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Effect of surface finish on roughness, color and gloss of ornamental granites

Sanmartín, P.[1]; Silva, B.[2]; Prieto, B.[3]

[1]Ph.D. Student, Dpt. Edafología y Química Agrícola, Fac Farmacia, Universidad de Santiago de Compostela, 15782-Santiago de Compostela, Spain. E-mail: patricia.sanmartin@usc.es

[2]Full Professor, Dpt. Edafología y Química Agrícola, Fac Farmacia, Universidad de Santiago de Compostela, 15782-Santiago de Compostela, Spain. E-mail: benita.silva@usc.es

[3]Full Professor, Dpt. Edafología y Química Agrícola, Fac Farmacia, Universidad de Santiago de Compostela, 15782-Santiago de Compostela, Spain (corresponding author). E-mail: beatriz.prieto@usc.es

Abstract

The effects of four of the most common types of surface finish on the appearance of five varieties of ornamental granite, all widely used in building construction and selected for their different colors, were analyzed by means of roughness, color and gloss measurements. The results demonstrated that different surface finishes produce differences in color, especially in the lightness parameter (L* CIELAB coordinate), and that the magnitude of these differences depends on the color of the ornamental granite and is greatest in dark colored rocks. However, the variation in the color parameters with the different surface finishes did not depend on roughness, and no general conclusions could be drawn as regards the influence of the roughness on the color of ornamental granite. Gloss values were affected by the color of the ornamental granite, but in a different way for smooth and rough surfaces. Variation in gloss also depended on the mineral composition of the rock. Gloss and roughness were inversely related, but only within the range of low roughness values. In addition, the color gamut of the studied ornamental granites was defined within the CIELAB color space. These results will contribute to providing a standardized, objective method of characterizing the color of granite, which will be useful for different workers in the field of building construction.

Keywords: color assessment; gloss; ornamental granite; roughness; surface finishes.

Introduction

Many of the most impressive monuments and buildings in the world are built from granite as this is one of the oldest, most durable and most respected of building materials. The popularity of granite in the building, construction, monument and tombstone industries is due not only to its resistance to weathering but also to its appearance. Selection of ornamental granites for new constructions is mainly based on their aesthetic properties as these define the architectural harmony of the construction with the surroundings and enhance the visual perception of the building. Several types of surface finish, such as polished, flamed, sawn, etc., have been developed in order to produce different appearances and thus increase the decorative potential of the granite. Surfaces finishes differ in terms of surface roughness and affect slab aesthetics since they induce variations in the perceived texture, color and gloss. Therefore, when appearance is the main selection criterion, aesthetic properties such as texture, color and gloss must be taken into account.

Texture is defined as the visual characteristic and tactile quality of the surface of a material, although the term is also used in geology to refer to the degree of crystallinity, grain size, and fabric (geometrical relationships) of the constituents of a rock. Two terms were therefore used in the present study: surface texture and petrographic texture. Obviously, the petrographic texture affects the surface texture. However, in the case of ornamental rocks, other surface properties such as the surface finish of the rock, which is not related to the petrographic texture because it is induced by humans, must be considered as is very important from an aesthetic point of view. Surface roughness is a measure of the surface texture and the parameter most frequently used to describe roughness is the average roughness (Ra or ΔRa), defined as the integral of the absolute value of the roughness profile over an evaluation length, and measured with a profilometer (ISO 4287-1, 1984).

Although color is the aesthetic property most often used in selecting building material, objective colorimetric characterization of different granitic rocks is not usually carried out in the granite industry, and operators must trust in their skill to differentiate colors. This leads to misunderstandings between architects and builders. This problem is reflected in the colorimetric terms used to classify granite. Terms such as “champagne cream” and “golden yellow” may suggest different colors to different people. One clear example is that of the granites commercialized as *Rosa Porriño* and *Rosabel*, which are classified as pink granites in some catalogues, and as red granites and grey granites respectively in others.

Likewise, despite the great acceptance of contact color-measurement devices for objective measurement of the color of granite (Grossi et al., 2007a, Iñigo et al., 2004, 1997) and other more homogeneous rocks (Durán-Suárez et al., 1995, García-Talegón et al., 1998, Grossi et al., 2007b), a standardized protocol enabling comparison of the results obtained by different authors and instruments has only recently been published (Prieto et al., 2010). In that work taking into account the high heterogeneity in color and texture of this plutonic rock, a protocol for characterization of their color and a methodology for the analysis of instrumental and surface factors that may affect the determination of their color were proposed using statistical tools and colorimetric criteria.

Gloss is an optical phenomenon related to the appearance of a surface and represents the capacity of a surface to reflect directed light (ASTM D523-1995). According to Hunter (1937) there are six different visual criteria related to the perception of gloss: (1) specular gloss, (2) sheen, (3) contrast gloss or luster, (4) absence-of-bloom gloss, (5) distinctness-of-image gloss, and (6) surface-uniformity gloss. In the particular case of ornamental rocks, the specular gloss is often used to monitor surface quality as it is related to the surface roughness (Huang et al., 2002, ASTM E430-1997).

Several studies have analyzed the relationships among these three aesthetic properties (roughness, color and gloss) in different materials (Ignell et al. 2009, Teng-Shih et al., 2008, Briones et al., 2006, Ariño et al. 2005, Eliades et al., 2004, Keyf and Etikan, 2004, Simonot and Elias, 2003, Dalal and Natale-Hoffman, 1999, Thomas, 1999, Barnett, 1973). Thus, it has been demonstrated that: i) there is an inverse relationship between roughness and gloss; ii) lightness (L* CIELAB coordinate) and chroma (C^*_{ab} CIELAB coordinate) of the color vary with roughness and gloss; iii) lightness (L* CIELAB coordinate) affects gloss, and iv) the magnitude of the change in color with superficial texture is governed by the color of the material. However, all these studies were carried out with homogeneous surfaces -from the point of view of color and composition- rather than arbitrary heterogeneous samples such as granite rocks.

In this sense, none of the above-mentioned studies included ornamental rocks. To date only one study examining the influence of the induced surface roughness on the color change of ornamental rocks has been published (Benavente et al., 2003). These authors demonstrated that the color variations caused by acid attack on building stones basically depend on variations in surface roughness and the type of rock.

In the present study, the effect of four of the most common surface finishes on the appearance of five varieties of ornamental granite, all widely used in building construction and selected for their different colors, was analyzed by means of roughness, color and gloss measurements, in order to provide an objective standardized method of aesthetic characterization useful for the different workers in the fields of construction and building materials.

Experimental

Rocks and mechanical surface finishes

Five varieties of ornamental rocks of very different color were selected: *Grissal*, a grey coarse-grained granite; *Rosa Porriño*, a pinkish, coarse-grained granite, *Blanco Cristal*, a white, medium-grained granite, *Silvestre* a white medium-grained with some ochre spots due to biotite weathering, and *Labrador Claro*, a bluish-black coarse-grained rock which although classified petrographically as a diorite-gabbro, was included in this study because its dark (almost black) color increased the color gamut of the rocks under study. *Labrador Claro* is one of the most commercialized of the darkest rocks and is also referred to as granite in the ornamental stone industry (Fig. 1). Each variety was petrographically and mineralogically characterized by optical microscopy. Information relating to petrographic classification, petrographic texture, mineral composition and mineral size grain of the studied rocks is shown in Table 1.

Five square specimens (36 cm^2) of each granitic rock were prepared with different types of surface finish. Four types of finish were applied to four of the granites, in order of increasing roughness: polished, honed, sawn and flamed (López Jiménez, 1996). Flamed and polished finishes cannot be applied to the *Silvestre* variety of granite, which is more weathered than the others, and these finishes were therefore substituted by bush hammered and polished without glow, respectively.

