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Original article

Color characterization of roofing slates from the Iberian Peninsula for restoration purposes

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ABSTRACT

Substitution of slate roofing tiles is a conventional operation during building restoration, since tiles are very difficult to restore or clean because of the high degree of alteration they suffer. Criteria for replacement of historical building stones must be based on geological, geotechnical and esthetic parameters, among which color is of great importance. In this sense, this paper constitutes a comprehensive and useful colorimetric study of roofing slates from the Iberian Peninsula, for the purposes of restoration. The color of 50 commercial varieties of roofing slate mined in quarries from the 12 mining districts in the Iberian Peninsula was analyzed with a spectrophotometer device, by considering the CIELAB color space. The results of the study were used to develop a protocol for characterizing the color of roofing slate and to define the color range of roofing slate from the Iberian Peninsula. In addition, the similarities and differences in the color and microstructure of the different commercial varieties of Iberian roofing slate were established and the limit of acceptability of replacement of one type of slate by another was determined. Parameter h_{ab} was found to be the most important CIELAB color coordinate as regards the formation of homogeneous color groups, and the specular component excluded (SCE) mode was most sensitive as regards detecting color differences between two samples.

1. Introduction

Slate has been used for centuries as a roofing material and the extraction of slate and other fissile rocks for roofing is probably as old as the art of building with stone [1]. There are some remains of slate roofs on Roman buildings in England [2] and many historical centers of European cities include Medieval and Renaissance buildings covered with slate, such as the monastery of *El Escorial* in Madrid (Spain). Before the slate industry began in the USA – slate was first quarried in the country in 1839 at Fair Haven (Vermont) – slate was exported from Europe, with France being the main producer, followed by Germany and the United Kingdom. Spanish slate deposits did not begin to be exploited industrially until the 1970s [3] in response to the exhaustion of mining resources in European quarries and the modernization of the production chain in Spain [4]. Nowadays, Spain is the principal producer of roofing slate in the world, and the main areas of exploitation are in the *Variscan* belt in the northwest of the Iberian Peninsula [1,5].

Slate can be used as roofing material because it contains a high proportion of phyllosilicates, which become aligned during metamorphism and develop a new set of planes in a process named schistosity or slaty cleavage (S_1) [6]. The material can therefore be split into thin slabs (2–8 mm thick), which maintain high mechanical strength and uniform surface [7,8]. In addition, its low water absorption index (< 0.6%) lends slate a waterproof character and makes it very resistant to frost damage and breakage due to freezing/thawing cycles [9]. However, slate tiles still undergo weathering and must be replaced by new ones, which in order to maintain the esthetic properties of the building, should be selected from the same quarry where the weathered slates were originally extracted. As the original quarry is often unknown, has been mined out or is no longer accessible, slate tiles must be obtained from other quarries in similar geological formations. In such cases, the criteria for replacement of historical building stones should be based on geological, geotechnical and esthetic parameters rather than on visual and purely qualitative-subjective methods and/or economic considerations [10,11], which too often results in inadequate replacement, giving rise to a patchwork of original and substituted slates (Fig. 1). This not only causes an unpleasant esthetic effect as regards the color of the roof, but does not comply with the basis of international criteria for restoration and the current legislation regarding national heritage monuments [12–14].

From a geological point of view, roofing slate is formed under very low metamorphic conditions (greenschists facies), with a relatively simple mineral composition of quartz, mica and chlorite, plus some accessory minerals. The mineralogy of Spanish roofing

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Fig. 1. Example of inadequate partial replacement of roofing slate.

slates is quite homogeneous [5,15,16], with three main components (mica, chlorite and quartz), secondary minerals (chloritoid, feldspars, iron sulphides and carbonates), and some accessory minerals. Examined with the petrological microscope, spanish roofing slate may present two different microtextures well defined, lepidoblastic, with small grain size, and porphido-lepidoblastic, with bigger blasts standing out the mica matrix. Both microtextures are characterized by the repetition of mica alignment formed during the metamorphism which coincides with S_1. The occurrence of sedimentation beds (S_0) can be easily detected by a third microstructure, granolepidoblastic, which is a mosaic of quartz crystals, present in these sedimentation beds under the form of sandy levels [17]. These mica alignments, which confer to the slates their anisotropic nature, together with the color are the two main factors involved in the appearance of the slates.

