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Chromaticism differentiations: a study of the diversified aesthetic appeal of the Ghiandone granite range.

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Abstract

This paper presents the results of the study of the change in colour of the Ghiandone granite, which is typically used for ornamental purposes, and of all its mineral constituents, whenever undergoing different surface finishings. Changes in roughness as well as gloss were recorded, and put in relation to CIE colour parameters. The study was carried out by using a spectrophotometer, in order to measure the colour coordinates in CIE L*a*b* and CIE L*C*h colour spaces of those stone samples which have been treated following traditional methods (i.e. polishing, bush-hammering and flaming) and advanced technologies (i.e. pure water-jet and abrasive water-jet); sawplane surfaces (from traditional gangsaw and diamond disk) were also considered in this study. The results show that lightness (L*) is the colour coordinate that experiences a higher variation when different surface finishings are applied, especially bush-hammering. In the CIE L*C*h colour space, polished and pure water-jet finished samples are characterized by higher chroma values than the others samples which are featured by higher lightness. Hue doesn't show any significant variation. When the total colour difference (ΔE*) is measured, pure water-jet also preserves the original colour of stone and minerals, similarly to the polishing. An inverse correlation between specular gloss values and mean average roughness have been documented.

Keywords: dimension stone; granite; spectrophotometer; CIE colour spaces; surface finishings.

1 Introduction

Stones are of many colours, depending on individual taste or prevailing fashion. The choice of the colour is intertwined with the surrounding environment and has to do with its availability in nature. Some rocks change their colour with age, and such change may often be aesthetically appealing [1].

Because of the increased demand for a wider colour range, rocks which can become strikingly different once polished and finished, and which are also the best option for monumental inscriptions are likely to have a wider appeal.

The red, pink, brown, buff, grey or white rocks are widely employed for building. Dark-grey, teal blue or black rocks are in demand for the internal structure or for other special uses, such as funerary arts.

The brownish or yellow tints of many limestones, marbles, travertines and sandstones and the red, brown or pink coloration of many granites are given to the presence of iron oxides that produce no stains.

Some of the most important parameters followed when planning to use any natural stone in buildings and monuments, are its optical properties. The appearance and optical properties can be checked by the naked eye [2]; however, it is necessary to define colours precisely, to describe them and to make sure that a second observer understands exactly all the nuances.

The L*a*b* colour space (also referred to as CIE L*a*b*) is currently one of the most popular spaces for measuring object colour and it is widely used in all fields. It is one of the uniform colour spaces defined by CIE in 1976 [3]. In this space, L* indicates lightness (white) and a* and b* are the chromaticity coordinates. Fig. 1 shows the a*, b* chromaticity diagram. In this diagram, the a* and b* indicate colour directions: +a* is the red direction, -a* is the green direction, +b* is the yellow direction, and -b* is the blue direction. The centre is achromatic; as the a* and b* values increase and the point moves out from the centre, the saturation of the colour increases. The L*C*h colour space uses the same diagram as the L*a*b* colour space, although it uses cylindrical coordinates instead of rectangular coordinates. In this colour space, L* indicates lightness and it is the same as the L* of the L*a*b* colour space, C* is chroma, and h is the hue angle. The value of chroma C* is 0 at the centre and increases according to the distance from the centre (Fig. 2). Hue angle h is defined as starting at the +a* axis and is expressed in degrees: 0° would be +a* (red), 90° would be +b* (yellow), 180° would be -a* (green), and 270° would be -b* (blue).

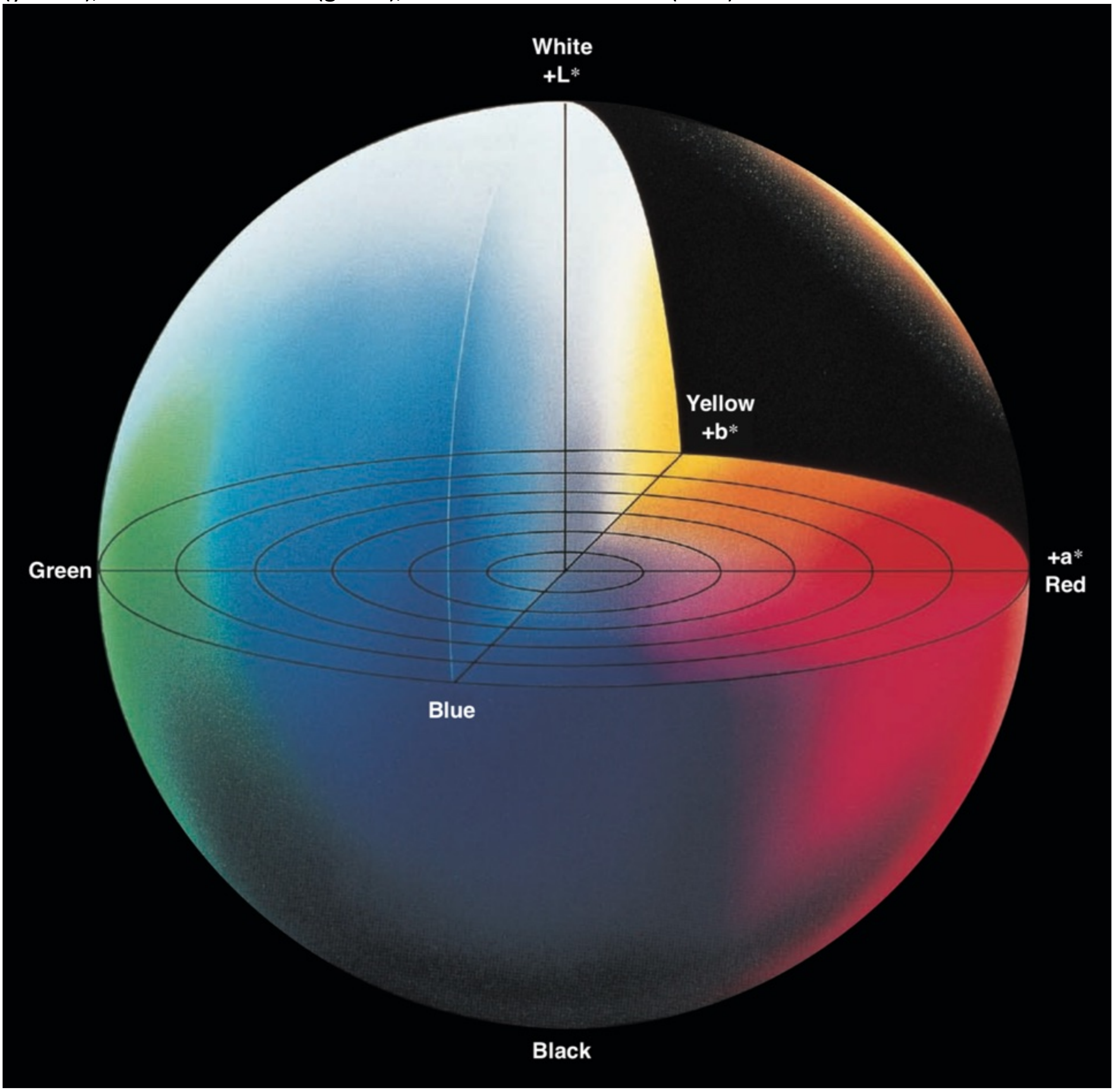


Fig. 1. Representation of colour solid for L*a*b* colour space (from Konica Minolta)

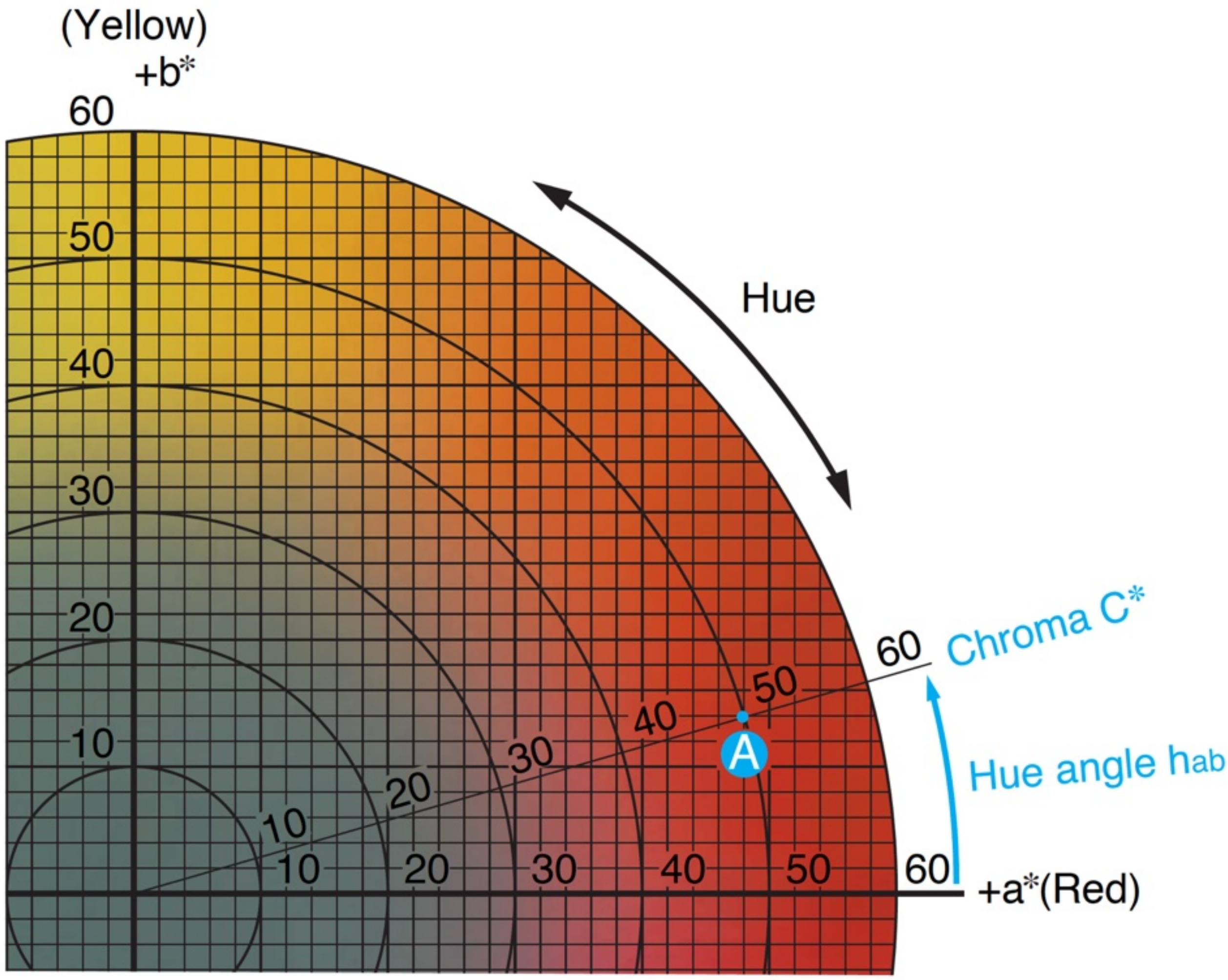


Fig. 2. L*C*h colour space (from Konica Minolta)

Many researchers have worked on this aspect, with the intention of evaluating the variation of the stone colour, whether by anthropic degradation or by natural causes.