Polishing is a surface treatment often used in granite stones, because it highlights all the colors and petrographic textures of the material. The polishing process is carried out with particles of different grain size, *i.e.* successively finer particles. The process can close the rock pores because during the polished process, the voids are filled with crushed material from the rock itself or from the abrasive materials used; the process makes the material more resistant to external aggressions as reduces its water absorbing capacity (Rojo et al., 2003). The resulting surface is flat and glossy, with a perceptually darker tone than achieved with other treatments. Honing is very similar to polishing, but the stone does not acquire the characteristic gloss. The honing process is similar to polishing, but only coarse-grained grinding particles are used, and a matt finish is achieved. Polishing without glow, an intermediate finish between polishing and honed, was also used. Sawing is a finish resulting from cutting the granite with steel sheets or diamond discs. This is usually carried out prior to applying another finish. The resulting appearance is even, matt and slightly rough, sometimes with small undulations caused by the cut. Flaming is carried out by heating the granite surface with a blowtorch. The thermal shock causes some mineral grains to be shed from the surface, particularly those fragmented by the saw. The result is a rough surface with a glassy appearance. This finish cannot be achieved in brownish, moderate or highly weathered granite (e.g. *Silvestre*), because it would modify the aspect of the surface unevenly, as a result of chemical alterations. Bush hammering is one of the most commonly used finishes; in earlier times, it was carried out by beating the stone manually with a bush hammer. Nowadays, the system is mechanized, so that it produces a more homogeneous rough finish.

Roughness measurements

Roughness measurements were performed to quantify the surface texture achieved on the granite specimens with the different surface finishes. Roughness was characterized with a non-contact laser profilometer (UBM Microfocus Measurement System, UBM Messtechnik GmbH, Ettlingen, Germany), with a measurement range of ±500 μm. The non-contact laser profilometer was equipped with a 780 nm wavelength laser triangulation sensor with a spot diameter of 1 μm and an axis and sensor resolution of 0.06 μm. One specimen of each studied rock and surface finish (except flamed and bush hammered finishes, which produce roughness above the threshold of 500 μm) was analyzed. In order to take into account the surface anisotropy of the ornamental granites, the laser profilometer was driven in a horizontal (X–Y) plane by a two-dimensional (2D) positioning system with two linear motor actuators. A total of six lines of 17.50 mm long, three on longitudinal axis (X) and three on transverse axis (Y), were scanned. The average roughness (Ra), defined as the integral of the absolute value of the roughness profile over an evaluation length (12.50 mm), was determined from the six measurements with a resolution or point density of 150 points/mm.

Color measurements

The color was measured with a GretagMacbeth (now XRite) portable spectrophotometer CE-XTH, equipped with OptiviewSilver/i QC Basic software. The measuring conditions fixed in the device were: diameter viewing aperture of 10 mm, illuminant D65 and observer 2º (CIE 1931) with a d/8º illumination/viewing geometry (Prieto et al. 2010). Since the surface of granite samples is not totally reflective or matt, inclusion or exclusion of the specular component may be important for color measurements. Thus, the measurements were made in both specular component included (SCI) and specular component excluded (SCE) modes. The SCI mode, in which the gloss trap of the spectrophotometer is closed, includes the total reflectance (considering both specular and diffuse reflections), whereas the SCE mode, with an open gloss trap, includes the diffuse reflectance and excludes most of the specular component and is therefore more sensitive to differences in color due to differences in surface roughness (Wyszecki and

Stiles, 1982). It is generally accepted in the field of color science that the SCE mode approximates the view with the naked eye, and the SCI mode is adequate for analyzing the intrinsic color of objects.

Following the protocol recently described by Prieto et al. (2010) for measuring the color of granite rocks, 14 readings were taken, with substitution in random zones of the surface of each of the five square specimens (36 cm^2) of each variety of granite and type of finish.

The CIELAB color space was selected to represent the color measurements, by use of two different sets of coordinates, Cartesian coordinates, CIEL*a*b*, and cylindrical coordinates, CIEL*$C^*_{ab}h_{ab}$. The first coordinates consider the lightness of the color L*, which varies from 0 black to 100 white, the redness-greenness changes a*, red (+) to green (−) axis, and the yellowness-blueness changes b*, yellow (+) to blue (−) axis. The other set of coordinates is defined by two cylindrical coordinates, the chroma of the color C^*_{ab} and the hue of the color h_{ab}, in addition to the lightness L*; C^*_{ab} and h_{ab} are related to a* and b* as: $C^*_{ab} = (a^{*2}+b^{*2})^{1/2}$ and h_{ab} = arctan (b*/a*).

The CIEL*a*b* coordinates are preferred for achromatic colors, while the CIEL*$C^*_{ab}h_{ab}$ coordinates are recommended for stronger colors (Catalina and Bruna, 1997). As this study attempted to cover the full range of granite colors, and chromatic and achromatic rocks were studied, both sets of coordinates were used.

The partial color differences, ΔL*, Δa*, Δb*, ΔC^*_{ab}, ΔH^*_{ab} , and the total color difference, ΔE^*_{ab}, were also calculated. ΔL* and ΔC^*_{ab} represent the difference between both considered values of L* and C^*_{ab} respectively, whereas ΔH^*_{ab} is given by $\Delta H^*_{ab} = [(\Delta E^*_{ab})^2-(\Delta L^*)^2-(\Delta C^*_{ab})^2]^{1/2}$ (CIE Publ. 15:2004). Following the recommendations for textured samples reported by Huertas et al. 2006, the classical CIELAB 1976 color equation, $\Delta E^*_{ab} = [(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2}$, was applied rather than the newer improved formulae.

Gloss measurements

Specular gloss was measured at an angle on incidence of 60º according to ASTM D 523-95 (ASTM D523-1995) with a GretagMacbeth (now XRite) portable spectrophotometer (CE-XTH). In order to obtain an overall description of each surface finish in each rock studied, 40 readings were taken, with substitution in random zones of the surface area, considering one specimen of each type of rock and surface finish and expressing the results as mean values. A previous study (Huang et al. 2002) was used as reference, where 20 measurements were made on more homogeneous granite with respect to color and texture.

Statistical analysis

Statistical analyses were performed with SPSS v17.0 for Windows. Average roughness values (Ra) and specular gloss (G^{60}) data were subjected to analysis of variance (ANOVA), at $p< 0.05$. CIELAB color data were subjected to a multivariate analysis of variance (MANOVA) at $p< 0.05$. A student's t-test ($p< 0.05$) was used to compare the CIELAB color coordinates obtained in specular component included (SCI) and excluded (SCE) modes.

Results and Discussion

The average roughness values (Ra, µm) induced by each surface finish in each ornamental granite are shown in Table 2. The same trend was observed in each granite studied: the Ra values increased significantly from the polished or polished without glow finish to the flamed or bush hammered finish. Comparison of Ra values with those obtained in other studies is difficult because the aim of most studies on the roughness of ornamental granite is to compare roughness before and after the salt crystallization test in order to analyze decay patterns in monumental granite (Alonso et al., 2008; López-Arce et al., 2010). Moreover, the latter studies did not provide any information about the surface finish of the samples. *Grissal* and *Rosa Porriño* are two of the granites studied by Alonso et al. (2008); they reported larger Ra values for *Rosa Porriño* than for *Grissal*, which is consistent with the results obtained here. Considering only the polished surfaces, *Labrador Claro* is the granite with the lowest Ra value, followed by *Blanco Cristal* and *Grissal*, then by *Rosa Porriño* and, finally, *Silvestre*.

The values of each color coordinate measured in the specular component included (SCI) and excluded (SCE) modes, for each type of ornamental granite and surface finish, are shown in Table 3. Considering the set of samples as representative of the ornamental granites, a range of values can be established for this type of rock. Thus, parameter L*, lightness, varied most widely, from 34.2 ± 0.5 in the darker rocks to 74.9 ± 1.0 in the lighter rocks in SCI mode, and between 30.7 ± 4.8 and 75.5 ± 3.5 in SCE mode. The chromatic parameter a* varied between 2.7 ± 0.5 and -0.9 ± 0.1 in SCI mode, and between 3.3 ± 2.6 and -0.8 ± 0.3 in SCE mode while the chromatic parameter b* varied between 7.4 ± 1.5 and -2.8 ± 0.3 in SCI mode and between 8.6 ± 3.6 and -1.4 ± 1.6 in SCE mode, so that the red component predominated over green in this type of rock, and the yellow predominated over blue (Fig. 2). On the other hand, and as expected, the lowest chroma values (C^*_{ab}: 1.1 ± 0.5 in SCI and 1.0 ± 0.6 in SCE) were obtained in *Labrador Claro* and the highest (7.6 ± 1.1 in SCI and 9.3 ± 4.2 in SCE) in *Rosa Porriño*. The range of values of h_{ab}: 71.8º ± 1.7º to 253.7º±6.1º in SCI and 71.5º ± 4.9º to 237.2º±46.0º in SCE mode enabled identification of possible tones for the studied ornamental granites in the a*-b* diagram, and tones resulting from the combination of blue and red were excluded (Fig. 2). It should be noted, however, that this wide variation in h_{ab} is scarcely noticeable because of the low chroma C^*_{ab}. In the present study, only sound stones were analyzed and higher chroma values may have been observed in the weathered granites as a result of the segregation of iron oxyhydroxides, a process that occurs as a consequence of weathering processes (Taboada and Garcia, 1999).

