EXFOLIATION MICROCRACKS IN BUILDING GRANITE. IMPLICATIONS FOR ANISOTROPY

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ABSTRACT

Granite is found in many world heritage monuments and cities. It continues to be one of the most widely used stones in today's construction, given its abundance, uniformity and durability. Quarrymen traditionally cut this rock along its orthogonal slip planes, where splitting is easier. Ranked by ease of splitting, these planes are rift, grain and hardway. Granite is traditionally quarried along the rift plane where coplanar exfoliaton microcracks coalesce developing a flat surface. This splitting surface minimizes the cost and effort of subsequent hewing. Rift plane was predominantly used on the fair face of ashlars in heritage buildings worldwide. Determining the petrographic and petrophysical behaviour of these three orthogonal splitting planes in granite is instrumental to understanding decay in ashlars and sculptures. The decay of building granite is different in each splitting plane.

Alpedrete granite was the stone selected for this study based on the orientation and distribution of exfoliation microcracks and the characterisation of their implications for the anisotropy of petrophysical properties such as ultrasonic wave propagation, capillarity, air permeability, micro-roughness and surface hardness. Inter- and intracrystalline microcrack length and spacing were also measured and quantified.

The findings show that the splitting planes in Alpedrete granite are determined by the orientation of exfoliation microcracks, which as a rule are generally straight and intracrystalline and determine the anisotropy of the petrophysical properties analysed.

Splitting planes are the orientation that should be applied when performing laboratory tests for the petrographic and petrophysical properties of building granite.

Keywords: Exfoliation microcracks, dimension stone, anisotropy, granite.

1. INTRODUCTION

Granite has been one of the most widely used construction stones throughout history due to its abundance, petrophysical characteristics, durability, compositional and textural uniformity. It is found on building façades, walls and sockets, on plinths for sculptures and as a base for large-scale structures. Microcracks play an essential role in building granite decay, they are due to genesis, tectonic history and denudation of the rocky massif where quarries are sited (Catlos et al., 2011).

The present study addresses exfoliation microcracks, i.e., microscopic fissures located between what in the literature are termed Bankung, Lägerklufte, exfoliation, sheet, sheeting, pressure-release, stress-release, unloading, offloading and post-uplift joints (Ziegler et al., 2014); generated due to decompression on and near the surface of the granite massif (Gorbatsevich, 2003). Referred to hereunder as exfoliation joints, they are found in all climates and in many types of rock, with specific characteristics that are common the world over. Flat and open, they are the youngest natural cracks in outcrops. The width of their openings narrows and their spacing grows (from millimetres to several metres) with depth. They are normally confined to a few decametres, i.e., to the quarry depth, although they may extend up to 100 m below the surface (Goodman, 1993). Their displacement is insignificant and their orientation sub-parallel to the actual surface of the relief or palaeo-relief. They may coalesce, producing macroscopic structures. Such exfoliation joints, which may spread laterally across distances of over 100 m, are used in quarries to define the ‘floor’ or springline in levels or banks. They accelerate alteration (Sajid et al., 2016) and may induce mass movements in granite slopes (Chigira, 1999).

Lateral expansion due to vertical or sub-vertical fractures favours the sub-vertical cracking and microcracking that originate granite tors or boulders, i.e., the remains of solid rock present in layers of mantle rock. Such regoliths, which may range in depth from a few to 25 m or even 30 m, exhibit a higher degree of alteration than the underlying granite (García-Rodríguez, 2015). The exfoliation microcracks found in tors are normally pseudo-concentric, giving rise to what is known as spheroid exfoliation. Traditionally, tors were used to hew ashlars for use in monument construction (Fort et al., 2010).

In traditional quarrying the slip planes formed by mineral orientations or the presence of oriented cracks (Chen, 1999) were used to extract and dimension granite blocks. The three orthogonal splitting planes are known as rift (R), grain (G) and hardway (HW) (Figure 1). Rift is the plane in which the stone is most readily split, followed by grain and lastly by hardway (Vasconcelos et al., 2009). Table 1 lists the names of these three planes in several languages.