In fact, many of the most impressive monuments and constructions in the world are built in stone not only because stone is the most ancient, most durable and most widespread among all building materials [4], but also for the great variety of colours and texture that it may have. The popular use of stone in buildings, monuments, street furnishings and funerary art is justified by its strength to weathering or degradation, as well as by its appearance. The choice of an ornamental stone for a new construction is generally driven by the aesthetic properties a specific stone has (technical properties being equal), because such properties define the architectural harmony of that construction with those nearby and improve the visual perception of the building.

It should be reminded that many weatherings and/or degradation of stones used for monuments and buildings are caused by environmental conditions and urban pollution; therefore, the stability of the stone colour is a parameter that must be understood and monitored [5].

Moreover, there are several types of surface processing/finishing which all make the same stone look different. In fact, each finishing produces a different surface roughness that influences the aesthetics, by conferring variation of the texture colours and luster to the eyes of the observer. Therefore, when the appearance of an ornamental stone is the first selective criterion, it is necessary to know how to concretely evaluate the aesthetic properties of the stone which will be used.

Using the CIE L*a*b* methodology, Biscotin et al. [6] evaluated different surface cleaning methods that can be applied to stone. Pozo et al. [7] assessed the efficiency of the biocrusts removal from ornamental granites by comparing the results obtained from different cleaning techniques by using both colorimetric measurements in the CIE L*a*b* colour space and microscopy studies. Durán-Suárez et al. [8] assessed the effects on reflectance and colorimetry related to the use of substances for the recovery and consolidation of a biocalcarenite used in buildings. Similarly, García-Talegon et al. [9] studied the colour change of some sandstones subjected to consolidating treatments, waterproofing and cycles of artificial ageing.

Benavente and al. [5] investigated the correlation between the variation of the roughness and the CIE L*a*b* and CIE L*C*h colour spaces parameters on different stones, used in buildings, which were subjected to acid-attack tests.

Grossi et al. [10] used a colorimeter to measure the effects of cleaning, with laser technology, on the surface of granite tiles.

Prieto et al. [11] proposed a protocol for characterizing the colour of heterogeneous rocks such as granites for ornamental use. Later, Sousa and Gonçalves [12] used a colorimeter to measure the colours of a granite in the CIE L*a*b* and CIE L*C*h colour space on both large slabs and small samples. Rivas and al. [13] proposed a functional data approach to evaluating colour changes in stone, that is based on applying a functional experiment design to the tristimulus curves resulting from the product of the power spectral distribution of the source, the stone reflectance curve and the matching colour functions of the standard observer. This method was applied to an analysis of colour changes in granite after the application of different desalination treatments. The results were compared with those obtained by the classical analysis of variance applied to the colorimetric coordinates CIE L*a*b*.

The effect of some traditional surface machining on the final appearance of different ornamental granites has been analysed by assessing its roughness, colour and gloss by Sanmartín and al. [4].

Another interesting study covered the Spanish slates. Prieto and al. [14] considered fifty commercial varieties in such a way as to define the tolerable colour ranges for the replacement of the slate tiles during the restoration of the buildings. The researchers used a spectrophotometer working in the CIE L*a*b* colour space.

The colorimetric study was also used for the evaluation of the altered state of the soapstone tiles that cover the statue of Christ the Redeemer in Rio de Janeiro, Brazil [15] and to estimate the behaviour of some granites, employed as cladding of buildings, if subjected to thermal shock as in the case of fires [16, 17]. The diagnosis of degradation, due to fires, of historical monuments built in stone, has been studied by Janvier-Badosa and al. [18] by colorimetric measurements and P wave velocity. Eren Sarıcı [19] studied the changes in surface gloss and colorimetric parameters (in CIE L*a*b* colour space) in marbles caused by thermal shocks and cycles of artificial ageing.

Spectrum measurements were performed on glossy slabs of various ornamental rocks, to show the accuracy of the theoretical colorimetric calculations on the perceptive differences of the appearance that takes the colour under different standard illuminations [20].

Other colour measurement methods were followed by Sanmartin and al. [21] with the use of a calibrated digital camera (used as a contactless colorimeter) to assess the colour of some granite artefacts. Always using a digital camera and the CIE L*a*b* colour space, Li and al. [22] proposed a research method for the assessment of the resistance of the rock-mass after the fire damage in the tunnels. Akkoyun and al. [23] developed a software based on image processing to determine the colorimetric properties of natural stones, studying, in particular, the various commercial typologies of Orosei marble. Later, Careddu and Akkoyun [24] used the technique of the elaboration of the images to evaluate the water-jet cleaning of the marble from graffiti.

Recently, Navarro et al. [25] assessed the effect of ultraviolet radiation on both chromatic parameters and gloss values in serpentinites used as dimension stones.

The importance of the colorimetric study of ornamental rocks is strongly highlighted by the academic literature. Its importance is reflected when dealing with problems pertaining to the restoration of monuments and/or buildings, and when the replacement of deteriorated or broken stone elements is necessary, especially when different stone materials with similar colorimetric characteristics are used.

The aim of the present study is to show how a different surface processing affects the colour and gloss of the Ghiandone granite, by analysing both the whole stone and each single mineral; the second purpose is to demonstrate quantitatively to what extent the pure waterjet finishing maintains the original colors of the rock when compared to other technologies. The academic research has shown that the different finish results obtained by water-jetting were never analyzed before from a colorimetric point of view.

2. Materials

The Ghiandone granite, commercially known as Rosa Limbara, is quarried in northern Sardinia, Italy. Thin sections of the natural stone samples (one of which is shown in Fig. 3) were prepared and they were then examined under a polarized microscope to determine both the textural features and the petrographic composition of the stone. This is a medium to coarse grained granitoid rock macroscopically featuring the presence of acorn-shaped of 1 to 8 cm megacrystals of K-feldspar, both automorphic and xenomorphic; on the scale of the outcropping they show weak orientation.

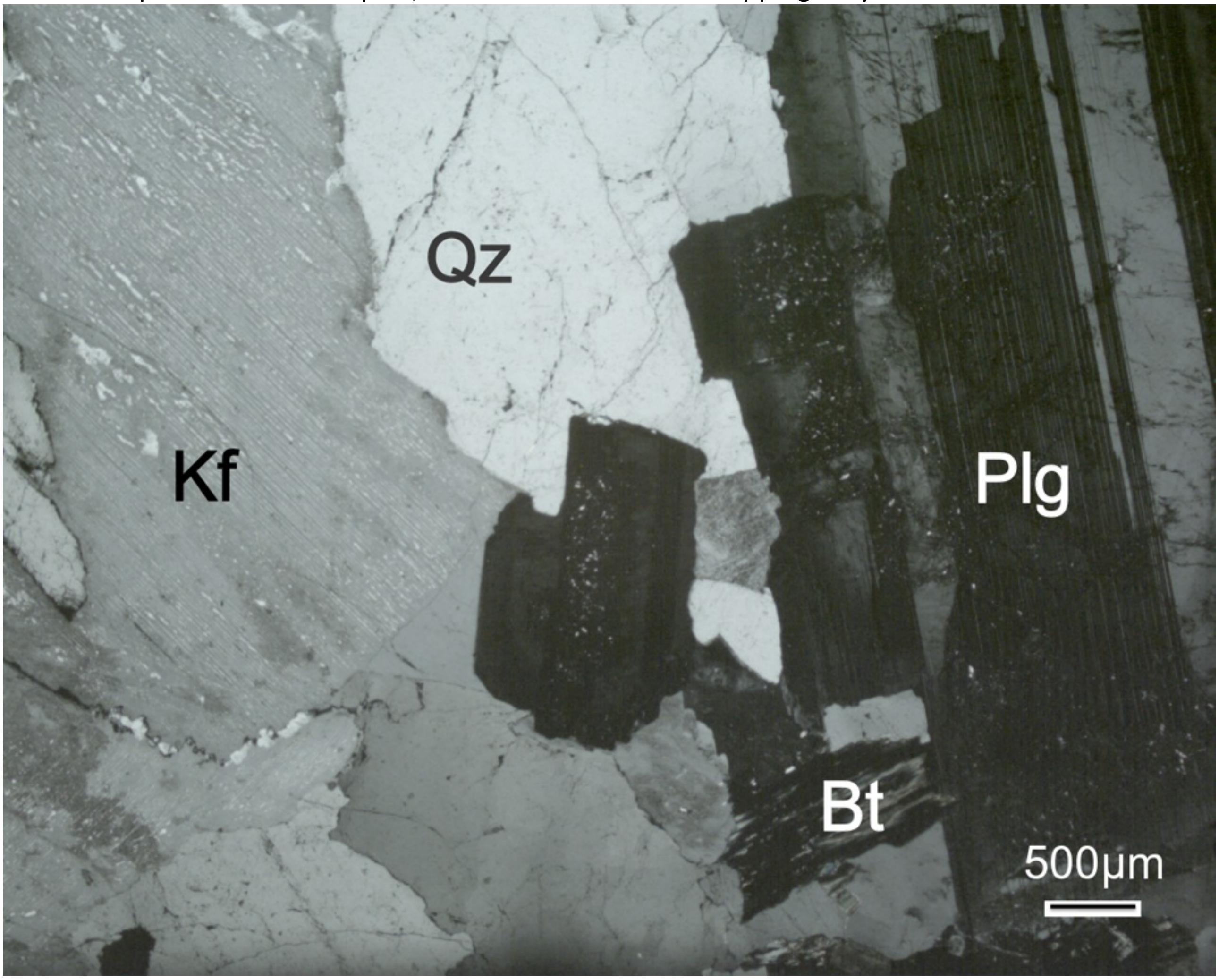


Fig. 3. Thin section (crossed nicols) from Rosa Limbara granite. Legend: Qz = Quartz, Kf = K-feldspar, Plg = plagioclase, Bt = Biotite.

Some of the physical and mechanical properties and grain size of the natural stone samples are 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 EN and ASTM. The two different standards were used to evaluate the same properties, because this stone is exported both to E.U. and U.S.A. [26].

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	2,626
Apparent density – UNI EN 1936:2007	kg/m^3	2,658
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

There are two main reasons why this stone has been chosen for this study. Firstly, by comparison with other granites, it is much easier to assess the colour of the much larger Ghiandone crystals with the exception of the biotite. Secondly, Ghiandone is generally sold easily, in any size and finish, globally, which is why we decide to test this stone for our research.

Three 10 cm x 10 cm x 2 cm specimens for each surface processing were used for the measuring tests. The considered surface processing technologies were the following:

- polished surface (POL): polishing is the final stage of smoothing as well as its final refinement in the aesthetic and chromatic sense; all residual pores are occluded and the surface becomes shiny, reflective and mirroring;
- saw-plane surface (by gangsaw, SPG): it is obtained by sawing with a traditional pendular steel-shot gangsaw. The appearance is definitely uneven because of the furrows created by the metal shot;

- saw-plane surface (by diamond disk, SPD): it is obtained by using diamond-coated disks that leave a semi-smooth surface, quite flat;
- bush-hammered surface (BH): it is a treatment given with the bush-hammer which is a percussion tool of specific shapes. Dents in the form of little white dots, looking and feeling like orange rind, and rises are created;
- flamed surface (FL); it is a thermal process that works by inflicting a very high heat (more than 2,000 °C) on the surface, which undergoes a thermal shock that causes dislodge and granulates a number of crystals, creating a typical kind of roughness [27];
- pure water-jet surface (PWJ); the water-jet blast the stone with a very high-pressure water jet; the result is a selective erosion of the stone's constituents, forming a rough surface whose irregularities are very similar to the rock's natural appearance. The finishing process that has been carried out in the DICAAr laboratory by using a Waterline 1620 numerical control waterjet cutting robot that was set with the following operational parameters (that have been selected on the basis of aesthetic, technical and economical assessments already described in previous research [28]): nozzle diameter = 0.30 mm, focusing tube diameter = 1.00 mm, water pressure = 300 MPa, jet inclination = 30° with respect to the horizontal plane, pass spacing (distance between water-jet parallel passes) = 5 mm, stand-off distance = 100 mm, and water-jet travel speed = 20 m/min;
- abrasive water-jet surface (AWJ): it is obtained by adding a small quantity of mass flow-rate garnet abrasive (0.2 kg/min) and changing the following operational parameters with respect to PWJ: focusing tube diameter = 1.40 mm, pass spacing = 10 mm and stand-off distance = 60 mm. The result is a more homogeneous erosion of the surface with respect the PWJ treatment [28].