When the surface of a smooth-colored object becomes rough, the apparent color of the object changes (Simonot and Elias, 2003), and therefore to determine whether the color of the ornamental granites varied with the surface finish or roughness, the present data were subjected to a MANOVA test for each type of ornamental granite and surface finish (Table 3). The surface finish had a significant effect on the color of granites measured in both SCI and SCE modes, unlike in other materials such as dental porcelain (Kim et al., 2003) and injection-molded plastics (Ariño et al., 2007), in which color variations due to differences in surface roughness were only observed using the specular component excluded (SCE) mode. Inclusion or exclusion of the specular component was important for measurement of the color of ornamental granite specimens, as there were significant differences (student t-test at $p< 0.05$) between the CIELAB color coordinates measured in both modes (Table 3). Thus, in SCE mode the b* values, and to a lesser extent the a* values, were significantly higher in most cases. A yellower and redder color was obtained in SCE mode compared to SCI mode (Figure 2). Moreover, standard deviations (S.D.) of the color parameters in SCE mode were higher than in SCI mode (Table 3).

In order to analyze color variations caused by the different surface finishes (roughness), the partial color differences (ΔL^*, Δa^*, Δb^*, ΔC^*_{ab}, ΔH^*_{ab}) and total color difference (ΔE^*_{ab}) between each surface finish and the smoother finish (polished or polished without gloss for *Silvestre*) were calculated (Table 4). Changes in total color (ΔE^*_{ab}), lightness (ΔL^*), chroma (ΔC^*_{ab}) and hue (ΔH^*_{ab}) were plotted against changes in roughness, expressed as logarithmic roughness difference [log(ΔRa)] (Figure 3). As the surface roughness of the granite increased, the apparent color of the rocks changed, as there were variations in total color, lightness, chroma and hue. The total color difference (ΔE^*_{ab}) between most of the surface finishes for the ornamental granites studied was perceptible (CIELAB units >3) (Prieto et al., 2010, Benavente et al., 2003). An upper limit of 6 CIELAB units was considered an acceptable color change (Hardeberg, 1999), and this upper limit was not surpassed in the lightest granites (*Blanco Cristal* and *Silvestre*). By contrast, the limit was greatly surpassed in *Labrador Claro*, the darkest rock, indicating that this type of ornamental granite is the most variable in color with the surface finish or roughness (Table 4, Figure 3).

A similar result was found by Benavente el at. (2003) in different types of marble and limestones, as in dark specimens with high chroma values the changes in total color (ΔE_{94}) were more affected by surface finish than in light-colored specimens with low chroma values, which scarcely showed any change in color in relation to finish.

In this regard, Prieto et al. (2006) defined the limits of the perceptual change in the humane vision for two of the granites used for this study: *Blanco Cristal* and *Rosa Porriño*. Following their results, we can assign qualitative terms to the total color changes, ΔE^*_{ab}, between different surface finishes. Thus, in *Blanco Cristal*, the total color differences between polished and honed and polished and flamed were inappreciable (< 2.63 units), whereas there was a slight difference in color between polished and sawn finishes (between 2.63 and 4.66 units). In *Rosa Porriño*, the differences in color between polished and honed, and between polished and sawn were evident (between 6 and 10.78 units), but the differences between flamed and polished were only slight (between 2.96 and 4.74 units).

Regardless of the type of granite and surface finish, the ΔE^*_{ab} values measured in SCE mode were slightly higher than those measured in SCI mode, except for sawn *Rosa Porriño*. The SCE mode therefore magnifies the differences due to surface finish or roughness on ornamental granite.

With regard to the partial differences in lightness, ΔL^*, more than half of the cases surpassed the visual threshold of 3 CIELAB units, and again the greatest difference in this color parameter was observed in *Labrador Claro* (Table 4, Figure 3). By contrast, although there were significant differences between C^*_{ab} and h_{ab} values, measured in both SCI and SCE modes, in relation to the different surface finishes for each ornamental granite (Table 3), there were scarcely any perceived differences (>3 CIELAB units) in either chroma (ΔC^*_{ab}) or hue (ΔH^*_{ab}) partial differences (Table 4, Figure 3). This is consistent with the fact that the value of C^*_{ab} is low in the rocks under study and thus differences are not appreciable and the hue angle may vary greatly without being of any real significance.

Analysis of these data revealed that lightness, L^*, is the color parameter most affected by changes in roughness. Ignell et al. (2009) reported similar findings for polymeric surfaces in which, the darker the material, the larger the increase in lightness L^*, as the surface became rougher.

However, the variation in color parameters, and therefore in the total color, with different finishes does not depend on roughness, since none of the parameters changed in relation to differences in the roughness of the surface and therefore no general conclusions could be drawn as regards the influence of the roughness on the ornamental granite color (Fig. 3).

As expected, the most important changes in parameter a*, which represents the redness-greenness changes, were obtained with the flamed finish. The action of fire on the granite causes dehydration of the oxyhydroxides from the biotite, giving rise to the formation of dehydrated oxides, e.g. hematies (Fe_2O_3) of a reddish color. However, this effect was not observed in the only stone that was already reddish in color, *Rosa Porriño*.

Mean specular gloss values at 60º, G^{60}(gu), of each surface finish in each type of ornamental granite are shown in Table 2. Many authors have reported an inverse relationship between roughness and gloss on homogeneous surfaces, from the point of view of color and composition (Briones et al., 2006, Ariño et al., 2005, Wang et al., 2000, Thomas, 1999, Hunter and Harold, 1987). However, in the case of the ornamental granites under study, although the gloss of smooth surfaces (polished) is more than 30 gloss units higher than gloss of the rough surfaces, gloss is not a function of roughness (Fig. 4), as it did not differ significantly within a wide range of roughness values (from 2.59 μm to more than 500 μm), except in the case of *Blanco Cristal* (Table 2). Moreover, analysis of the gloss values within that range of roughness, *i.e.* without considering polished finish, revealed a slight increase in gloss with increased roughness (Table 2). This lack of agreement with the findings of other studies may be explained by the following: (i) neither of these studies was accomplished with arbitrary heterogeneous samples, such as granite rocks, in which the relationship between roughness and gloss may be more complex as there is competition between surface and volume scattering; (ii) high values of roughness were considered in the present study, and this relationship probably only exists in the range of the lower roughness values (from Ra: 0.26 µm to Ra: 5.53 µm in this case); (iii) although the Ra values are consistent with the surface finish, i.e. Ra increases from the polished or polished without glow finish to the flamed or bush hammered finish, it should be noted that optical methods for measuring roughness can be very problematic when the measured object is transparent (Rodriguez et al., 2009) and quartz crystals in polished granites can be highly transparent, and iv) the studied material is a polymineral rock in which the gloss of each mineral is different and the overall surface gloss depends on the exposed area of each mineral. Most of the minerals in ornamental granites tend to split along definite crystallographic structural planes (cleavage planes) (López-Arce et al., 2010) giving rise to smooth surfaces, and therefore the treatments used to achieve the different finishes may increase the total surface roughness but also create small flat surfaces that may cause a slight increase in gloss. Thus, for instance, the increases in roughness and gloss between sawn and flamed finishes, probably occur because of the increase in the coherent component of the reflected light owing to an increase in the number of flat surfaces (as large as the size of the mineral grains).

Moreover, gloss values are affected by the color of the rock because as lightness (L*) decreased, the gloss increased in smooth specimens (polished) (Fig. 5). Given that the material under study is a polymineral rock, the refraction index of the different minerals must be taken into account as this property is directly related to gloss. The refractive index (Díaz Mouriño, 1976) of the most abundant minerals, quartz, feldspar and plagioclases, in the lightest of the rocks under study (*Blanco Cristal*, *Rosa Porriño*, *Silvestre* and *Grissal*) is around 1.5, while the refractive indexes of two of the most abundant minerals in Labrador Claro are higher (Pyroxene: 1.6-1.7; Olivine: 1.6-1.8). The lower gloss of polished *Grissal* relative to polished *Blanco Cristal*, *Rosa Porriño* and *Silvestre* may be related to the lower amount of biotite, which is among the minor minerals that having the higher refractive index (1.5-1.7).