The traditional quarrymen needed the existence of exfoliation microcracks to make the artisanal splitting of granite blocks easier. In historic granite quarries the presence of well-defined R was essential to operation, to ensure that blocks could be cut with less effort by hammering wedges into the granite in direction R. Quarrymen traditionally identified the rift plane touching the granite planes on the grounds of surface roughness, for plane R is smoother than planes G and HW. A granite quarry with no or a weak R is usually not productive.

Today ground penetrating radar (GPR) is used to locate blocks and exfoliation joints and to identify fresh rock in ornamental granite quarries (Porsani et al., 2006). As the granite is normally cut with diamond-blade tools or jet flames (Baltuille et al., 2004), R no longer conditions the quarry, although joints and microcracks continue to be help define the banks and extract large blocks (Sousa, 2007, 2010; Yarahmadi, 2015).

Stone anisotropy can be defined as the difference of measure when a property is measured along different axes. Due to the anisotropy, the granite position on buildings define its hydraulic and mechanical behavior (Fort et al., 2011) as well as its resistance to decay, particularly when it, and hence the microcracks it bears, are subject to temperature change (Gómez-Heras et al., 2009; Freire-Lista et al., 2015a).

The exfoliation microcracks had never been studied from the point of view of the anisotropy applied to building ashlars. This paper aims to instrumentally determine the role of exfoliation microcracks in the anisotropy in granite used in construction and characterise the anisotropy of petrophysical properties when measured along the three splitting planes (rift, grain and hardway) in Alpedrete granite. It has been observed that these microcracks have great importance in the building granite decay processes. With the findings in hand, this orientation can be reproduced in new constructions, restorations and petrophysical tests, particularly in accelerated ageing tests conducted to study granite specimen durability.

2. MATERIAL AND METHODS

2.1 Granite samples

The stone quarried in the Guadarrama Mountains (Spanish Central System) is generically known as Piedra Berroqueña (Freire-Lista and Fort, 2016a). One of the varieties is Alpedrete, a medium-to-fine grained, sub-automorphic, equigranular monzogranite (Fort et al., 2011). It has been widely used as a building material in Madrid and surrounding areas, as well as in France. It has been nominated as a Global Heritage Stone Resource (Freire-Lista et al., 2015b) given its traditional use in emblematic monuments and its export potential. The literature contains many references to its origin tectonic deformation (Villaseca et al., 2009), historic quarries, petrological characteristics, durability and use in buildings (Fort et al., 2010, 2013; Pérez-Monserrat et al., 2013).

The samples were taken from a historic granite quarry at Alpedrete (40°39'45.7"N 4°00'47.7"W), approximately 40 km northwest of Madrid. A quarryman cut a single block in the traditional manner, along the orthogonal rift, grain and hardway planes (Figure 2). Three chips (<1 cm^2) were also taken from each splitting plane for electron microscope observation. Surface micro-roughness was measured on each splitting plane (rift, grain, hardway) of the traditionally quarried block. Ten 7×7×7 cm specimens were cut from the block by disk saw at low speed (120 rpm) and low voltage. A thin section was taken on each splitting plane from one of the specimens for observation under an optical microscope. The following parameters were measured in the remaining nine specimens: surface hardness, P- and S-wave velocity (Vp and Vs), capillary absorption and air permeability. The tests were conducted on the three splitting planes on all nine specimens, after they had been dried at 70 °C to a constant weight (<1 ‰ variation in two consecutive weighings over 24 h) and cooled to ambient temperature in a desiccator with silica gel.

2.2 Analytical techniques

2.2.1 Optical surface micro-roughness (OSR)

Optical surface micro-roughness was measured non-destructively along the three splitting planes (R, G and HW) on the unsawn, unpolished sample. The TRACEiT handheld roughness meter used delivered high precision 3D topography with a resolution of 1 micrometre on the Z axis and 2.5 micrometres on the X and Y axes. Measuring field dimensions were 5×5 mm. A total of 2000 data points on the X/Y axes were recorded for each measurement. Roughness parameters were computer calculated as laid down in European and international standard DIN EN ISO 4287. These Roughness parameters are R_a, it is the arithmetic mean of the absolute values of the deviations from the mean; R_q, it is the square root of the deviation and R_z, it is the sum of the vertical distances between the five highest and five lowest values found for the sample.