The appearance of each specimen is shown in Fig. 4.

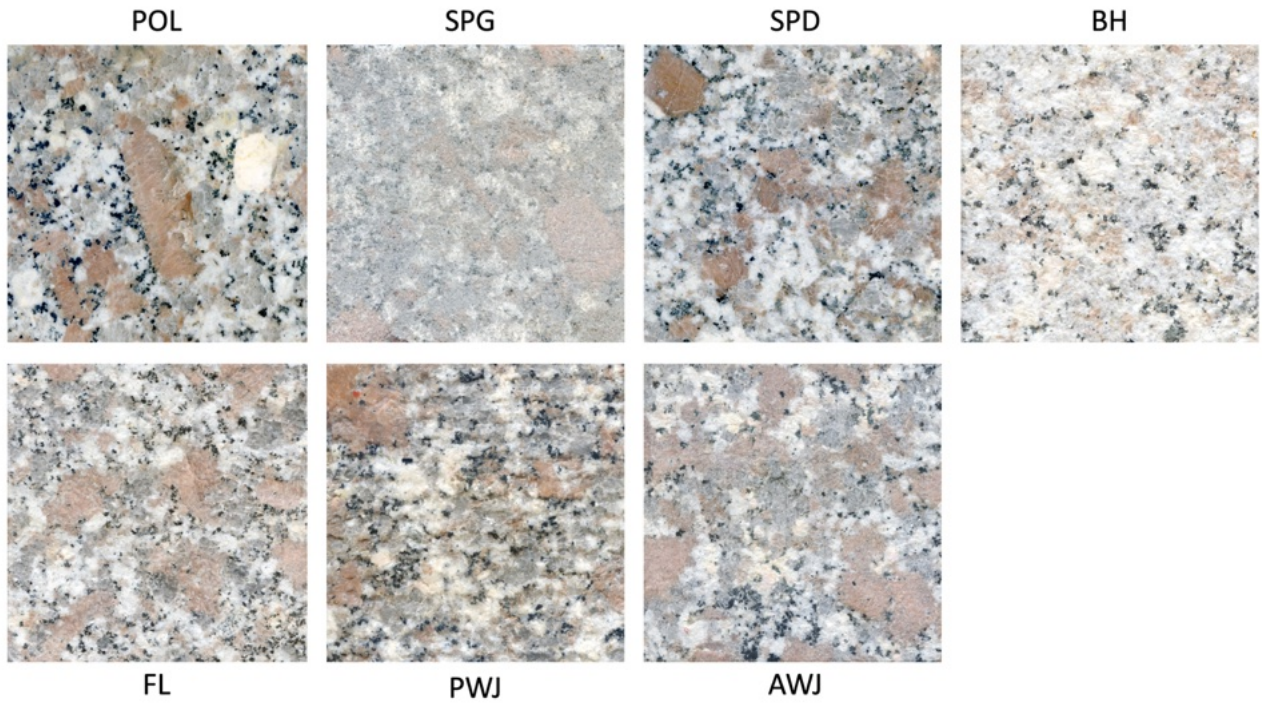


Fig. 4. Rosa Limbara granite specimens worked by different surface treatment technologies.

3. Methods

3.1 Colour measurements

The colour was measured with a bench-top spectrophotometer CM-3610A provided by Konica-Minolta 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 [11]). The diameter of the target mask has been set at 4 mm diameter when measuring the single crystal and 25.4 mm diameter when measuring the whole stone. Figure 5 shows the two target masks with the scale on Ghiandone granite sample.

Fig. 5. The 25.4 mm diameter and the 4 mm diameter target masks used in this study.

Because the surface of granite samples is not totally reflective or matte, inclusion or exclusion of the specular component may be important for colour measurements [4].

The method of colour measurement, which excludes the specular reflectance, is called SCE (Specular Component Excluded). Once 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 diffuse reflectance is measured. This produces a colour evaluation which correlates to the way the observer sees the colour of an object. When using the SCI mode, the specular reflectance is included with the diffuse reflectance during the measurement process. This type of colour evaluation measures the entire appearance regardless of the surface conditions.

For the above reason, in this study, the measurements were made in both SCI and SCE modes.

Following previous studies [11, 4] a similar protocol for measuring the colour of granite has been adopted: 9 readings were taken of random zones of the surface for each of the three specimens (100 cm^2) and for each type of surface finishing during the measuring of the whole stone colour (25.4 mm target mask diameter); 6 readings were taken for each single mineral type (K-feldspar, plagioclase, quartz and biotite) of each of three specimens of each type of surface finishing with the aim of assessing the colour of the single mineral (4 mm target mask diameter). The instrument automatically repeats three times the measurement for each readings, before providing an average result.

As well explained by Sanmartín [4], the CIE L*a*b* coordinates are preferred for achromatic colours, whereas the CIE L*C*h* coordinates are recommended for stronger colours. Because this study's objective was to try to assess the granite colours and since the surface technologies which were used typically change the chromatic or achromatic range of the stone, both sets of coordinates were used.

Moreover, following the recommendations for textured samples reported by Huertas et al. [30], the classical CIEL*a*b* [3] colour equation (1):

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

was applied rather than the newer improved formulas.

3.2 Gloss measurements

The Micro-TRI-Gloss meter used has been provided by BYK Gardner. The gloss measurement range is expressed in GU (gloss units) and ranges from 0 to 100. When determining surface gloss numerically, a light is directed towards the surface of the sample – at defined angle – and the reflected light is measured photoelectrically (reflectometer). Measurements were done at 20°, 60° and 85° for each stone sample. The measurement unit conforms to the standards ISO 2813 [31], ISO 7668 [32] and ASTM D-523 [33].

Literature suggests that the measurement of gloss on polished stone surfaces may incur in measurement inaccuracies [34]. In fact, some mineral types show partially transparent surfaces which in part diffuse the incident light internally. This internal diffusion effect creates a component of diffused light that alters gloss measurement, which should only be regarded as one component of specular reflected light. This problem is easily solved by re-measuring each sample several times. In this study, we carried out eight measurements on each sample following eight different directions as shown in Fig. 6.

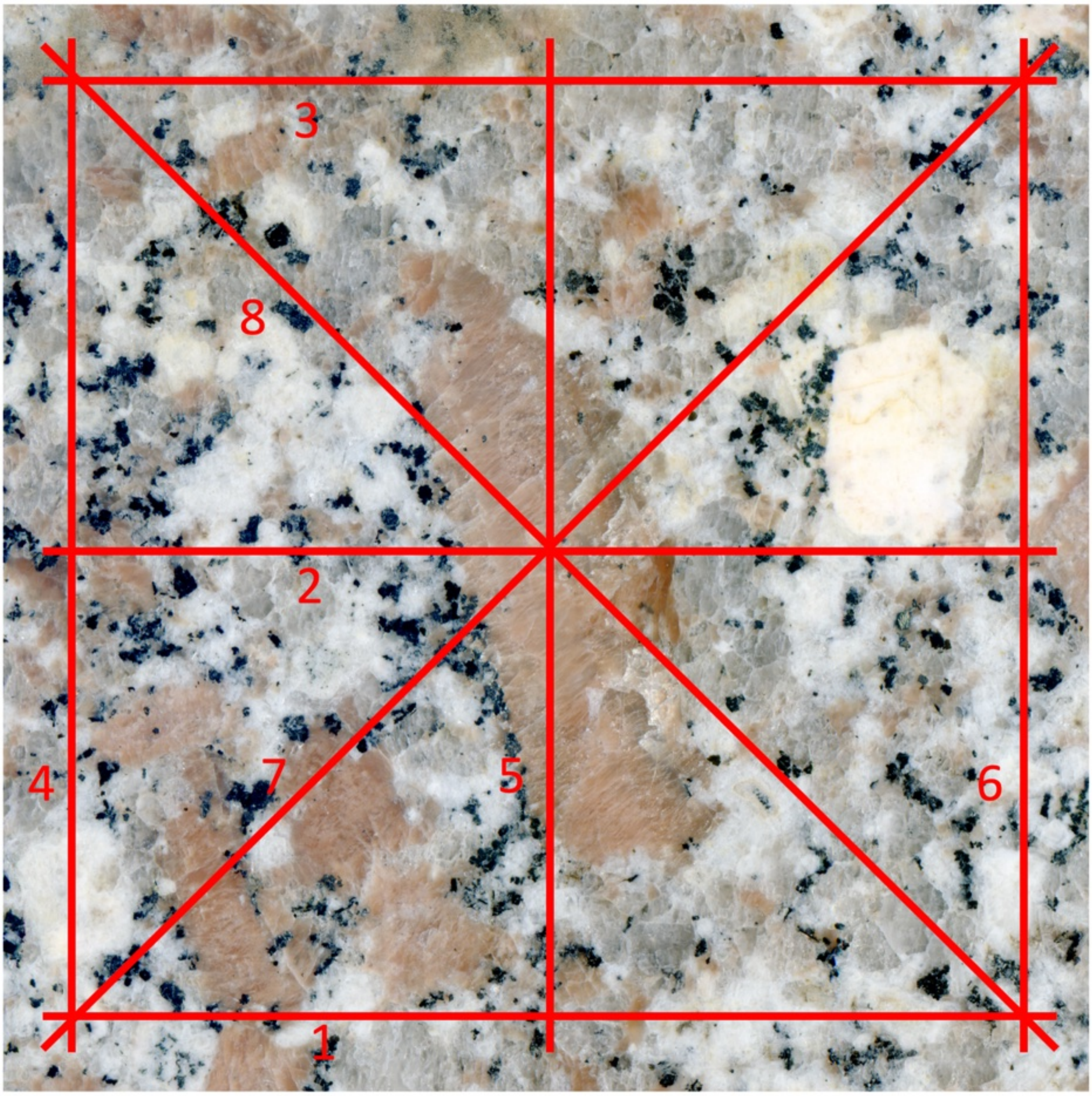


Fig. 6. Eight different directions for gloss measurement used in this study.

3.3 Roughness measurement

The roughness profile of the finished veneers was carefully analysed using a Feinprüf Perthen S3P mechanical comparator. The measurements were carried out along the whole length of each specimen with each reciprocal distance of 1 cm.

For each specimen the following parameters were determined in accordance with DIN 4768 [35] and ISO 4287 [36]: R_a (mean roughness), R_z = (average distance between the highest peak and lowest valley in each sampling length), R_{max} (maximum roughness depth) and W_t (waviness depth). Surface roughness profiles were examined along the x and y directions by 1 cm spacing.

