shows significant oscillations [39].

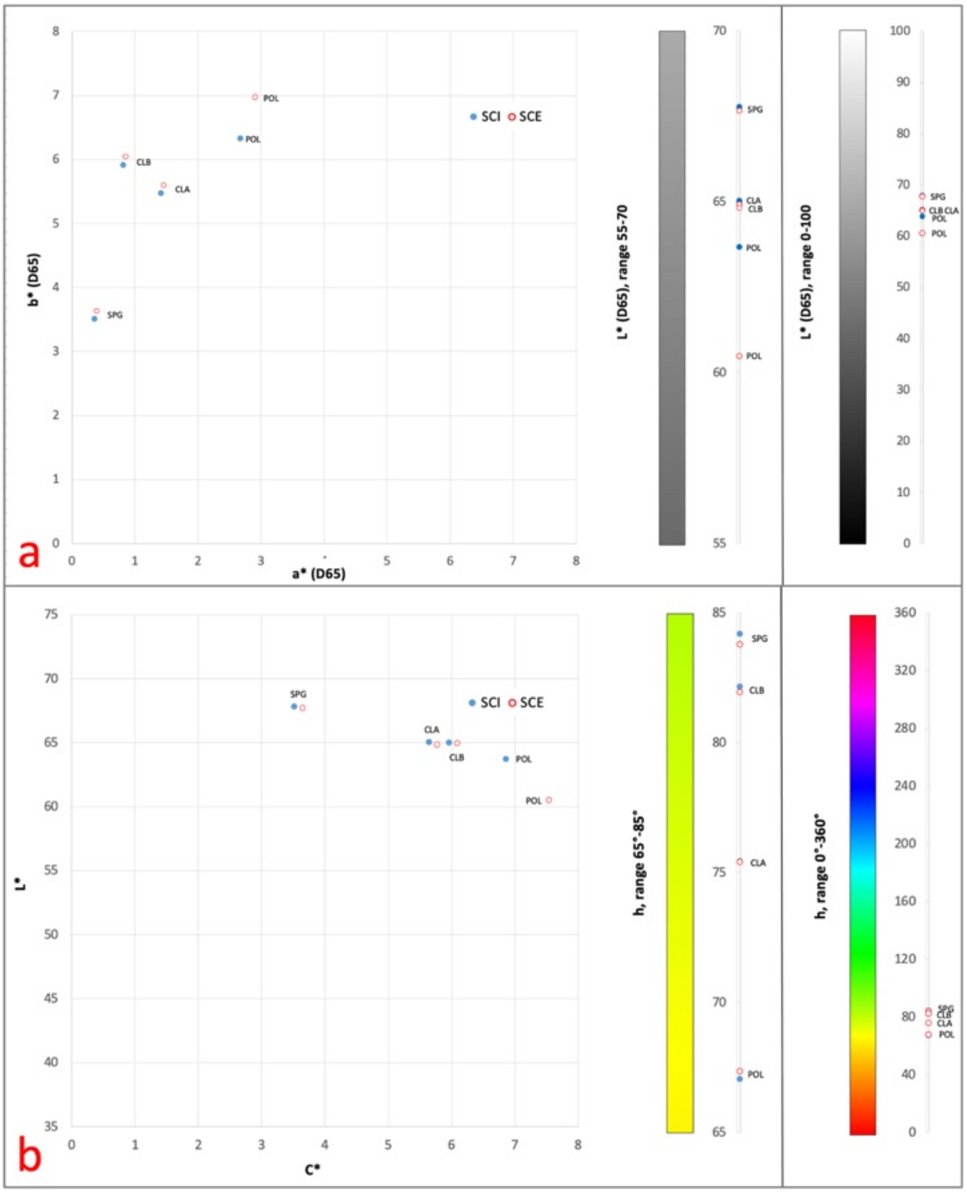
Plagioclase shows the highest strength among all phases due to its compactness and absence of fractures.

In K-feldspars the action of the water-jet is favoured by the presence of spatial discontinuities in terms of cleavage planes. The K-feldspar removal capacity by the water-jet changes according to the orientation of the water-jet with respect to the cleavage planes [38].

Conversely, in quartz the presence of spatial discontinuities favours its easy removal. As reported in the biography, quartz is the most sensitive mineral to the action of the water-jet, showing a good proportionality between the volume of the crater produced by the erosion and the pressure of the flow [39]. On quartz crystal, the water-jet mainly produces irregular cavities irrespective to the mineral form. The biotitic phases from the granites show a good resistance due to their plastic deformability [37].