Fifteen micro-roughness readings were taken on the freshly cut, unsawn, unpolished surface along planes R, G and HW and the mean was calculated for each plane.

2.2.2 Scanning electron microscope (SEM)

The morphological study of the surfaces on small Alpedrete granite chips (planes R, G and HW) that were unexposed prior to detachment (hereafter ‘unexposed surfaces’) was conducted with a JEOL JSM 6400 scanning electron microscope. The operating conditions were: voltage acceleration, 0.2^{-40} kV; current, 6×10^{10} A; vacuum, 10^{-5} Torr; resolution, 35 Ǻ at a distance of 8 mm; and voltage acceleration for imaging, 35 kV and 20 kV. The microscope was used in conjunction with an Oxford Inca energy dispersive spectrometer (EDS) with a resolution of 133 eV to 5.39 kV. The samples (<1 cm^3) were sputter coated with gold to enhance their conductivity; observation focused primarily on the microcracks.

2.2.3 Fractography

Three thin sections, one parallel to each plan (R, G and HW) were taken from a Alpedre granite sample soaked in fluorescine (Figure 3).

The samples were petrographically characterised on an Olympus BX 51 polarised light microscope (PM) attached to an Olympus DP (6 V / 2.5 Å) digital camera running on (version 3.2) DP-Soft Olympus software. The microcracks were characterised with the same instruments using an Olympus U-RF-T mercury lamp for fluorescence microscopy (FM).

The three thin sections were micrographed under polarised and mercury lamp light. A mosaic covering approximately 10 cm^2 was built with the micrographs of each thin section and microscopic technique. Polarised microscopy was used for the mineralogical study and fluorescent microscopy to study the microcracks.

These two mosaics (obtained with crossed polarised light and mercury lamp or fluorescent light) for each plane (R, G and HW) were then merged into a single image over which five equidistant 15 mm parallel lines have been drawn were divided into two groups. The number of microcracks cutting across these lines was counted to calculate linear microcrack density (Sousa, 2014). The microcracks were grouped by the type of crystal (quartz (Qz), plagioclase

(Pl), potassium feldspar (K-Fsp) or biotite mineral (Bt)) affected and their location (inter- or intracrystalline). Intracrystalline microcracks appears as straight lines in the analysed thin sections. They were divided into two groups, those parallel to plane R and no parallel to plane R. The former were regarded as exfoliation microcracks. Linear microcrack density was determined by counting the microcracks and dividing the total number by the sum of the length of all the lines (75 mm). The distance between exfoliation microcracks was also measured and the mean found.

2.2.4 Surface hardness

Surface hardness was measured with an Equotip 3(D) electronic rebound tester, which, with an impact energy of just 11 Nmm, did not harm the samples (Kawasaki et al., 2002; Aoki and Matsukura, 2007; Viles et al., 2011). Ten readings were taken on each sawn side parallel to planes R, G and HW of all nine cubic Alpedrete granite specimens and the mean for each plane was calculated. The measurements were taken with the instrument facing downward, vertically and perpendicularly to the plane and at least 5 mm from the edge to avoid possible edge effects. Care was also taken to not measure near visible hollows on the rock surface.

Hardness is expressed here as the Leeb (L) or Leeb hardness (LH) number, i.e., the ratio of the rebound velocity to the impact velocity multiplied by 1000.

2.2.5 Ultrasound wave velocity (V_p and V_s)

V_p ultrasonic pulse measurement is a very useful technique for determining microcracks (Vasconcelos et al., 2009). In this study V_p was measured as specified in Spanish and European standard UNE EN 14579, 2007, using a CNS Electronics PUNDIT pulser (precision: ±0.1 μs). Its 11.82 mm diameter, 1 MHz transducers were secured to the Alpedrete granite surface with a carboxymethyl cellulose glue and water.

S-wave velocity was measured on a Panametrics high voltage Model 5058 PR pulser-receiver connected to a phosphorous digital Tektronix oscilloscope. Its 25.4 mm diameter, 0.5 MHz V151 Panametrics transducers were secured to the samples with a gel containing 80 % sugar (primarily fructose and glucose) and (approximately) 20 % water. The pulse frequency used was 20 Hz with 200 Ω attenuation.