However, in rough specimens there was a direct relationship between gloss and L* as gloss increased with lightness. Ignell et al. (2009) obtained similar results with rough surfaces of polymineral materials, although they did not find any relationship between gloss and lightness in smooth surfaces. These authors argued that as gloss is governed by diffusely reflected light on rough surfaces, and surface texture is independent of color, the increase in gloss is probably associated with bulk scattering, and since lighter specimens are less absorbent, this contribution is expected to be more pronounced as the lightness increases.

By contrast, Chroma (C^*_{ab}) did not affect the gloss of either polished or rough finishes (Fig. 5).

Conclusions

The study of the effects of different types of surface finish on the aesthetic properties of ornamental granites revealed that:

- Roughness induced by different types of surface finish on the granite surface causes a change in the color (in most cases perceptible), mainly due to changes in L* values. Moreover, the magnitude of the change in color with roughness is governed by the color of the material, and is higher in rocks with the lowest L* values. However, the variation in color parameters, and therefore in the total color (ΔE^*_{ab}), with different finishes, does not depend on roughness, since the values of these parameters do not change with changes in the roughness of the surface. No general conclusions could therefore be drawn as regards the influence of the roughness on the ornamental granite color.

- In ornamental granites there is an inverse relationship between gloss and roughness only for low values of roughness. Moreover, gloss values are affected by the color of the rock but in different ways in smooth and rough surfaces. Color and L* are inversely related in smooth surfaces and directly related in rough surfaces. The mineral composition of polymineral rocks must be taken into account as it determines the topography of the rough surface and also the refractive index.

- The specular component excluded (SCE) mode magnifies the differences in color due to surface finish or roughness on ornamental granite.

Moreover, the results obtained in this study enable identification of the area of the CIELAB color space in which the color of the studied ornamental granites is defined: in the range of the maximum values L*: 74.9±1.0, a*: 2.7±0.5, b*: 7.4±1.5, C^*_{ab}: 7.6±1.1 and h_{ab}: 253.7º±6.1º in SCI mode, and L*: 75.5 ± 3.5, a*: 3.3 ± 2.6, b*: 8.6 ± 3.6, C^*_{ab}: 9.3 ± 4.2 and h_{ab}: 237.2º±46.0º in SCE mode; the minimum L*: 34.2±0.5, a*: -0.9±0.1, b*: -2.8±0.3, C^*_{ab}: 1.1±0.5 and h_{ab}: 71.8º±1.7º in SCI mode and L*: 30.7 ± 4.8, a*: -0.8 ± 0.3, b*: -1.4 ± 1.6, C^*_{ab}: 1.0 ± 0.6 and h_{ab}: 71.5º ± 4.9º in SCE mode. Although h_{ab} (hue) varied most widely, the variation does not have any real significance because of the low chroma of all the studied rocks.

The information obtained in this study should be taken into account when aesthetic criteria are used in selecting ornamental granites for building and construction materials.

However, it should be highlighted that the polymineral nature of the material under study is a handicap since there is no specific methodology to determine properties such as gloss and roughness, which are affected by this polymineral nature; future research should focus on this subject.

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Table

Table 1. Petrographic classification, petrographic texture, mineral composition and mineral grain size of the ornamental granites studied.

***Blanco Cristal* (Biotite adamellitic granite; Texture: heterogranular-panallotriomorphic of medium grain)**				
Mineral	%	Mineral size(mm)		
		Mean	Maximun	Minimun
Quartz	26	1.7±1.0	5.4	0.3
Feldspar-K	29	3.2±1.7	5.5	0.6
Plagioclases	27.5	1.6±0.9	3.7	0.7
Biotite	9	0.9±0.3	1.6	0.6
Moscovite	2	0.4±0.1	0.5	0.2
Chlorite	4.5	0.5±0.2	0.4	0.3
***Grissal* (Alcaline granite; Texture: porphyritic-panallotriomorphic of coarse grain)**				
Mineral	%	Mineral size(mm)		
		Mean	Maximun	Minimun
Quartz	30.5	2.6±0.9	4.2	1.1
Feldspar-K	34.5	7.0±6.0	17.6	1.3
Plagioclases	20.75	2.0±1.4	4.2	0.3
Biotite	8.5	0.6±0.3	1.0	0.3
Moscovite	0.5	0.2±0.1	0.3	0.1
Chlorite	3.5	0.7±0.4	1.3	0.3
***Rosa Porriño* (Biotite adamellitic granite; Texture: porphyritic-panallotriomorphic of coarse grain)**				
Mineral	%	Mineral size (mm)		
		Mean	Maximun	Minimun
Quartz	30	3.6±2.3	8.2	0.8
Feldspar-K	33	5.7±5.2	14.4	1.3
Plagioclases	21	3.3±2.5	8.0	0.6
Biotite	9	1.4±0.9	3.2	0.3
Chlorite	3.5	0.8±0.5	1.6	0.3
***Labrador Claro* (Diorite-Gabbro with labradorite feldspar; Texture: phaneritic-hipidiomorphic of coarse grain)**				
Mineral	%	Mineral Size (mm)		
		Mean	Maximun	Minimum
Feldspar	48	8.7±4.1	15.3	3.5
Pyroxene	16.5	3.9±3.0	9.6	1.0
Olivine	6.5	0.8±0.5	1.4	0.4
Biotite	3.5	1.6±1.7	4.8	0.3
Amphiboles	5.5	1.8±1.5	4.6	0.5
Opaques	15	0.5±0.3	1.0	0.3
Apatite	4.0	0.5±0.2	0.6	0.2
***Silvestre* (Two mica adamellitic granite; Texture: equigranular-panallotriomorphic of medium grain)**				
Mineral	%	Mineral Size (mm)		
		Mean	Maximun	Minimum
Quartz	29	2.0±0.6	2.9	0.5
Feldspar-K	26	2.2±1.0	3.8	1.0
Plagioclases	24	1.9±0.8	3.2	1.0
Biotite	8	1.0±0.3	1.6	0.4
Moscovite	8	1.2±0.6	2.0	0.3
Chlorite	3.5	0.5±0.2	1.0	0.3

Table 2. Roughness average, *Ra* (µm, micrometers), and specular gloss, G^{60} (gu, gloss units), of each ornamental granite and surface finish. Ra data are the mean of 6 measurements ± S.D. G^{60} data are the mean of 40 measurements ± S.D.

Different superscript letters indicate significant differences ($p < 0.05$) between the mean values of six measurements for the roughness and forty measurements for the specular gloss in the same type of granite in relation to surface finish.

G: Grissal, BC: Blanco Cristal, RP: Rosa Porriño, LC: Labrador Claro, S: Silvestre, (p) polished, (pwg) polished without gloss, (h) honed, (s) sawn, (b) bush hammered, (f) flamed.

	Ra (µm)	Specular gloss, G^{60}(gu)
*G*p	0.4±0.2[a]	67.4±10.8[a]
*G*h	4.4±1.8[b]	17.0±9.9[b]
*G*s	21.8±2.2[c]	19.0±4.5[b]
*G*f	above limit	15.6±1.2[b]
*BC*p	0.4±0.2[a]	69.9±5.8[a]
*BC*h	3.5±0.8[a]	22.0±6.0[b]
*BC*s	25.4±4.8[b]	24.6±0.3[b]
*BC*f	above limit	35.0±12.0[c]
*RP*p	0.6±0.3[a]	77.2±6.6[a]
*RP*h	5.3±1.7[b]	21.5±6.6[b]
*RP*s	24.0±4.0[c]	24.8±2.9[b]
*RP*f	above limit	23.9±2.7[b]
*LC*p	0.3±0.2[a]	89.3±3.4[a]
*LC*h	3.5±2.1[a]	8.5±0.6[b]
*LC*s	21.8±5.0[b]	12.5±5.4[b]
*S*pwg	2.6±1.6[a]	19.9±7.8[a]
*S*h	4.1±0.7[a]	18.2±5.3[a]
*S*s	23.1±4.0[b]	18.2±1.1[a]
*S*b	above limit	22.5±7.2[a]

Table 3. CIELAB color coordinates of each ornamental granite and surface finish, measured with the spectrophotometer in SCI and SCE modes. Data are the mean of 70 measurements ± S.D.