Although color is one of the main factors involved in the perceived appearance of a material, and therefore of great importance in restoration work, no studies concerning the objective characterization of this property in roofing slates have yet been published. The aims of the present study were therefore the objective characterization of the color of 50 commercial varieties of roofing slate mined from the 12 mining districts in the Iberian Peninsula [18], and the evaluation of the differences in color, in order to establish homogeneously colored groups of roofing slates. Moreover, microstructure features [6] as S_1, S_0 and the intersection between them (S_1/S_0 angle), which forms a set of lineation named intersection lineation (L_0), were analyzed. This information will help improve the replacement of roofing slates in restoration work.

2. Material and methods

2.1. Roofing slates

Slate is a fine-grained rock formed by the low-grade metamorphism of sedimentary clays [19]. The main minerals are quartz and phyllosilicates (mica and chlorites), with variable amounts of albite, chloritoid, and small amounts of tourmaline, zircon, rutile, iron sulfides and carbonates [20]. The latter two minerals are potentially highly alterable and therefore undesirable in top quality roofing slate.

Not all types of slate are useful for roofing tiles. Thus, the European Committee of Standardization defines *slate* as 'a fine-grained very low- to low-grade metamorphic rock possessing a well-developed fissility parallel to the planes of slaty cleavage' and *roofing slate* as 'rocks that are easily split into thin sheets along planes of slaty cleavage, caused by very low- to low-grade metamorphism due to tectonic compression' [21]. Commercial slate slabs are obtained by splitting, creating uneven surfaces and a natural looking finish, which contrasts with other ornamental rocks most often traded polished.

In this study, 50 commercial varieties of roofing slates from quarries in the 12 different mining districts of the Iberian Peninsula (Fig. 2) were considered. The name relative to the origin, mining district, stratigraphic level and the color description by visual assessment are given for each type of roofing slate studied in Table 1.

2.2. Colorimetric characterization: measuring protocol

With the purpose of determining the reproducible and comparable color of roofing slates, a measuring protocol, which takes into account the minimum number of measurements and the minimum area of measurement required to quantify roofing slate color in relation to the dimensions of the measuring head (circular viewing aperture), was established following the methodology proposed by Prieto et al. [22] for granite rocks. The protocol combines colorimetric measurements and the corresponding statistical analysis. Four different sizes of surface area (36, 54, 72 and 90 cm^2) of each of three specimens of the 50 commercial varieties of roofing slate ($50 \times 12 = 600$ specimens) were measured with a Minolta colorimeter, equipped with two interchangeable diameter viewing apertures, CR-300 (8 mm) and CR-310 (50 mm), and a portable spectrophotometer GretagMacbeth CE-XTH, with two diameter viewing apertures of 5 and 10 mm. The measuring conditions were: CIE standard daylight illuminant D65, 1931 (2°) CIE standard colorimetric observer, and integrating sphere geometry in which the light is uniformly diffuse in all directions illuminating the sample, and is observed at 0° in relation to normal for the colorimeter (d/0°) and at 8° for the spectrophotometer (d/8°). Twenty measurements were executed at random by reflection in speculate component included (SCI) mode, with each aperture (5, 8, 10 and 50 mm) on each surface area of the 600 specimens of roofing slates.

The CIELAB color space was used to define the measuring protocol by considering the Cartesian coordinates: $L^*a^*b^*$, where L^* represents the lightness of the color, which varies from 0 black to 100 white, a^* the red-green coordinate on a red (+) to green (−) axis, and b^* is the yellow-blue coordinate on a yellow (+) to blue (−) axis.

All of the data were subjected to multivariate analysis of variance (Manova) and the Tukey-b multiple comparison test by use of the SPSS 15.0 statistical software.

2.3. Colorimetric characterization: roofing slate color

Once the measuring protocol was defined, the color of each commercial variety of roofing slate was characterized by carrying out six measurements at random positions on three specimens (36 cm^2) by use of a GretagMacbeth CE-XTH spectrophotometer with a diameter viewing aperture of 10 mm (Section 3.1). The measurements were performed in both the specular component included (SCI) mode and specular component excluded (SCE) mode, as it has been suggested that SCE geometry is more useful for the detection of small color differences in other materials [23–25]. SCI mode, with the gloss trap of the spectrophotometer 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 [26]. In general, it is an accepted theory