4.1 Colour

Fig. 9a shows a comparison of the colour coordinates between the L*a*b* values of the surfaces studied. The cleanings, obtained with both abrasives, show similar values in the Cartesian plane a-b; the colours of the cleaned surfaces move more towards the natural colours of the stone (represented by the polished surface, POL) than the colours of the starting surface (SPG).



Figures 9. a: Values of the a*, b* CIELAB coordinates and L* CIELAB lightness for the different surface. b: Values of the CIELAB chroma C*, L* and CIELAB hue angle h for the different surface. CLA = surface cleaned by abrasive A; CLB = surface cleaned by abrasive B; POL = polished surface; SPG = gangsaw-plane surface. Lightness L* is shown in two different scales to facilitate reading.

These results are also confirmed in the L*C*h colour space as shown in Fig. 9b. It should be noted that the hue values (*h*) of the cleaned surfaces move towards to the values of the starting surface (SPG), particularly in the samples in which abrasive B was used. However, when evaluated over 360°, the hue values are very close to each other, showing that the difference between the values is very small.

As was to be expected, in each sample, the SCI and SCE values are very close to each other with the only exception of the polished samples, where the difference is magnified for the reasons already explained in section 3.2.

Table 3. Partial colour differences (ΔL*, Δa*, Δb*) and total colour difference (ΔE*) between the original saw-plane surface and each of the other cleaned surface finishes, in SCI and SCE modes. Polished surface values are also reported.

	SCI				SCE			
	ΔL*(D65)	**Δa*(D65)**	**Δb*(D65)**	**ΔE*(D65)**	**ΔL*(D65)**	**Δa*(D65)**	**Δb*(D65)**	**ΔE*(D65)**

SPG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POL	-4.11	2.32	2.83	5.50	-7.18	2.51	3.33	8.30
CLA	-2.75	1.06	1.97	3.54	-2.84	1.06	1.96	3.61
CLB	-2.78	0.46	2.41	3.71	-2.73	0.46	2.41	3.67

Although the two abrasives restore a very similar surface to the original one, as can be seen from the ΔE* values in the Table 3, abrasive A seems to have a better result. In fact, when considering observing the ΔE* values with respect to the "just noticeable difference" (JND) it is known that an unexperienced observer notices the difference when $2 < \Delta E < 3.5$ [40].

4.2 Roughness

Table 4 shows that the roughness of the samples subjected to paint removal is similar to that of the original surface (SPG), particularly when abrasive A is used.

Table 4. Roughness values, measured in μm, for the different surfaces (R_a = Mean roughness; R_z = Average distance between the highest peak and lowest valley in each sampling length; R_{max} = Maximum roughness depth).

Type of surface	R_a	R_z	R_{max}
Sawplane	22,1	108,3	160,2
Cleaned (abrasive A)	24,8	125,8	169,9
Cleaned (abrasive B)	27,8	140,6	190,6

The small differences with the original surface (before painting) are related to what was described earlier: the 'selective' action produced by the AWJ on the different crystals of the granite implies a greater 'excavation' at the more sensitive crystals (i.e. quartz) and lesser at the more resistant crystals (i.e. plagioclase).

These values, taken together with the colorimetric parameters, show how abrasive water-jet cleaning can restore the stone surface to its original appearance.