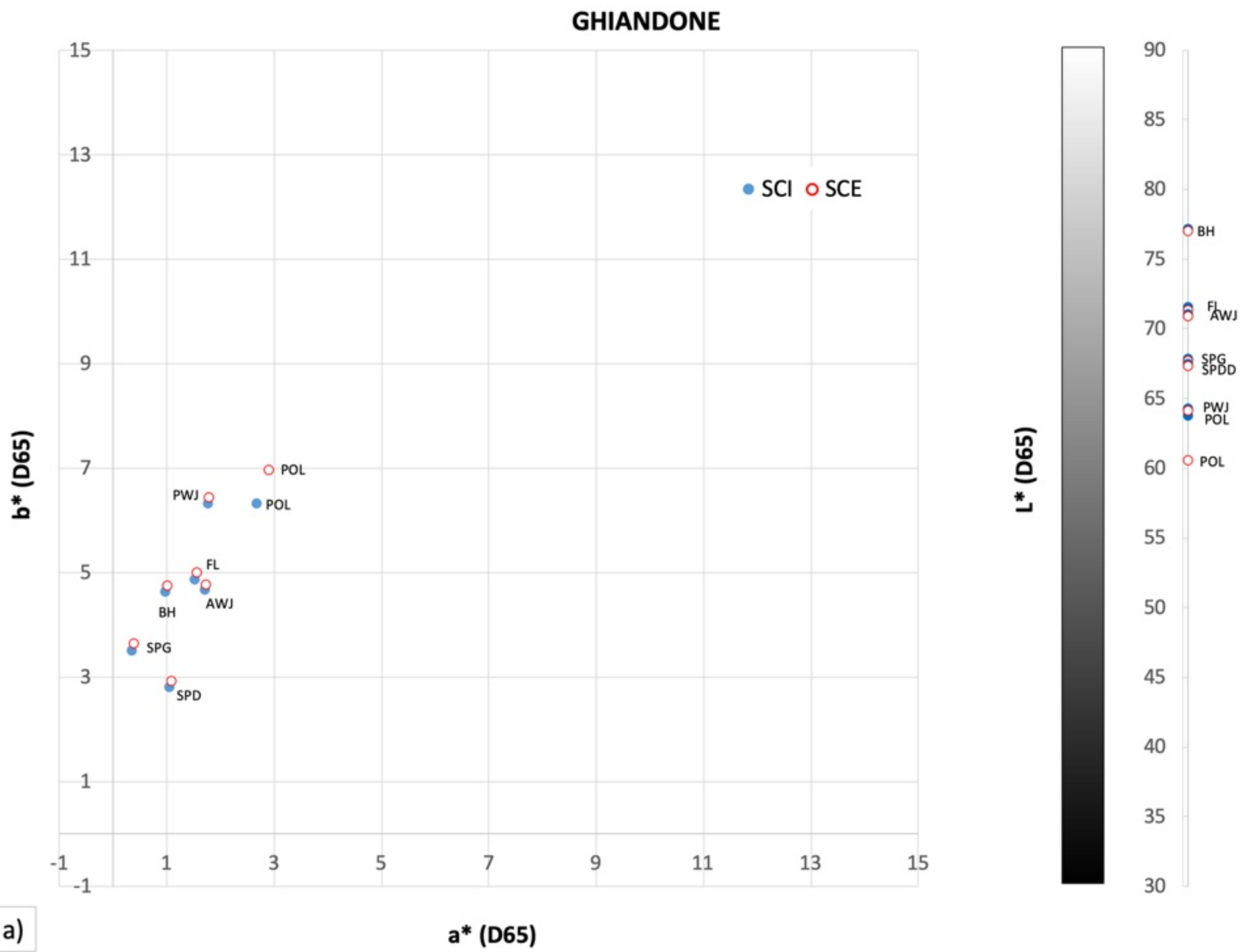
For this study, a mechanical profile comparator has been used to measure even the roughest surfaces (PWJ, BH, FL) which otherwise would not have been detectable by a non-contact laser profilometer (used especially in car body paints) which would be unsuitable for this purpose. The laser profilometer is able to detect roughness of an order of one micron (and less) but cannot measure roughness higher than 100 microns. On the contrary, a good mechanical profile comparator is able to measure roughness in the range of 5 micron to 1 mm.

4 Results and discussion

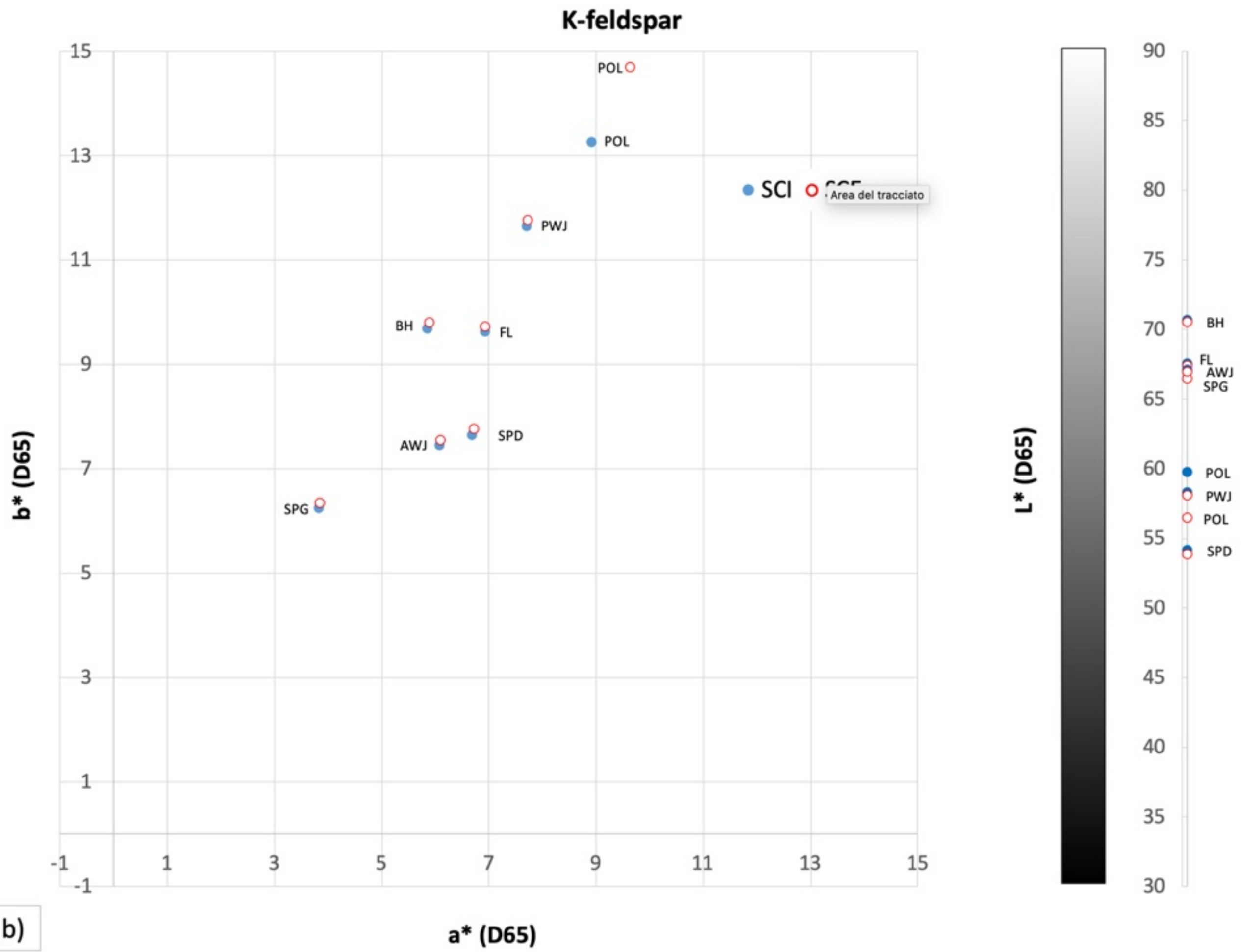
It was decided to ignore any data about biotite colour measurement because of the small size of this black mineral, which makes the colour measuring of each crystal difficult.

4.1 L*a*b* colour space

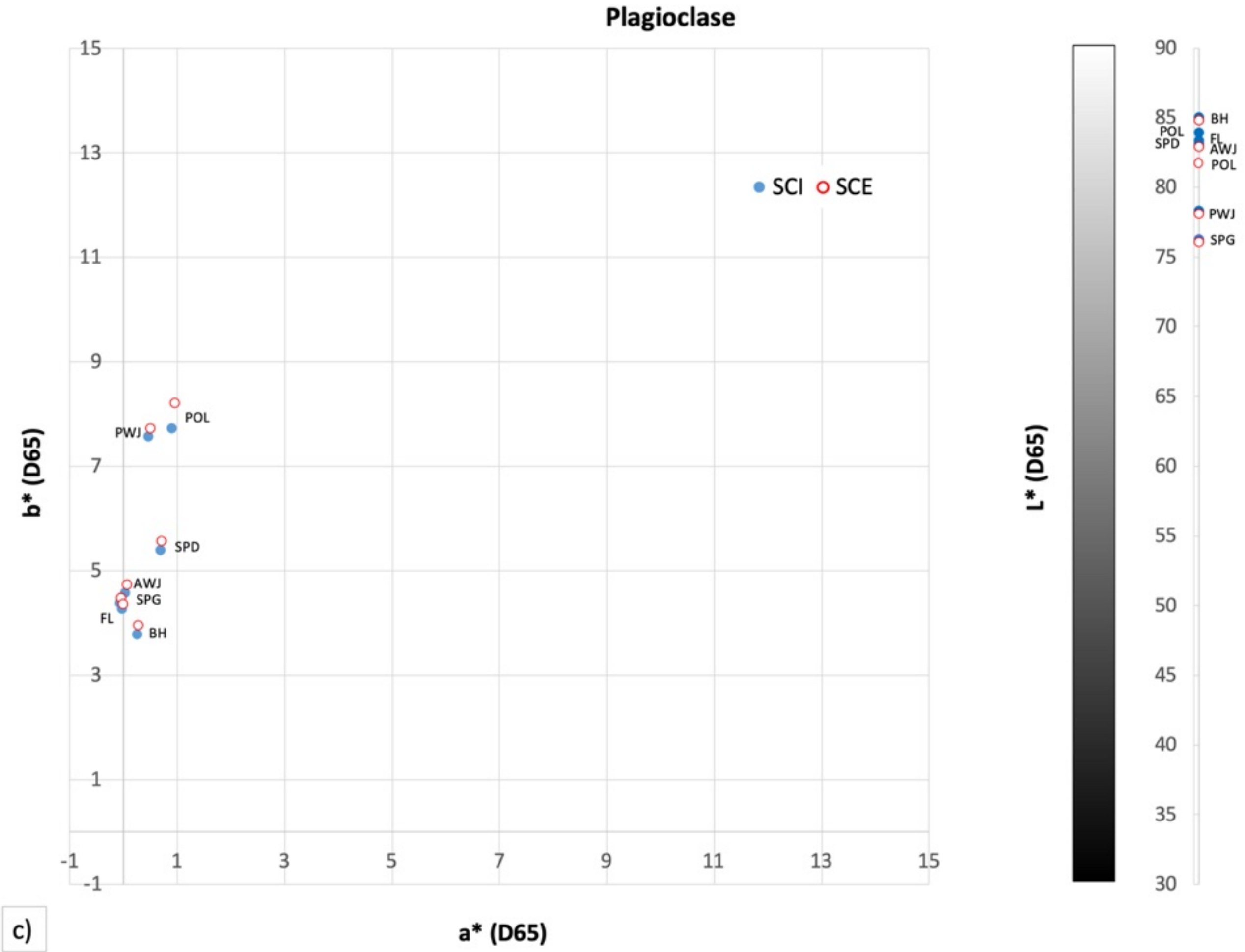
Figs. 7, from a to d, show the values of the a*, b* and L* chromatic coordinates corresponding to the different surface finishing technologies.