Different superscript letters (small letter) indicate significant differences ($p < 0.05$) between the means of five independent granite specimens (the reported color parameters for each specimen are the mean values of fourteen measurements) for the values of CIELAB parameters: L*, a*, b*, C^*_{ab}, h_{ab} in the same type of granite in relation to surface finish; and different superscript letters (capital letter) indicate significant differences ($p < 0.05$) for each type of granite and surface finish between SCI and SCE modes.

G: Grissal, BC: Blanco Cristal, RP: Rosa Porriño, LC: Labrador Claro, S: Silvestre, (p) polished, (pwg) polished without gloss, (h) honed, (s) sawn, (b) bush hammered, (f) flamed.

	SCI (specular component included) mode					SCE (specular component excluded) mode				
	L*	a*	b*	C^*_{ab}	h_{ab} (º)	L*	a*	b*	C^*_{ab}	h_{ab} (º)
*G*p	62.5±1.4$^{a, A}$	-0.9±0.1$^{a, A}$	1.0±0.4$^{a, A}$	1.5±0.3$^{a, A}$	143.5±12.8$^{a, A}$	59.4±7.0$^{a, B}$	-0.8±0.3$^{a, B}$	0.9±0.8$^{a, A}$	1.3±0.7$^{a, A}$	142.0±29.0$^{a, A}$
*G*h	67.1±1.4$^{b, A}$	-0.8±0.1$^{b, A}$	0.4±0.5$^{b, A}$	1.2±0.2$^{b, A}$	164.6±17.5$^{b, A}$	68.1±5.4$^{b, A}$	-0.7±0.3$^{a, B}$	0.5±1.2$^{a, A}$	1.2±1.0$^{a, A}$	163.7±42.1$^{b, A}$
*G*s	66.5±1.0$^{b, A}$	-0.9±0.1$^{ab, A}$	2.4±0.8$^{c, A}$	2.6±0.7$^{c, A}$	112.0±6.5$^{c, A}$	65.5±4.2$^{c, A}$	-0.8±0.3$^{a, A}$	2.4±0.7$^{b, A}$	2.6±0.7$^{b, A}$	110.7±6.8$^{c, A}$
*G*f	71.3±1.9$^{c, A}$	-0.3±0.2$^{c, A}$	3.2±0.5$^{d, A}$	3.2±0.5$^{d, A}$	97.6±2.7$^{d, A}$	70.8±4.6$^{d, A}$	-0.4±0.3$^{b, A}$	2.8±1.1$^{c, A}$	2.9±1.1$^{b, A}$	99.6±7.9$^{d, A}$
*BC*p	73.3±1.5$^{a, A}$	-0.6±0.1$^{a, A}$	3.6±0.2$^{a, A}$	3.7±0.2$^{a, A}$	100.6±1.5$^{a, A}$	71.0±4.8$^{a, B}$	-0.5±0.3$^{a, B}$	3.7±0.9$^{a, A}$	3.7±0.9$^{a, A}$	99.2±6.9$^{a, A}$
*BC*h	74.5±1.1$^{ab, A}$	-0.4±0.1$^{b, A}$	2.2±0.7$^{b, A}$	2.2±0.7$^{b, A}$	105.2±4.5$^{b, A}$	75.5±3.5$^{b, A}$	-0.5±0.3$^{a, A}$	2.8±0.9$^{b, B}$	2.9±0.9$^{b, B}$	101.0±6.5$^{b, B}$
*BC*s	72.7±1.0$^{c, A}$	-0.3±0.3$^{b, A}$	7.4±1.5$^{c, A}$	7.4±1.5$^{c, A}$	93.3±2.4$^{c, A}$	74.6±1.9$^{b, B}$	-0.6±0.2$^{a, B}$	5.2±1.0$^{c, B}$	5.2±1.0$^{c, B}$	96.7±2.7$^{c, B}$
*BC*f	74.9±1.0$^{b, A}$	-0.2±0.1$^{c, A}$	3.1±0.5$^{d, A}$	3.2±0.5$^{d, A}$	93.8±3.4$^{c, A}$	75.0±6.5$^{b, A}$	-0.2±0.3$^{b, A}$	2.5±0.9$^{b, B}$	2.5±0.8$^{d, B}$	95.5±8.5$^{c, A}$
*RP*p	60.4±2.9$^{a, A}$	2.7±0.5$^{a, A}$	7.1±1.0$^{a, A}$	7.6±1.1$^{a, A}$	71.8±1.7$^{a, A}$	61.0±8.1$^{a, A}$	3.3±2.6$^{a, A}$	8.6±3.6$^{a, B}$	9.3±4.2$^{a, B}$	71.9±8.6$^{a, A}$
*RP*h	66.4±1.6$^{b, A}$	1.6±0.4$^{b, A}$	4.5±0.7$^{b, A}$	4.8±0.8$^{b, A}$	73.9±4.0$^{a, A}$	67.4±5.8$^{b, A}$	2.0±1.5$^{b, A}$	5.8±2.4$^{b, B}$	6.2±2.7$^{b, B}$	72.3±10.1$^{a, A}$
*RP*s	67.9±0.8$^{c, A}$	0.6±0.1$^{c, A}$	4.3±0.4$^{b, A}$	4.4±0.4$^{b, A}$	83.9±1.4$^{b, A}$	67.6±3.8$^{b, A}$	1.1±1.0$^{c, B}$	5.1±1.6$^{b, B}$	5.3±1.8$^{b, B}$	80.0±7.8$^{b, B}$
*RP*f	63.9±1.6$^{d, A}$	2.3±0.2$^{a, A}$	6.8±0.6$^{a, A}$	7.2±0.6$^{a, A}$	72.6±1.1$^{a, A}$	66.2±5.7$^{b, B}$	2.6±1.4$^{ab, A}$	7.5±2.4$^{c, A}$	7.9±2.7$^{c, A}$	71.5±4.9$^{a, A}$
*LC*p	34.2±0.5$^{a, A}$	-0.4±0.1$^{a, A}$	-1.2±0.1$^{a, A}$	1.3±0.1$^{a, A}$	244.5±5.8$^{a, A}$	30.7±4.8$^{a, B}$	-0.4±0.4$^{ab, A}$	-1.1±1.0$^{a, A}$	1.4±0.8$^{a, A}$	237.2±46.0$^{a, A}$
*LC*h	50.0±1.4$^{b, A}$	-0.7±0.1$^{b, A}$	-2.8±0.3$^{b, A}$	3.0±0.3$^{b, A}$	253.7±6.1$^{b, A}$	48.0±3.4$^{b, B}$	-0.6±0.3$^{a, B}$	-1.4±1.6$^{a, B}$	1.9±1.0$^{b, B}$	219.4±58.8$^{a, B}$
*LC*s	61.0±0.9$^{c, A}$	-0.4±0.1$^{a, A}$	1.0±0.5$^{c, A}$	1.1±0.5$^{c, A}$	119.3±11.8$^{c, A}$	58.8±2.5$^{c, B}$	-0.4±0.2$^{b, A}$	0.6±0.9$^{b, B}$	1.0±0.6$^{c, A}$	148.6±48.7$^{b, B}$
*S*pwg	70.5±1.2$^{a, A}$	-0.2±0.1$^{a, A}$	5.8±0.4$^{a, A}$	5.8±0.4$^{a, A}$	92.2±1.4$^{a, A}$	69.6±4.3$^{a, A}$	0.0±0.4$^{a, B}$	5.8±1.1$^{a, A}$	5.8±1.1$^{a, A}$	90.1±4.1$^{a, B}$
*S*h	74.9±0.2$^{b, A}$	-0.2±0.1$^{a, A}$	3.5±0.5$^{b, A}$	3.5±0.5$^{b, A}$	94.0±1.4$^{b, A}$	73.7±2.5$^{c, B}$	-0.3±0.2$^{b, A}$	2.5±0.8$^{b, B}$	2.6±0.8$^{b, B}$	96.9±4.8$^{b, B}$
*S*s	70.8±2.0$^{a, A}$	-0.1±0.2$^{b, A}$	3.8±0.5$^{b, A}$	3.8±0.5$^{b, A}$	91.4±2.2$^{a, A}$	71.6±2.2$^{b, A}$	-0.1±0.3$^{a, A}$	4.2±1.1$^{c, B}$	4.2±1.1$^{c, B}$	91.6±3.2$^{c, A}$
*S*b	74.0±0.4$^{b, A}$	0.1±0.1$^{c, A}$	4.4±0.2$^{c, A}$	4.4±0.2$^{c, A}$	89.4±0.8$^{c, A}$	74.1±2.7$^{c, A}$	0.2±0.2$^{c, B}$	4.7±0.9$^{d, B}$	4.7±0.9$^{d, B}$	88.0±2.6$^{d, B}$

Table 4. Partial color differences (ΔL^*, Δa^*, Δb^*, ΔC^*_{ab}, ΔH^*_{ab}) and total color difference (ΔE^*_{ab}) between the polished finish (polished without gloss for Silvestre) and each of the other surface finishes for each ornamental granite, measured with the spectrophotometer in SCI and SCE modes.