V_p and V_s were measured four times each on the sides parallel to planes R, G and HW of all nine cubic specimens on opposite faces (direct measurement). The mean for each side was calculated.

2.2.6 Capillarity water absorption

The capillarity test was conducted as laid down in Spanish and European standard UNE-EN 1925, 1999, with slight modifications. The specimens were weighed after drying (m_d) to a precision of 0.01 g and the area of the base (expressed in m^2) was calculated to a precision of 0.1 mm.

The nine Alpedrete granite specimens were placed in a tank with a 3±1 mm film of water: three resting on plane R, three on plane G and three on plane HW. The tank was then lidded with an air-tight seal to prevent evaporation. The specimens were periodically weighed to determine the amount of water absorbed during the 38 day trial, finding the mean for each group of three specimens. The 24 hour and 38 day water absorption coefficients (Weight of water gain per area by time) were calculated for each splitting plane of the Alpedrete granite.

2.2.7 Air permeability

Air permeability was measured with a hand-held, non-destructive NER TinyPerm II minipermeater (MTP). The findings, i.e., the time it took the granite to absorb a given volume of air, were then converted into air permeability expressed in millidarcys (mD).

The instrument's 22 mm rubber nozzle was pressed against the rock specimen to ensure airtightness. As air was withdrawn from the rock it was expelled through the 9 mm aperture on the nozzle, connected to a microcontroller unit that monitored the transient vacuum pulse created at the sample surface. After the vacuum filled up with air, the unit calculated the characteristic value of the parameters measured. Its software delivered a value t (time), related to air permeability K (in millidarcys), as per Equation (1):

$$t = -0.8206 \times \log_{10}(K) + 12.8737 \qquad (1)$$

Permeability was measured with the instrument in a static vertical position on the flat surface of each splitting plane, to which it was secured with a clamp to ensure uniform contact pressure during the test.

Five permeability readings were taken on each splitting plane in the nine specimens. Lastly, the mean of the readings was found for each plane (R, G and HW).

2.2.8 Anisotropy

Anisotropy in rock depends on the specific physical property measured. The anisotropy index (dM) (Guydader and Denis, 1986) was obtained for each of the petrophysical properties, measured in the three directions (R, G and HW).

$$dM = [1 - (2\ PP_{min} / (PP_{mean} + PP_{max}))] \times 100 \qquad (2)$$

where PP_{max}, PP_{min} and PP_{mean} are respectively the maximum, minimum and mean values of the petrophysical property measured in the three spatial directions.

3. RESULTS

3.1 Optical surface micro-roughness

Optical surface micro-roughness varied in each splitting plane. As shown in Table 2, the parameters analysed were highest in plane HW and lowest in plane R.

3.2 Scanning electron microscopy (SEM)

Figure 4 shows the (uncut and unpolished) unexposed surfaces along planes HW (a) and R (b) in Alpedrete granite. The HW unexposed surface exhibited an *en echelon* pattern: the microcracks tended to be perpendicular, generating a rough surface. The micrograph of plane R in (b), in contrast, showed a flatter surface.

3.3 Fractography

Figure 5 shows the micromosaics made from the thin sections taken in the three Alpedrete granite splitting planes. Figure 5R is the micromosaic parallel to plane R, in which most of the microcracks were found to be intercrystalline. Figure 5G, the micromosaic parallel to the grain plane, exhibited a considerable number of straight and pseudo-parallel intracrystalline microcracks. The micromosaic parallel to the hardway plane depicted in Figure 5HW had straight, parallel microcracks, although they were smaller than the exfoliation microcracks parallel to plane R.

Intracrystalline microcracks were observed primarily in the G and HW planes; in other words, as they were parallel to plane R, the thin section running in that direction would not cut across intracrystalline microcracks (table 3).

By mineral content, quartz accounted for most of the microcracks, followed by plagioclase, potassium feldspar and the biotite group minerals. The linear exfoliation microcrack density was highest for the grain plane and lowest for the rift plane; the exfoliation microcracks were spaced at a mean distance of 0.69 mm.

3.4 Surface hardness

The surface hardness data for each plane of Alpedrete granite are listed in Table 4. The three planes exhibited similarly high L values, with the highest recorded for plane HW and the lowest for plane R. The anisotropy index for hardness was found to be dM=2.8 %.