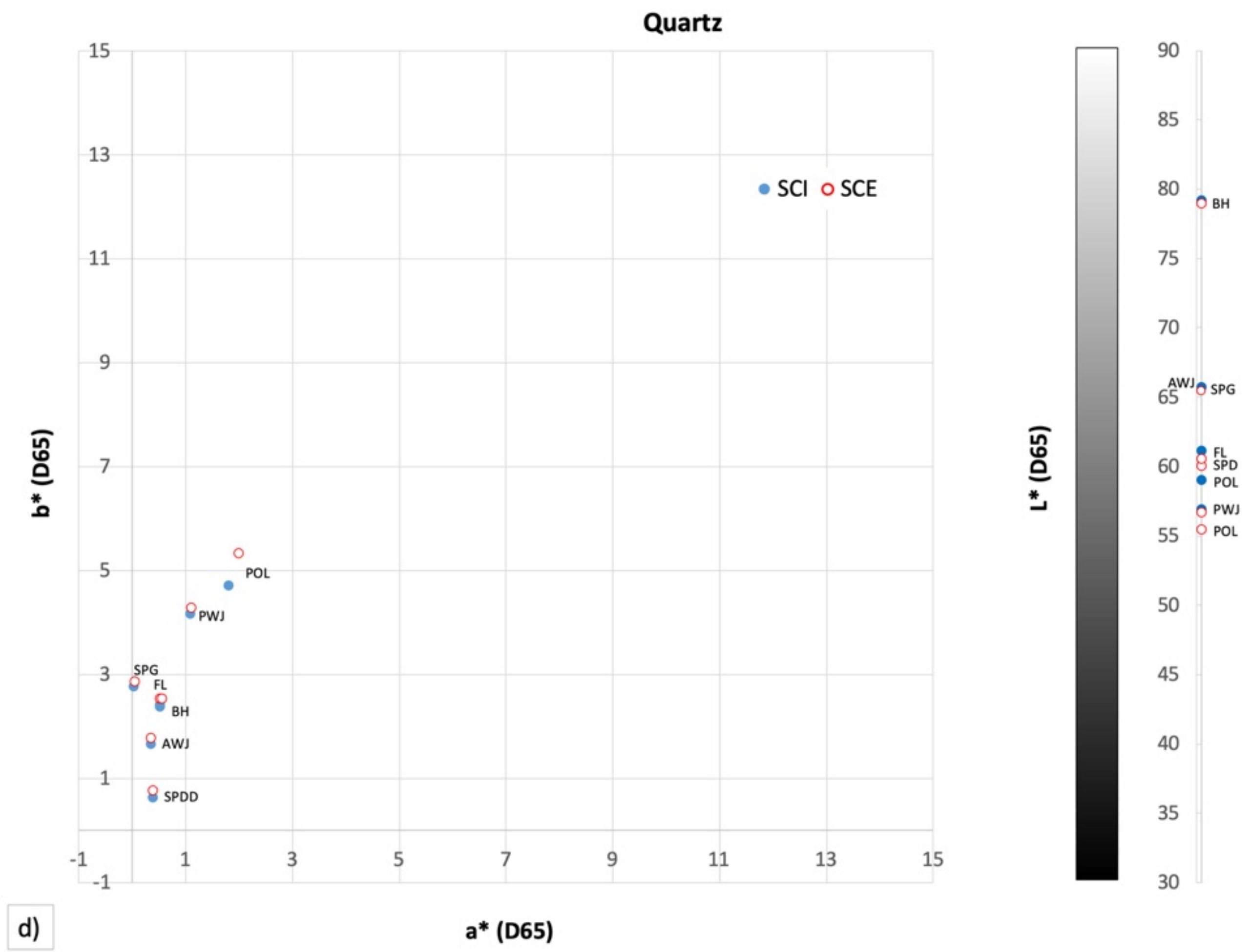

GHIANDONE
SCI
SCE
b* (D65)
a* (D65)
L* (D65)
POL
PWJ
POL
FL
BH
AWJ
SPG
SPD
BH
FL
AWJ
SPG
SPDD
PWJ
POL
POL

a)


K-feldspar
b* (D65)
a* (D65)
L* (D65)
POL
PWJ
BH
FL
SPD
AWJ
SPG
SCI
Area del tracciato
15
13
11
9
7
5
3
1
-1
90
85
80
75
70
65
60
55
50
45
40
35
30

b)


Plagioclase
SCI
SCE
b* (D65)
a* (D65)
L* (D65)
POL
PWJ
SPD
AWJ
SPG
FL
BH
c)



Figs. 7. Values of the a*, b* and L* chromatic coordinates to the different surface processing; a) Ghiandone, b) K-feldspar, c) plagioclase, d) quartz.

When looking at the a*-b* graphs of the whole stone (Fig. 7a), data show SCE values which are slightly higher than the SCI ones (the difference is slightly greater in the b* than a*). As expected in the case of the polished surface, the difference between SCE and SCI is even greater; in fact, for objects with shiny surfaces, the reflected specular light is relatively strong and the diffused light is weaker. On rough surfaces with a low gloss, the specular component is weak and the diffused light is stronger. The same considerations could be drawn for K-feldspars, plagioclase and quartz as shown in the Fig. 7 from b to d.

Regarding colours, the PWJ sample is the closest to the POL sample. This confirms what this team of researchers had thought before [37-39]: while breaking rock crystals, pure water-jet preserves the natural colour of the stone. In fact, the crystals breakages occur more easily, especially when cleavage planes are parallel to the direction of the water-jet; in this case, the grains are not deformed neither milled and their natural colours are preserved.

With regard to the whole stone (Fig. 7a), the FL and AWJ samples have similar values, particularly in AWJ where the a* has the same value as PWJ. This consideration is confirmed when considering plagioclase grains (Fig. 7c); on the contrary, there is a difference in b* values of K-feldspars when considering the FL and AWJ samples. This can be easily explained with the different behaviour that K-feldspar seems to have when exposed to the two different technologies: the flaming darkens the crystal while the water-jet preserves the colour, by breaking it in its plane cleavage.

The BH sample, despite having a b* value similar to FL and AWJ, has an a* lower (Fig. 7a). When considering quartz (Fig. 7d), BH and FL samples have similar a* and b* values.

The SPG sample shows even lower values; this is due to the sawing technology which combines the traditional steel-shot gangsaw with a mixture of water, steel-shot and lime in order to saw the block into slabs and to avoid the oxidation of the blades and the steel-shot. This kind of sawing process turns the stone grey.

The SPD sample shows the lowest a* and b* values in the whole stone and quartz (Figs. 7a and 7d) because this kind of cutting technology doesn't produce major differences from mineral to mineral: the colours are generally opaque.

As shown in Fig. 7b, the different surface technologies affect the K-feldspar more than anything else. The POL and PWJ samples have high values of a* and b*, while SPG has the lowest values in both.

The a* values don't show any significant difference in plagioclase (Fig. 7c). More significative is the variation of b*; moreover, it is possible to notice the formation of two separate groups of values, with POL and PWJ on the upper side and the others with a minor b*on the lower side.

As shown in Fig. 7d, quartz is enhanced after being polished, more than after any other process that may negatively impact the a* values.

Regarding L* values, they seem to be the opposite when compared to a* and b*. In fact, the BH sample shows the highest value; this is due to the fact that the impact created by this technology destroys the crystals by grinding them and by shifting their colour towards white. The FL and AWJ samples have similar L* values (less SPG, similar to SPD).

The PWJ and POL samples have a similar lower L* value; this seems to be the result of the use of differentiated technologies, which tend to lighten the stone surface.

Generally, SCI and SCE values in L* differ very little (SCI is slightly higher than SCE) with the exception of the POL sample, where SCI value is about 3-4 units higher; the reason for this is explained at the beginning of this chapter.

The considerations carried out on the whole Ghiandone can be applied to K-feldspar, in which, a L* value is lower than the whole stone by about 5 units (Figs 7a and b). Unlike the previous two, in plagioclase, L* values are higher and similar (Fig. 7c).

With regard to quartz, the values of L* are more dispersed, proving that this mineral is the hardest to work on to be finished because of its brittleness. The quartz L* value in the BH sample measures almost 80 units (Fig. 7d).

As explained at the beginning of this chapter, it's not possible to discuss biotite. However, it seems that both of the a* and b* values of the AWJ and SPDD samples tend to zero; in general, a* is close to zero in all samples with the exception of the FL sample (which also has the highest b*). The SPG samples show the highest L* values while, the POL sample shows the lowest L* value; this is because the colour of biotite is black. As for plagioclase, the POL sample, shows a SCI L* value which is higher than SCE by approximately 6 units.