G: Grissal, BC: Blanco Cristal, RP: Rosa Porriño, LC: Labrador Claro, S: Silvestre, (p) polished, (pwg) polished without gloss, (h) honed, (s) sawn, (b) bush hammered, (f) flamed.

	SCI (specular component included) mode						SCE (specular component excluded) mode					
	ΔL^*	Δa^*	Δb^*	ΔC^*_{ab}	ΔH^*_{ab}	$\mathbf{\Delta E^*_{ab}}$	ΔL^*	Δa^*	Δb^*	ΔC^*_{ab}	ΔH^*_{ab}	$\mathbf{\Delta E^*_{ab}}$
*G*f-p	8.8	0.6	2.2	1.7	1.5	**9.1**	11.4	0.4	1.9	1.6	1.1	**11.6**
*G*s-p	4.0	0.1	1.4	1.1	1.0	**4.2**	6.1	0.0	1.5	1.3	0.7	**6.3**
*G*h-p	4.6	0.1	-0.6	-0.4	0.5	**4.6**	8.7	0.1	-0.4	-0.1	0.4	**8.7**
*BC*f-p	1.6	0.4	-0.5	-0.5	0.4	**1.7**	4.0	0.3	-1.2	-1.2	0.3	**4.2**
*BC*s-p	-0.6	0.3	3.8	3.7	0.7	**3.8**	3.6	-0.1	1.5	1.5	0.1	**3.9**
*BC*h-p	1.2	0.2	-1.4	-1.4	0.2	**1.8**	4.5	0.0	-0.9	-0.8	0.4	**4.6**
*RP*f-p	3.5	-0.4	-0.3	-0.4	0.2	**3.5**	5.2	-0.7	-1.1	-1.4	0.0	**5.4**
*RP*s-p	7.5	-2.1	-2.8	-3.3	1.2	**8.3**	6.6	-2.2	-3.5	-4.0	1.0	**7.8**
*RP*h-p	6.0	-1.1	-2.6	-2.8	0.3	**6.6**	6.4	-1.3	-2.8	-3.1	0.0	**7.1**
*LC*s-p	26.8	0.0	2.2	-0.3	2.1	**26.9**	28.1	0.0	1.7	-0.4	1.7	**28.2**
*LC*h-p	15.9	-0.2	-1.6	1.6	0.2	**16.0**	17.3	-0.2	-0.3	0.5	0.0	**17.3**
*S*b-pwg	3.5	0.3	-1.4	-1.4	0.2	**3.8**	4.5	0.2	-1.1	-1.1	0.2	**4.6**
*S*s-pwg	0.3	0.2	-1.9	-1.9	0.0	**2.0**	2.0	-0.1	-1.6	-1.6	0.1	**2.6**
*S*h pwg	4.4	0.0	-2.3	-2.3	0.0	**4.9**	4.1	-0.3	-3.3	-3.2	0.9	**5.3**

Figure 1

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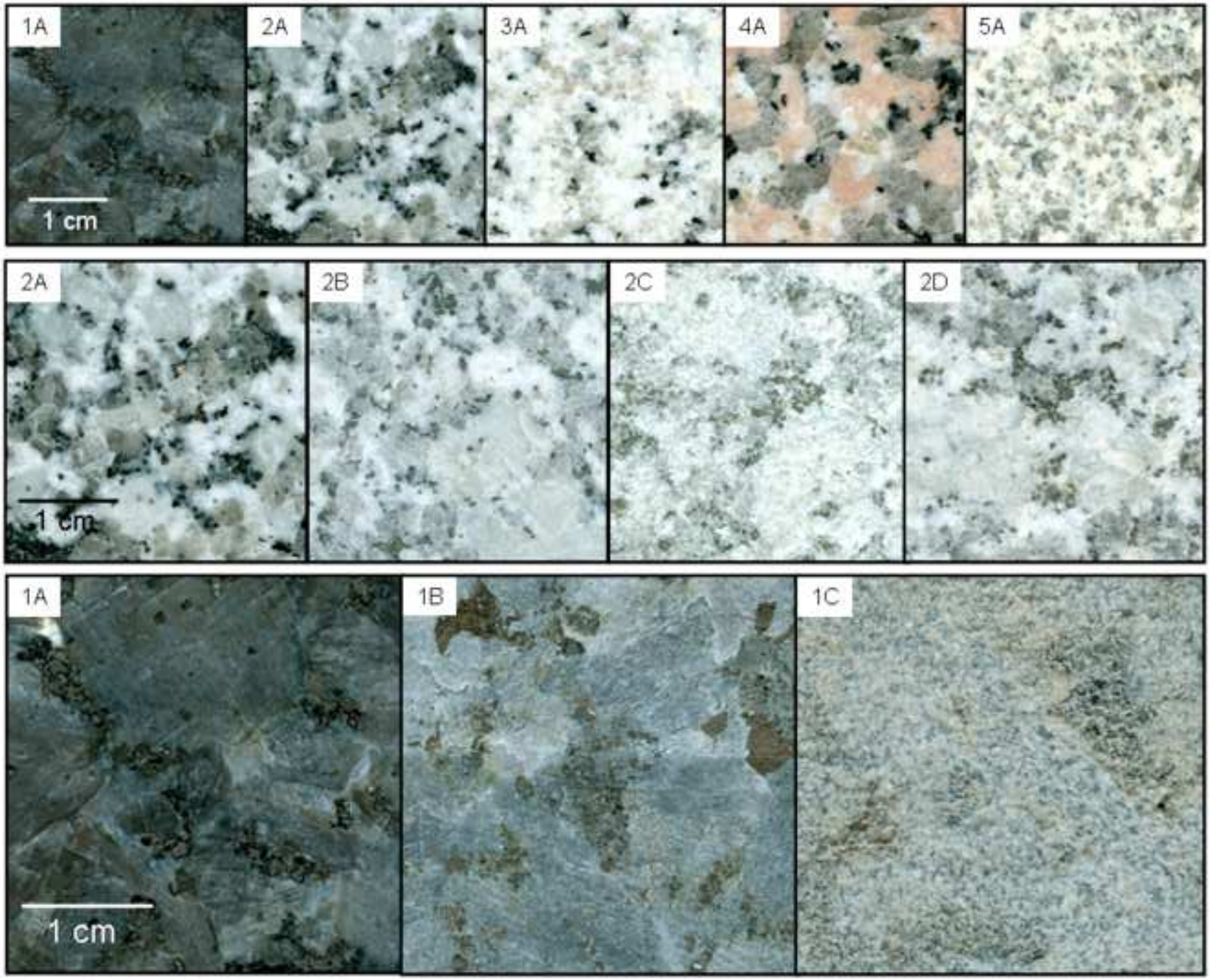