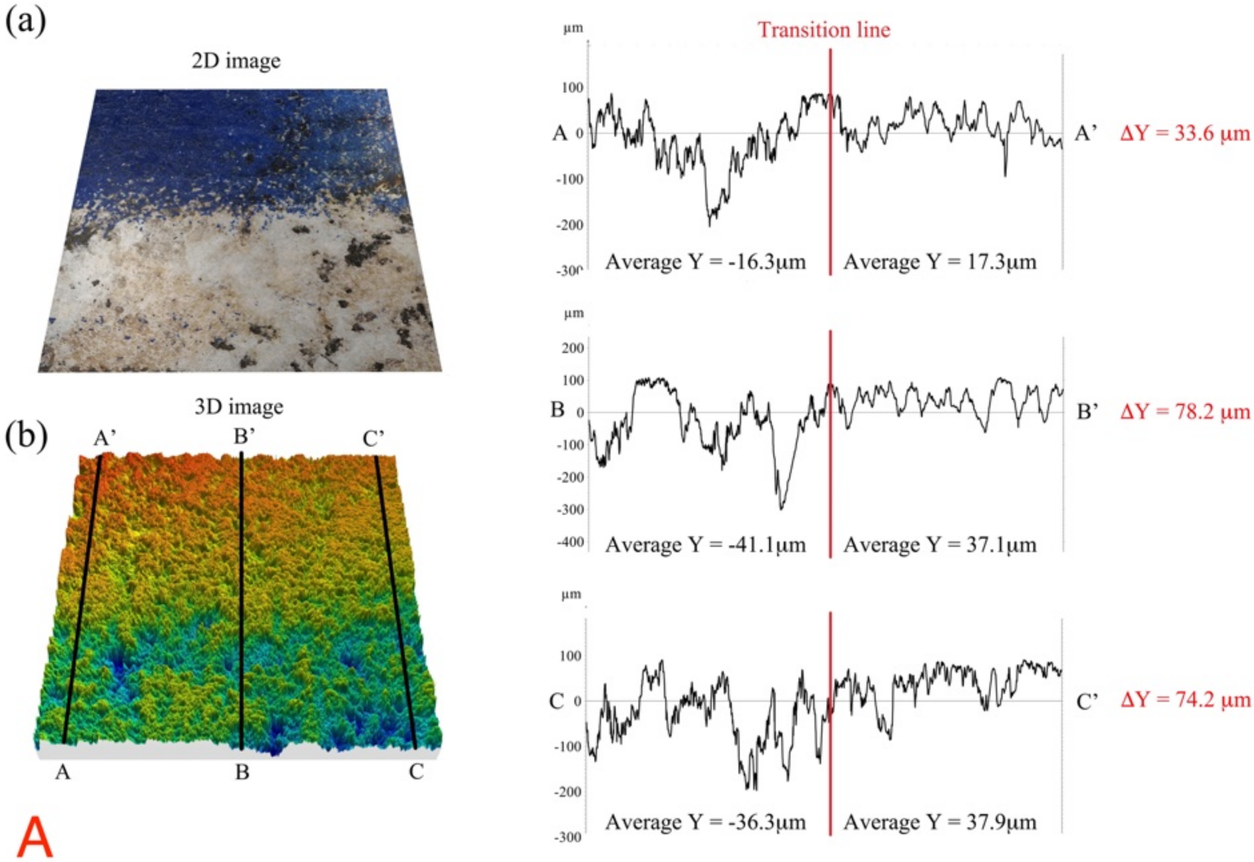
4.3 Material removal

Figures 10A and 10B show both the 2D orthophoto of sample surface subjected to AWJ cleaning (by using abrasives A and B respectively). The scanning surface (3x3 cm) includes the transition line between painted and cleaned area and the 3D micro-topographic map with cross section positions. In Figs. 10, two 3D micro-topographic maps are illustrated by coloured thematic areas where red and white topographically represent prominent areas while green and blue areas represent depressions. As already explained in the methods, three cross-section profiles A-A', B-B', C-C' were made from these surfaces and are exhibited in the corresponding photos. On the right of both the figures, the 3 cross sections are present with the relative ΔY. It is easy to identify how the area subject to cleaning is always less elevated than the painted area. This is due to the removal of a thin layer of material following the passage of the abrasive water-jet.