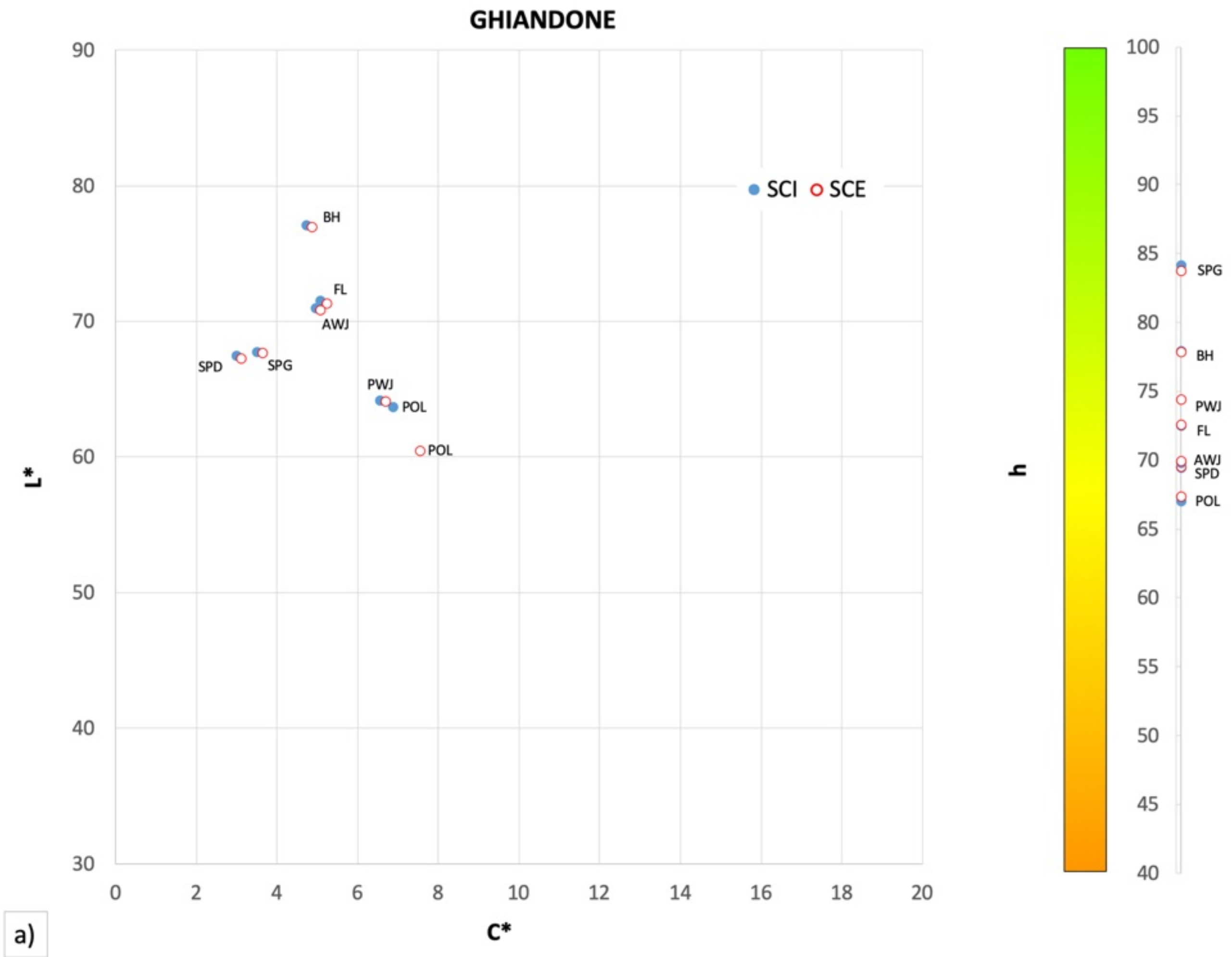
4.2 L*C*h colour space

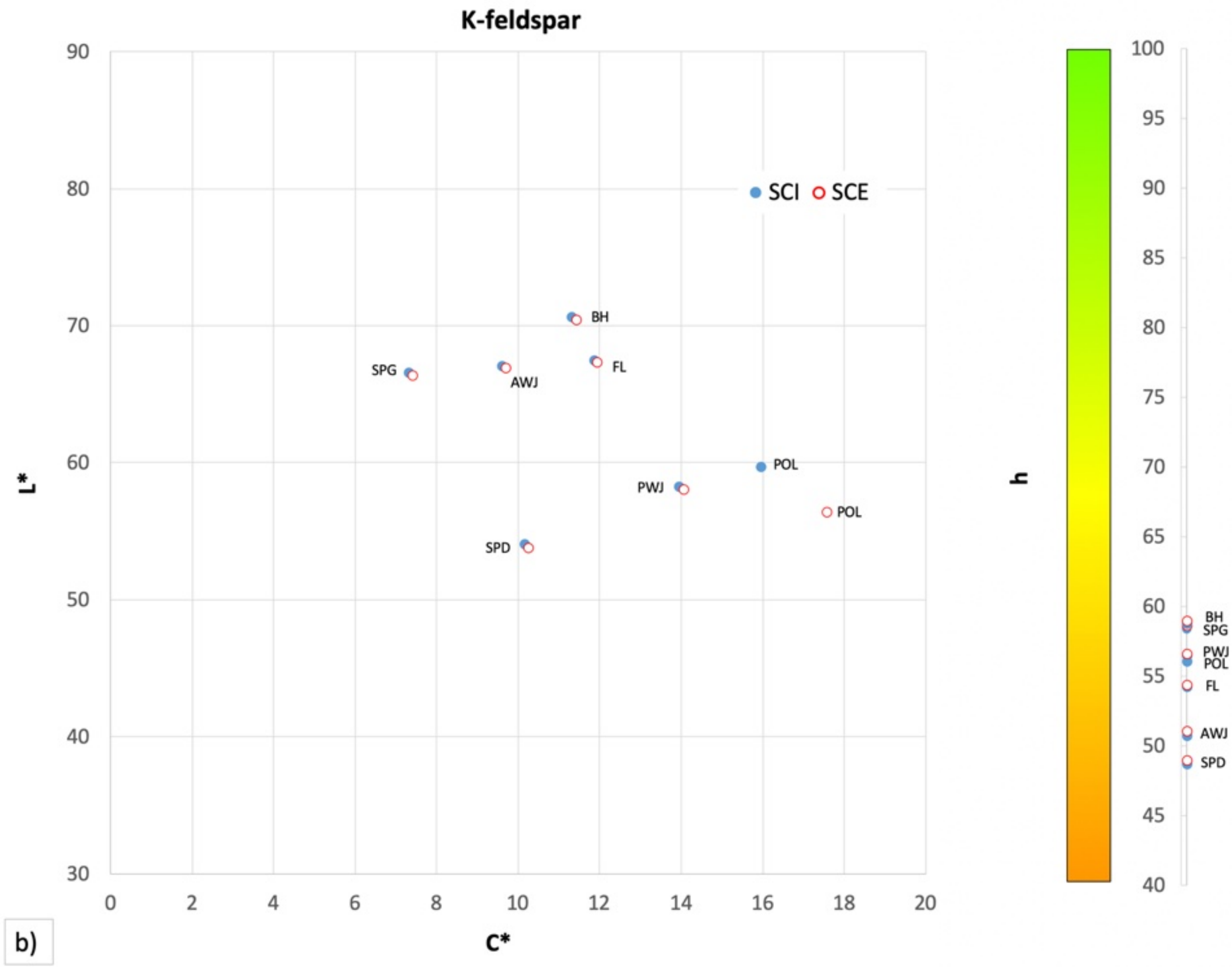
Regarding the entire Ghiandone part, Fig. 8a shows the detachment between the POL and PWJ samples, characterized by a higher chroma, with the other finished surfaces that have instead a higher lightness.

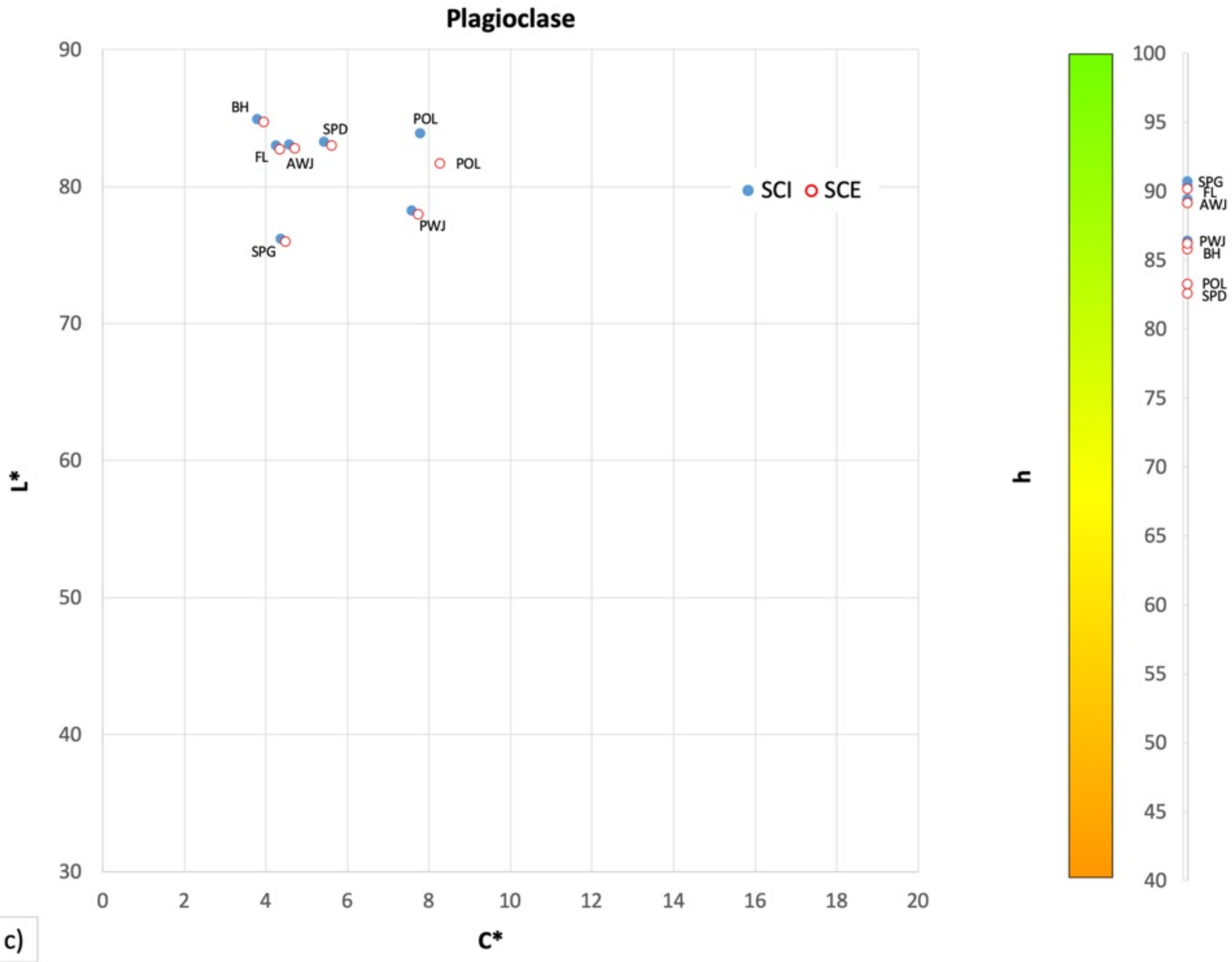
Same considerations can be drawn for K-feldspars (Fig. 8b), with the exception of the SPD sample that is characterized by a lower lightness.

Plagioclase also shows higher chroma in the POL and PWJ samples (Fig. 8c) while L* values are similar to the other samples.

Quartz doesn't show any significant variation in chrome (Fig. 8d); however, in the PWJ and POL samples quartz has lower values of L* than the other samples.

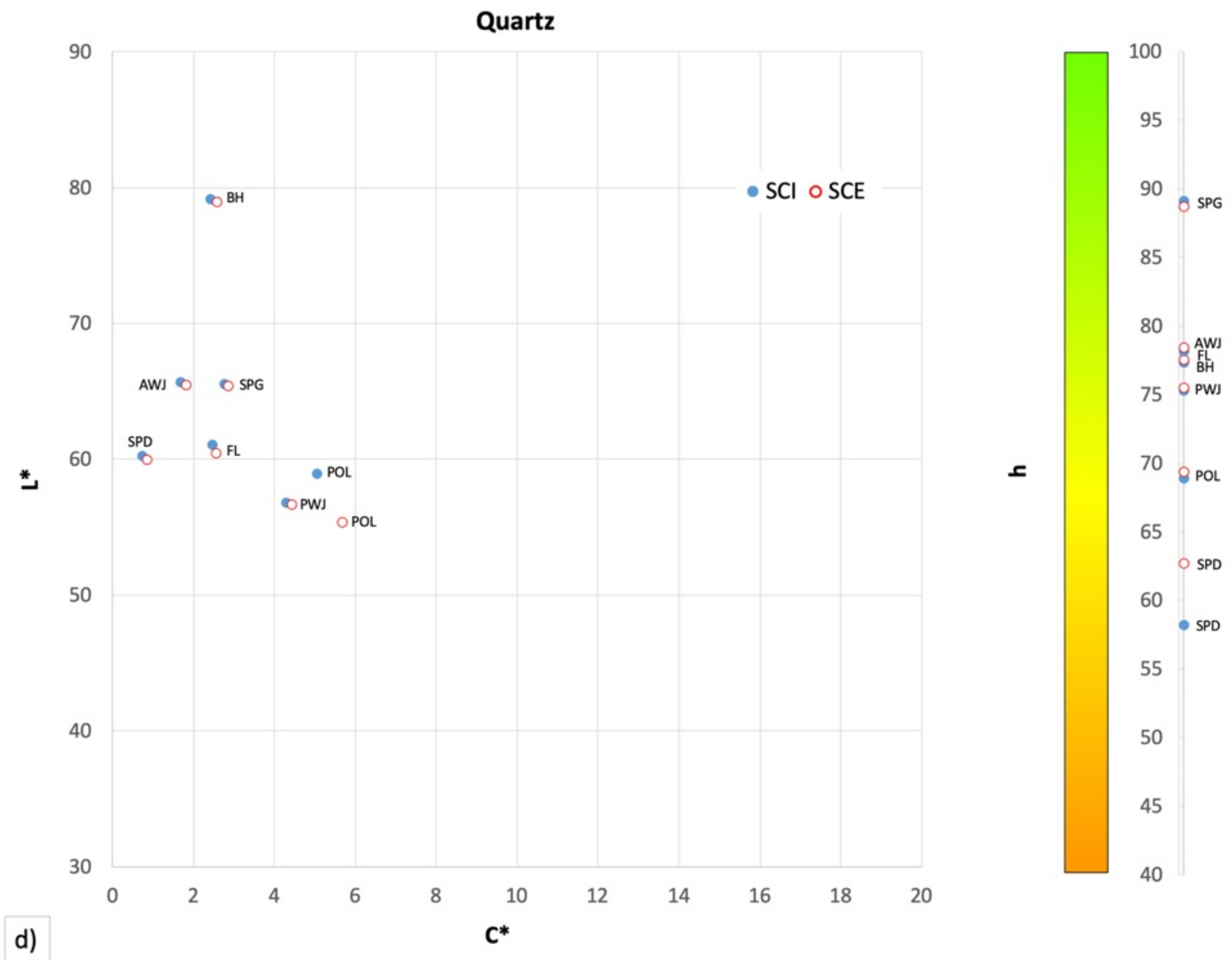

GHIANDONE
SCI
SCE
L*
C*
h
BH
FL
AWJ
SPD
SPG
PWJ
POL
a)