Figure 2

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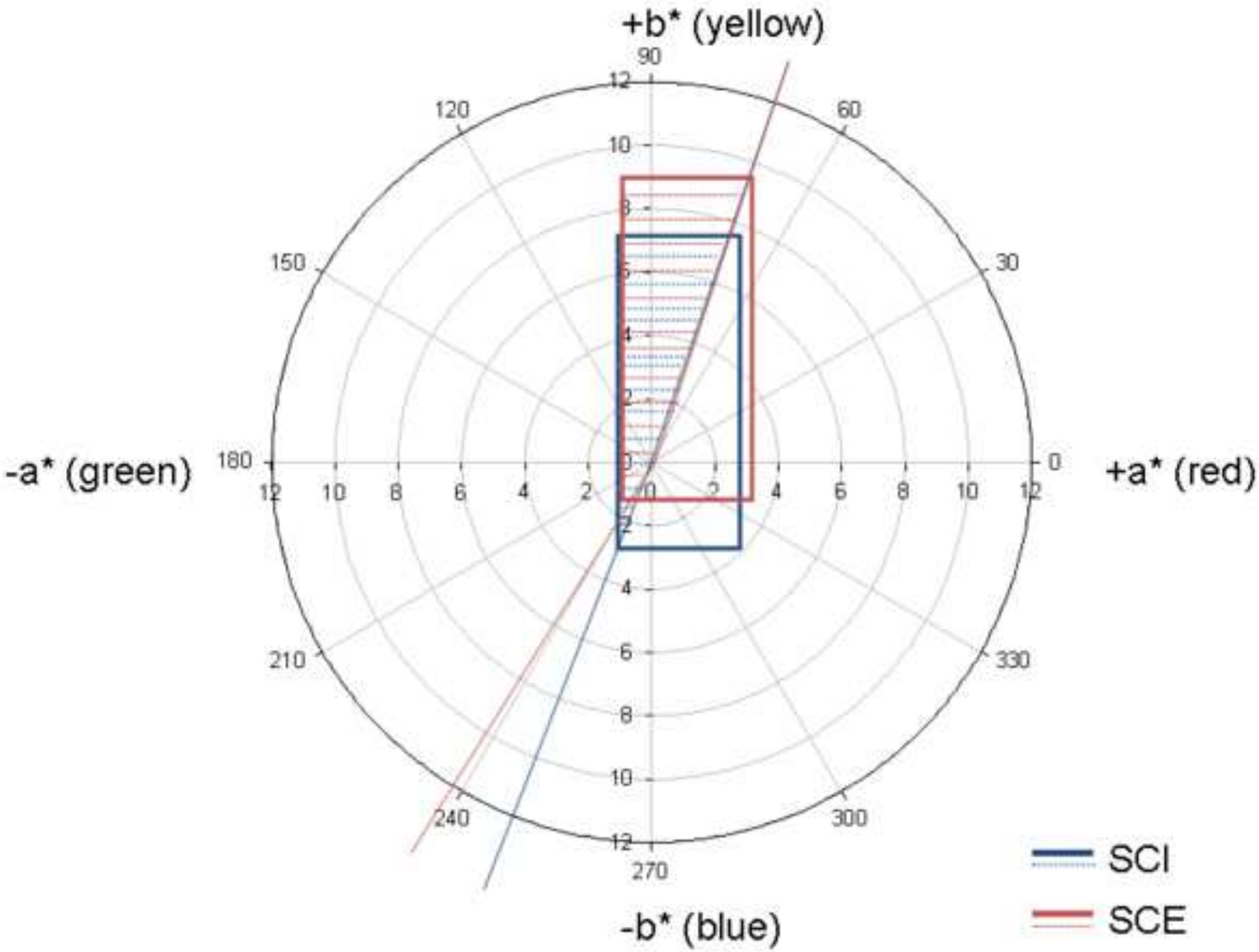

Figure 3

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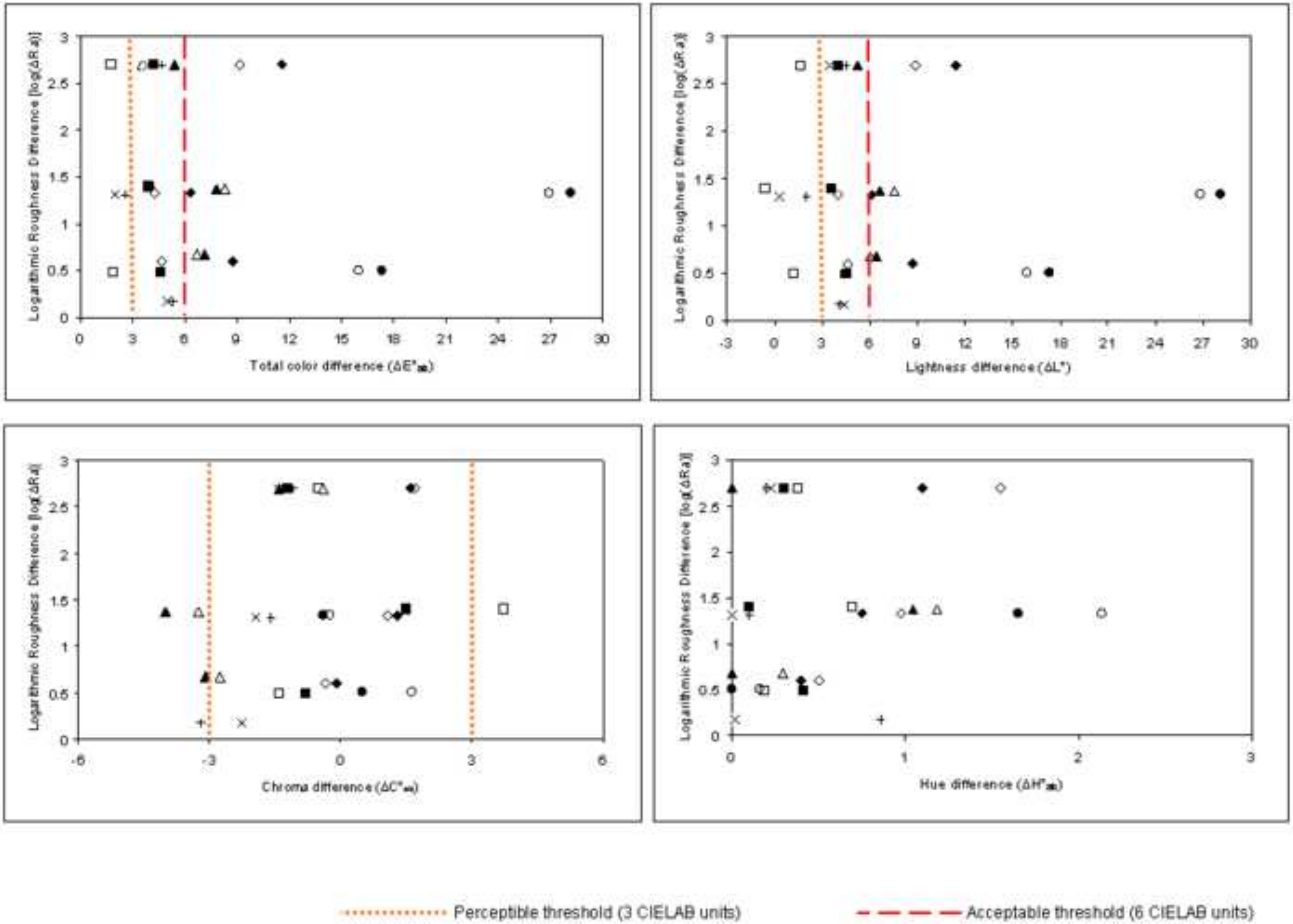