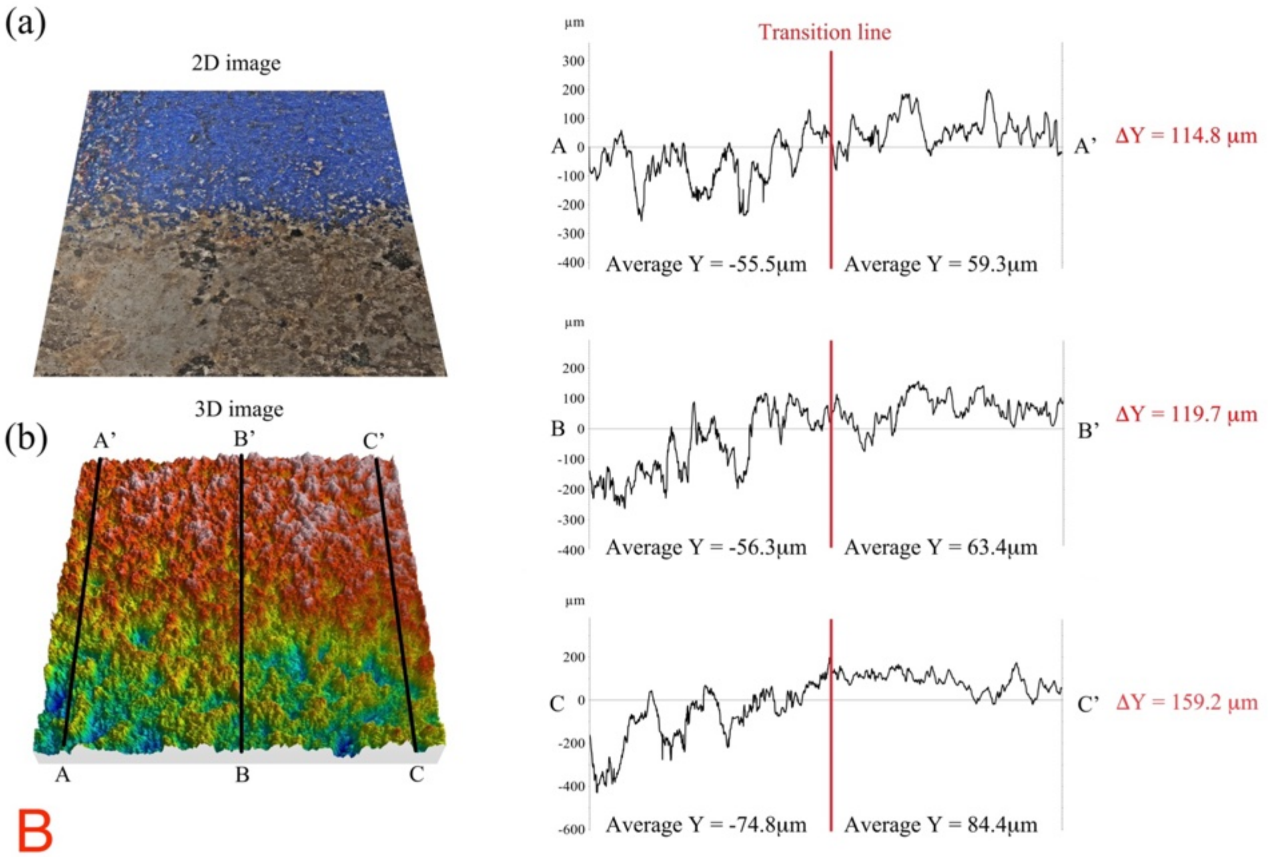
In Fig. 10A, showing the sample cleaned by A abrasive, it can be seen that in profile 1, a difference $\Delta Y = 33.6$ μm between painted and cleaned area is identified. In profiles 2 and 3, a ΔY of 78.2 μm and 74.2 μm are respectively recorded. The average thickness of removed material in the sample is therefore considered the arithmetic mean of the three ΔY, in this case 62 μm.

In Figs. 10B, showing the sample cleaned by B abrasive, the first profile identifies a difference $\Delta Y = 114.8$ μm. In profiles 2 and 3, a ΔY of 119.7 μm and 159.2 μm are respectively recorded. The average thickness of removed material in the sample is therefore 131.2 μm.

In the sample cleaned through B abrasive a layer of material thicker than the abrasive A was therefore removed. This is essentially due to a higher *Q* value.



Figures 10A: (a) 2D orthophoto of sample surface subjected to A abrasive cleaning. The scanning surface (3x3 cm) includes the transition line between painted and cleaned area, (b) 3D micro-topographic map with cross section positions.



Figures 10B: (a) 2D orthophoto of sample surface subjected to B abrasive cleaning. The scanning surface (3x3 cm) includes the transition line between painted and cleaned area, (b) 3D micro-topographic map with cross section positions.

The chewing gum was easily removed from the surface together with the paint (see Fig. 11).