K-feldspar
SCI
SCE
BH
FL
SPG
AWJ
POL
PWJ
SPD
L*
C*
h
0
2
4
6
8
10
12
14
16
18
20
30
40
50
60
70
80
90
100
95
85
75
65
55
45
b)



Plagioclase
90
80
70
60
50
40
30
L*
0
2
4
6
8
10
12
14
16
18
20
C*
BH
SPD
POL
FL
AWJ
POL
PWJ
SPG
SCI
SCE
100
95
90
85
80
75
70
65
60
55
50
45
40
h
SPG
FL
AWJ
PWJ
BH
POL
SPD

c)



Figs. 8. Values of the C*, L* and h chromatic coordinates to the different surface processing; a) Ghiandone, b) K-feldspar, c) plagioclase, d) quartz.

Unlike in [14], hue is not the most important CIE L*C*h colour coordinate; this is due to the fact that in the present study, differently from the slates, we have studied a heterogeneous rock which is composed by different mineral types. Lightness is surely the most important (Fig. 8a) and most distinctive feature.

The same consideration can be drawn with K-feldspars, where hue varies even less (Fig. 8b). Fig. 8c shows a higher concentration of plagioclase measurements with high values of lightness and hue. Regarding quartz, h doesn't show any significant variation; as explained previously, quartz shows a higher L* value in the BH sample (Fig. 7d).

Moreover, Fig. 8a shows that hue is not a distinctive colour coordinate such as chroma. In this graph, where L* is not considered, the chroma is higher in the POL and PWJ samples, while the BH sample results in low values, like FL, AWJ and SPG. SPD has low values in both parameters.

The SPG sample shows K-feldspars with lower chroma (Fig. 8b). Regarding plagioclase (Fig. 8c), the C* values highlight even more the difference between the two groups of finished surfaces (POL-PWJ, and the others); in the BH sample, the plagioclase has the lowest C* value.

The values referring to quartz are also quite more frequent on the low-value side of the graph (Fig. 8d); C* and h*are both lower in the SPD sample.

Biotite measurements do not suggest any consideration.

4.3 Total colour difference (ΔE*)

Fig. 9 summarizes the total colour differences (ΔE*) in Ghiandone, K-feldspar, plagioclase and quartz for each surface finishings.

Fig. 9. Total colour differences (ΔE*) in Ghiandone (a), K-feldspar (b), plagioclase (c) and quartz (d) for each surface finishings.

As you can see from Fig. 9, bush-hammering mostly changes the colours of the rock and its components, with the exception of the plagioclase, where, the ΔE* values are generally lower. In fact, because of its natural whitish colour, plagioclase has low ΔE* once its surface finishing has been completed (especially once the stone surface has turned up white).

Pure waterjet finishing preserves the original colours of the stone and its minerals more than any other process (with the except of polishing).

The overall colour difference is more evident when SCE is taken into account; this is due to the fact that the surface finish makes the stone surface rough resulting in increased reflectance, as already explained in subchapter 4.1.

Some exceptions have been noticed, especially in the case of plagioclase, where ΔE* of both the SPG and PWJ samples is higher in SCI than SCE.

4.4 Correlations between CIE colour coordinates and roughness measurement.

Ghiandone is the only range used in this part, because it was not possible to carry out any roughness measurement on each single crystal.

When considering absolute values of CIE colour coordinates (a*, b*, L*, C* and h) and roughness measurements (R_a, R_z, R_{max} and W_t), there is not any correlation. Table 2 summarizes the roughness measurements.

Table 2. Roughness values, measured in μm, for the different finished surfaces.

Type of surface (ID)	R_a	R_z	R_{max}	W_t
POL	0.4	5.0	0.6	0.5
SPG	22.1	108.3	160.2	100.3
SPD	4.5	30.0	37.0	12.8
FL	21.4	107.8	160.0	343.2
BH	32.4	162.8	225.6	274.4
PWJ	41.4	205.5	293.6	513.3
AWJ	24.8	125.8	169.9	182.7

However, when considering the total and partial colour differences (ΔE*, ΔL*, ΔC* and Δh*) referred to the POL sample with the average roughness difference (ΔR_a also referred to the POL sample), some interesting considerations can be drawn. All values are summarized in Table 3.

Table 3. Partial colour differences (ΔL*, Δa*, Δb*, ΔC*, Δh) and total colour difference (ΔE*) between the polished surface and each of the other surface finishes for Ghiandone granite, in SCI and SCE modes. The mean roughness difference (ΔR_a) is also reported.

Type of surface (ID)	SCI						SCE						
	ΔL*	**Δa***	**Δb***	**ΔC***	**Δh**	**ΔE***	**ΔL***	**Δa***	**Δb***	**ΔC***	**Δh**	**ΔE***	**ΔR_a**
POL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPG	4.11	-2.32	-2.83	-3.35	1.46	5.50	7.18	-2.51	-3.33	-3.90	1.49	8.30	21.65
SPD	3.78	-1.63	-3.53	-3.88	0.17	5.42	6.80	-1.82	-4.04	-4.43	0.23	8.12	4.10
FL	7.84	-1.15	-1.47	-1.78	0.55	8.05	10.81	-1.35	-1.97	-2.32	0.59	11.07	20.98
BH	13.41	-1.69	-1.70	-2.14	1.07	13.62	16.45	-1.89	-2.21	-2.69	1.12	16.71	32.00
PWJ	0.52	-0.91	0.00	-0.31	0.86	1.05	3.60	-1.11	-0.52	-0.86	0.88	3.80	41.01
AWJ	7.29	-0.97	-1.67	-1.91	0.25	7.54	10.34	-1.17	-2.19	-2.47	0.30	10.63	24.40

It is important to explain why the POL sample has been taken as the reference state for comparison: the polishing results in surfaces with the maximum enhancement of the stone's decorative and aesthetic qualities [40]; since this process changes the colour back to the natural (original) colour of the stone, POL has been chosen as the reference state for comparison in our research.

When taking into account all ΔE* values (apart from SCI and SCE values) there are low correlations with ΔR_a (0.16 for SCE and 0,10 for SCI); a similar conclusion was also found by Sanmartín et al [4]. However, if PWJ data are not considered (because these samples show very low ΔE* values and higher ΔR_a), correlation rises to 0.77 and 0.76 respectively, as shown in Fig. 10. This fact can be easily explained by the breakage of the crystals on the cleavage planes when using the pure water-jet. However, this process does not produce any small craters-shaped nor it creates any impact that would fade away or dull the stone colours, as can be seen in the macro-photos of Figs. 11a and 11b. Therefore, the PWJ treatment keeps the colours almost unaffected regardless of the roughness.

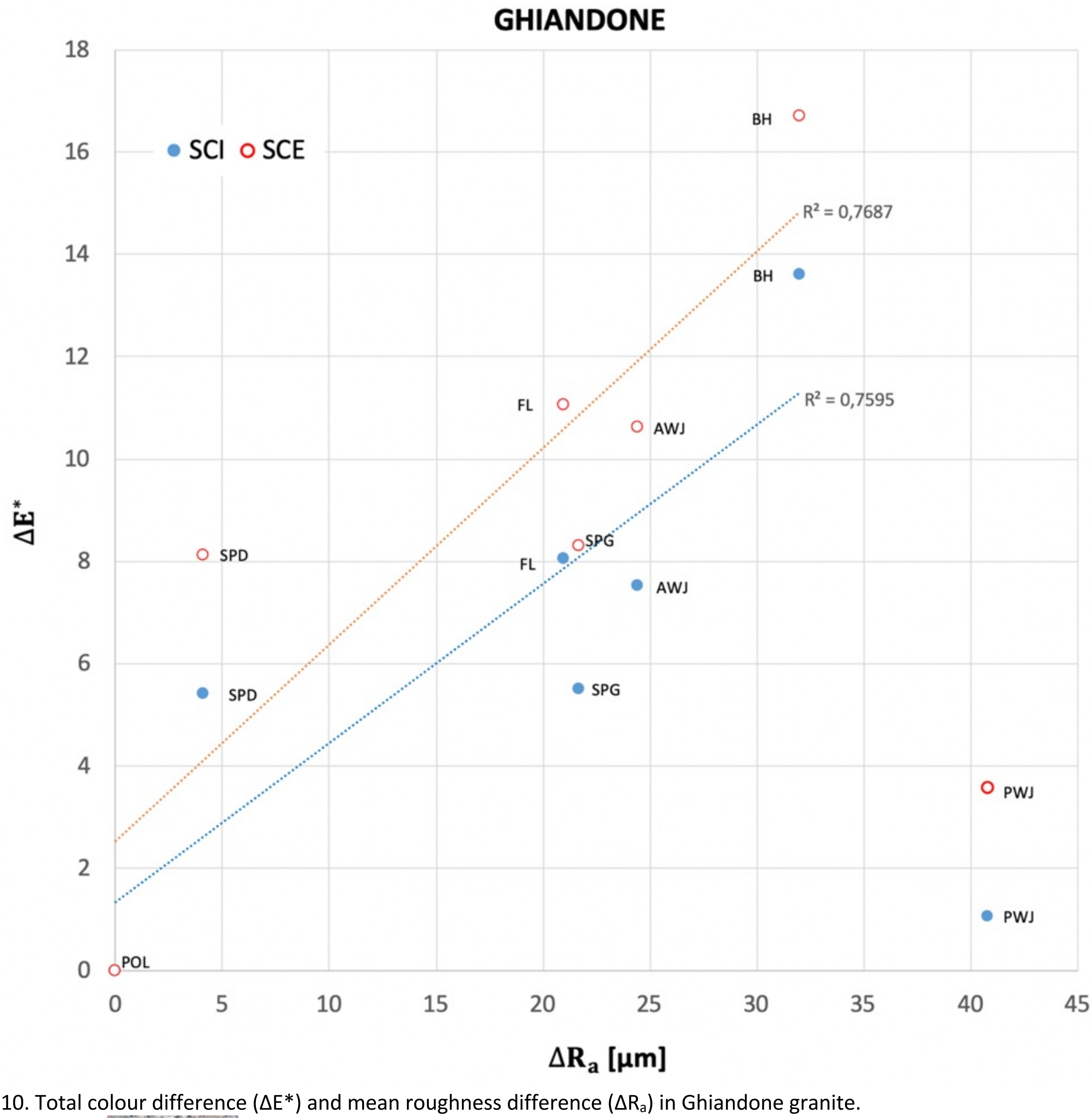
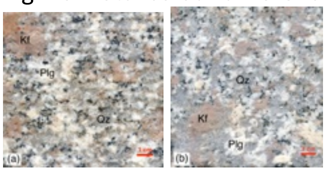


Fig. 10. Total colour difference (ΔE*) and mean roughness difference (ΔR_a) in Ghiandone granite.