Figure 4
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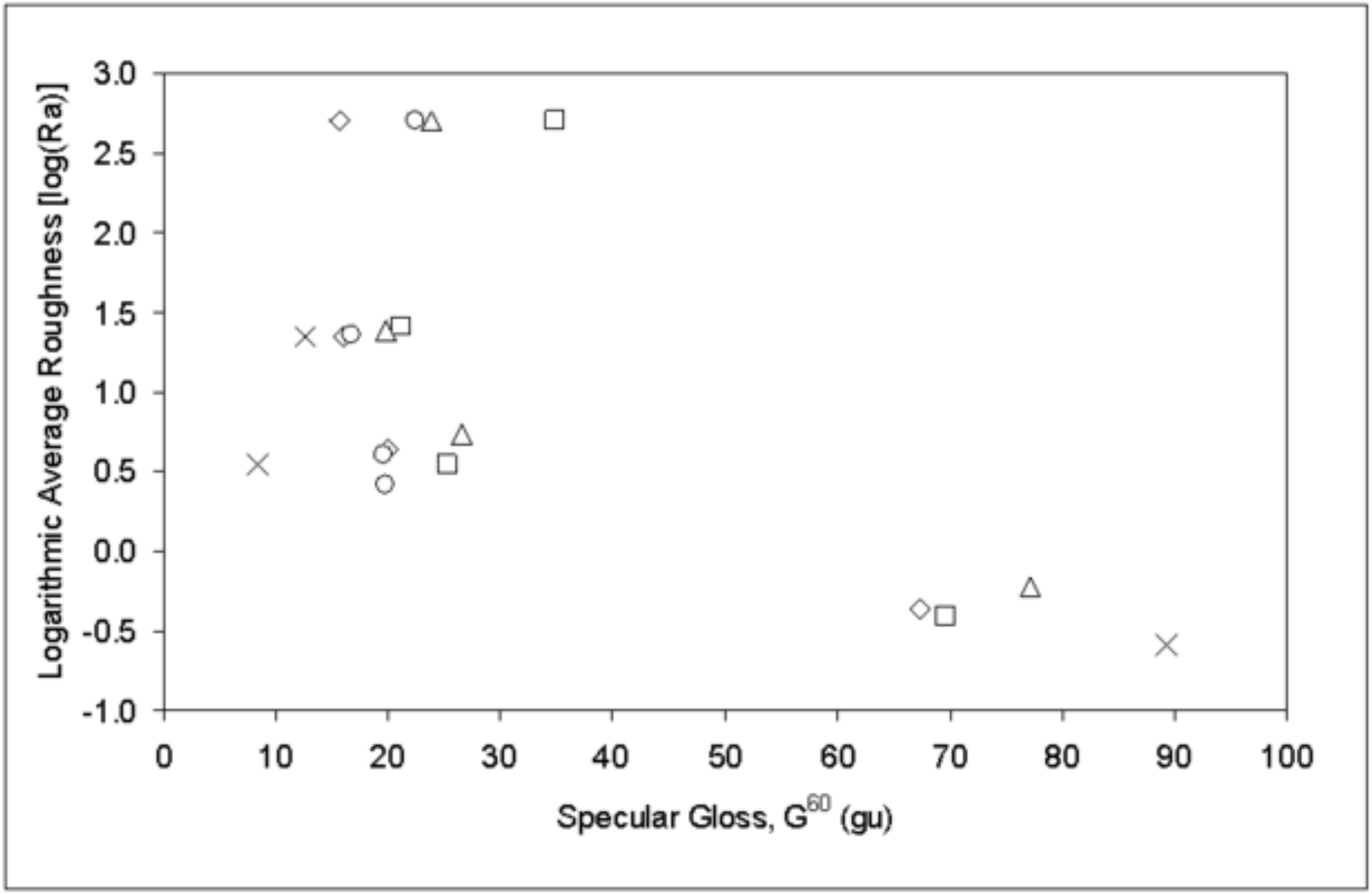

Figure 5
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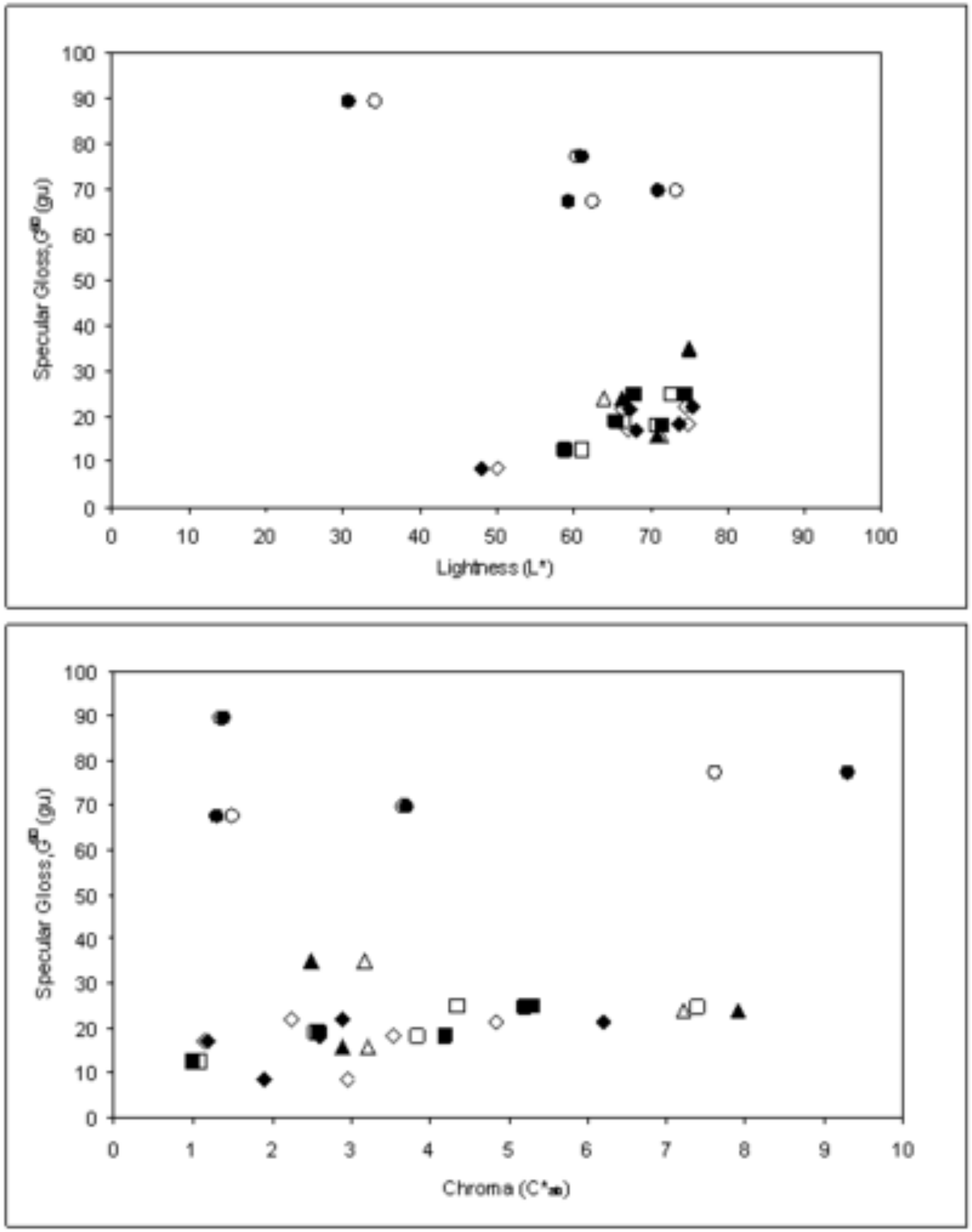

Figure Captions

Figure 1. Macroscopic appearance of the ornamental granites studied. (1) *Labrador Claro*, (2) *Grissal*, (3) *Blanco Cristal*, (4) *Rosa Porriño*, (5) *Silvestre*. (A) Polished finish (B) honed finish, (C) sawn finish, (D) flamed finish.

Figure2. a*-b* diagram: representation of the area in which the parameter a*, b* and h_{ab} of the ornamental granites studied, using the specular component included (SCI) and excluded (SCE) modes, are included. Only the filled area should be considered.

Figure3. Relationships between the roughness, expressed as logarithmic roughness difference [log(ΔRa)] with changes in total color (ΔE^*_{ab}), lightness (ΔL*), chroma (ΔC^*_{ab}) and hue (ΔH^*_{ab}), calculated between the polished finish (polished without gloss for *Silvestre*) and each of the other surface finishes for each ornamental granite, measured with the spectrophotometer in SCI and SCE modes. ◊ Grissal, □ Blanco Cristal, Δ Rosa Porriño, ○ Labrador Claro, using SCI mode (open symbols) and SCE mode (solid symbols); x Silvestre (SCI mode); + Silvestre (SCE mode).

Figure 4. Relationship between the roughness, expressed as logarithmic roughness difference [log(ΔRa)] with specular gloss measured at 60º (G^{60}). ◊ Grissal, □ Blanco Cristal, Δ Rosa Porriño, x Labrador Claro, ○ Silvestre.

Figure 5. Relationships between the specular gloss measured at 60º (G^{60}) with the lightness (L*) and the chroma (C^*_{ab}). ○ Polished, ◊ honed, □ sawn, Δ flamed, using SCI mode (open symbols) and SCE mode (solid symbols).