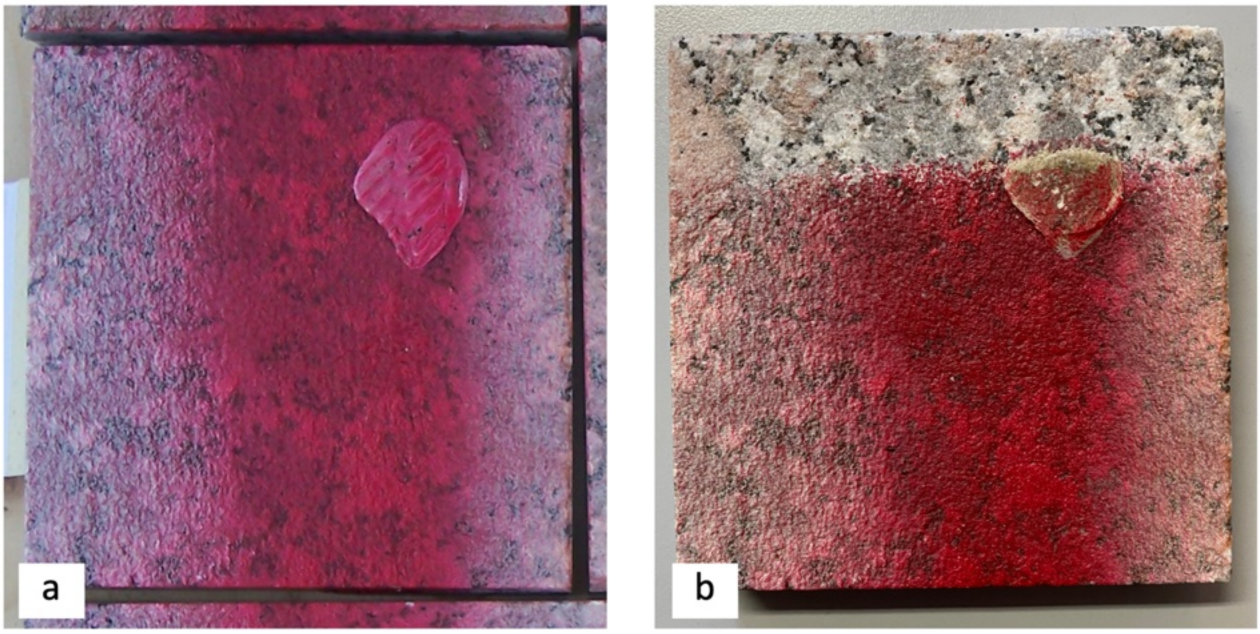


Figure 11. Result of chewing-gum removal: a) vandalized condition, b) after cleaning.

5. Economic consideration

The economical features and operational costs of stone slabs surface finishing with water-jet were stated in a previous study in detail [41]; so that, it can be said that: considering both technical and economic parameters as the surface finishing velocity, the ownership costs of the plant, the operating costs and labour cost (in the Italian market), we have obtained the total unit cost (C_t) ranging from 2.59 €/m^2, when abrasive A is used, to 4.56 €/m^2 when abrasive B is used. The main parameters which affect C_t are both the inter-distance between passes i (smaller i value gives higher C_t value) and the travel speed (faster v_t value gives lower C_t value). However, it should be noted that this range allows a very good gain when compared with the current unit price in European market for paint removing (from 13 to 60 €/m^2) from paving and cladding.

6 Conclusion

The assessment of abrasive water-jet technology on spray-paint graffiti removal from granite was analyzed and discussed considering two different commercial abrasives.

Colorimetric investigations performed on the samples both previous painting and after cleaning revealed that this method is effective in paint removal, restoring the surface aesthetic like the original one. The total color difference (ΔE*) after cleaning shows values lower than 4 units for both abrasives; although these results are a bit higher than the JND, the surface aesthetic appearance is surely acceptable.

Moreover, the micro-photographic mapping demonstrated that abrasive water-jet cleaning produces very low damage on the granite when the operative parameters (as abrasive flow-rate, water pressure) were well-chosen, especially when abrasive A is used.

This is also confirmed by roughness measurements that show the roughness parameters (R_a, R_z and R_{max}) very close to those of the original saw-plane surface.

Although presented here as an accessory experiment, it can be stressed that the abrasive water-jet removed easily the chewing-gum from the stone.

The study demonstrated the economic feasibility of the AWJ technology in removing graffiti from Ghiandone granite. We must highlight the importance of calibrating the operating parameters according to the material and the desired results: it should be borne in mind that a different typology of granite is expected to give different results in terms of paint removal.

Other stone surfaces (e.g. flamed and bush-hammered) will be considered in future research developments; the mechanism of graffiti removal by AWJ will be studied as well. Weathered surfaces will also continue to be included in the research.

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