Figs. 11. Aesthetic finish difference between two samples: the finish obtained via pure water-jet (a) and the one via abrasive water-jet (b). Legend: Qz = Quartz, Kf = K-feldspar, Plg = plagioclase, Bt = Biotite.

Same considerations can be drawn from the correlation between ΔL* and ΔR_a, where R^2 rises from 0,19 to 0,79 if PWJ values are excluded (Fig. 12).

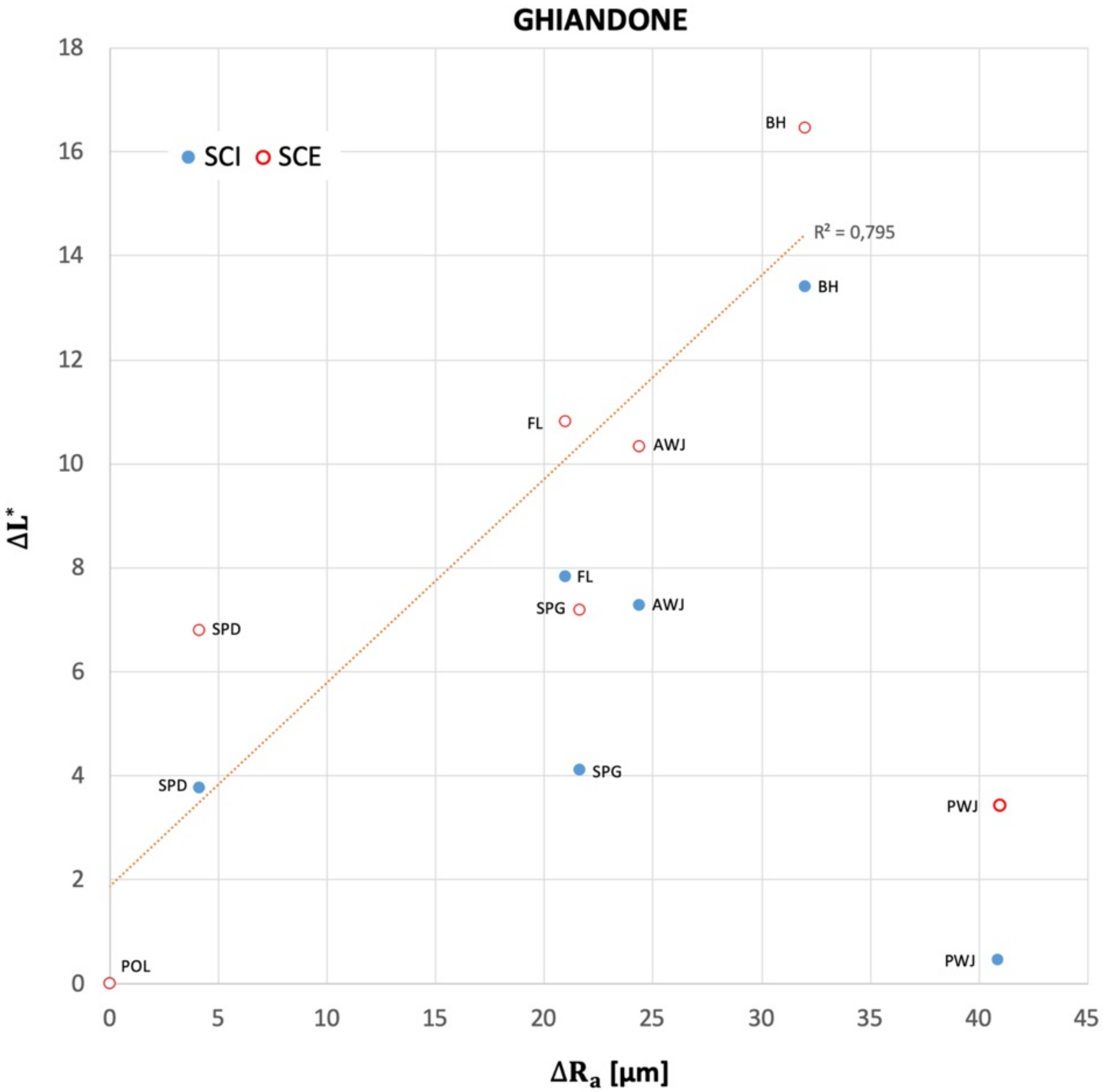


Fig. 12. Lightness difference (ΔL*) and mean roughness difference (ΔR_a) in Ghiandone granite.

Lower correlations have been found when considering ΔC*, Δh and ΔR_a.

4.5 Correlations between gloss and roughness measurement.

Table 4 presents the three gloss measurements for each surface finishes of Ghiandone granite.

Table 4. Gloss values, expressed in Gloss Unit [GU], for the different finished surfaces.

Type of surface (ID)	20°	60°	85°
POL	67.26	77.86	88.36
SPG	0.53	1.30	0.39
SPD	0.66	2.90	18.43
FL	0.74	2.84	0.48
BH	0.75	1.45	0.14

PWJ	0.45	1.20	0.56
AWJ	0.56	1.36	0.23

It seems there is an inverse correlation between the ΔR_a and the three gloss values. Correlations are of exponential type, and they are higher for the gloss 85° (Fig. 13). However, literature data about the roughness-gloss correlation are controversial [4] and further investigation should be carried out.

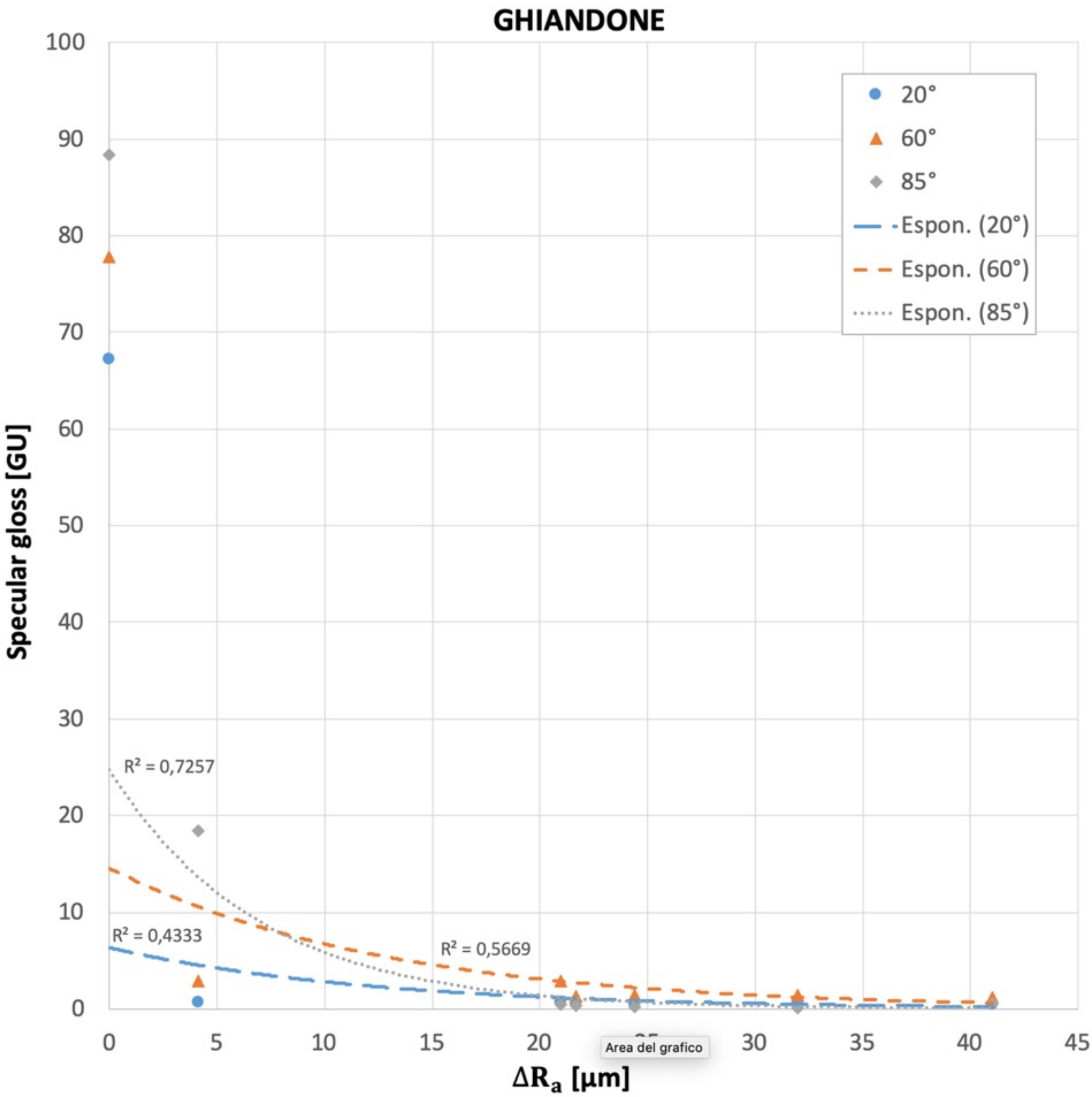


Fig. 13. Correlations between specular gloss (measured at 20°, 60° and 85°) and mean roughness difference.

5 Conclusions

The colour of the rock has paramount importance in design, depending on the technical properties of the same rock. No less important is the surface finishing, which is the result of further processing carried out on the slabs to obtain different looks depending on their colour, brightness and smoothness.

The study of the effects of different types of surface finishing on the aesthetic properties of Ghiandone granite and its crystals revealed that:

- Different surface finishings can dramatically change the stone colour, while producing a similar roughness on the stone. Vice versa, samples with completely different roughness values can show similar colours (POL and PWJ). So, there is no general rule regarding the impact of roughness on the Ghiandone granite colour;
- In CIE L*a*b* colour space, L* is the colour coordinate that shows higher variation (compared with a* and b*), when different surface finishings are applied. The BH sample shows the higher increase of L*;
- In the CIE L*C*h colour space, two different groups of samples are highlighted: the POL-PWJ samples group, which is characterized by higher chroma values, and the all remaining samples, which are characterized by higher lightness. Hue doesn't show any significant variation;
- An inverse correlation between specular gloss values and ΔR_a has been found. However, further research is needed to support this argument.

In the end, colour measurements were instrumental in defining the total colour difference (ΔE*) in the CIE L*a*b* colour spaces in order to verify the differences which might exist between the rocks and minerals of polished samples and of those which were subjected to different surface finishings, and to measure their values. Bush-hammering is the treatment that mostly changes the overall colour of the rock and its minerals; on the contrary, pure waterjet finishing is the treatment which mostly preserves the colours the Ghiandone granite and its minerals.

Finally, it should be kept on mind that different ornamental stones (marble, granite, travertine, and so on) may produce different results with regard to their colour coordinates, roughness and gloss values. For this reason, we believe that the methods herein described should be used to study further different stone types.

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