3.5 Ultrasonic wave velocity (V_p and V_s)

The V_p and V_s values are given in Table 5. The P-wave velocity reading perpendicular to plane R was 17.5 % lower than when the direction was perpendicular to plane HW and 12.2 % lower than when perpendicular to plane G. The V_s value measured perpendicular to plane R was 2 % lower than when perpendicular to plane HW and 5.7 % lower than when perpendicular to plane HW. The anisotropy index, dM, for V_p was 12.9 % and for V_s 3.7 %.

3.6 Capillary water absorption

The granite studied exhibited a very low water absorption coefficient. The data in Figure 6 and Table 6 for the capillarity coefficient on the first and 38th days show that the capillary coefficient declined and anisotropy rose over time.

3.7 Air permeability

Air permeability in granite is favoured by microcracks and conditioned by their distribution.

The air permeability values obtained were very low, nearly negligible in plane R (0.4 millidarcys) and somewhat higher for planes HW (2.2 millidarcys) and G (2.5 millidarcys). The anisotropy index, dM, for air permeability was calculated to be 83.0 %.

4 DISCUSSION

Anisotropies due to microstructure, textural and mineral orientation or stratification (Siegesmund, 1996) can determine the splitting planes in some types of rocks. However, like many other building granites around the world, Alpedrete granite does not present a marked mineralogical orientation (figures 3 and 5) and ease of splitting is determined by exfoliation microcracks. Rift plane, with its coalescent coplanar exfoliation microcracks, affords a straighter and smoother cut than the other granite orientations (Yin and Wong Chau, 2014).

Exfoliation microcracks may be inter-, intra- or transcrystalline. In Alpedrete granite exfoliation microcracks were predominantly intracrystalline, straight and not always interconnected. Those features distinguished them from the open microcracks found at depths of hundreds of metres, attributable to tectonic forces and so meaningful in hydrocarbon and water prospecting (Hooker et al., 2015).

Intercrystalline microcracks are formed more readily when the crystal surface is oriented perpendicularly to stress-release because the boundary between crystals may be brittle. In biotites, when the exfoliation planes are perpendicular to stress-release, they widen more readily (Siegesmund et al., 1991). Macles and perthites may exert microstructural control in feldspars, and the alteration of plagioclase cores to form sericite modifies exfoliation microcrack propagation due to the more plastic behaviour of the latter mineral. In contrast, no clear microstructural control of microcrack development is present in quartz crystals and in this study quartz was the crystal with the largest number of exfoliation microcracks. Consequently, a larger fraction of quartz crystals generates a larger rift. Although each stone has a characteristic rift, studies on Inada granite (Chen et al., 1999) also showed that intercrystalline microcracks prevailed in the rift plane, while the grain plane concurred with the orientation of the intracrystalline microcracks.

In accelerated ageing tests on granite (Freire-Lista et al., 2016) pre-existing microcracks were observed to play an instrumental role in freeze-thaw- or thermal shock-induced decay (Vázquez et al., 2015; Liu et al., 2015; Jyh-Chau et al., 2015). Few accelerated ageing tests on granite have been performed considering exfoliation microcracks. Granite samples have been cutted according to the splitting planes in this study and exfoliation microcracks have been differentiated from others microcracks. The orientation of exfoliation microcracks should be borne in mind, both in ancient ashlars often oriented in keeping with these microcracks or in cladding on today's buildings. That is why the samples used for ageing tests should be cut according to the splitting planes to reproduce the orientation of historic granite ashlars.

As shown by the micromosaics in Figure 5, the length of exfoliation microcracks depends on the splitting plane and is shorter in the hardway than in the grain plane. These microcracks are depicted schematically as ellipsoids in Figure 7. Plane R is parallel to the largest and median axes of the ellipsoids, plane G to the smallest axis and plan HW to the smallest and median axes. It has been observed that the exfoliation microcracks are small and not connected.

Bromblet et al. (1996) reported that granite scaling is determined by petrophysical factors including total porosity, capillary water absorption kinetics, evaporation kinetics, air permeability and water vapour conductivity, which are also the source of the greater durability of crystalline rocks with small crystals. They made no mention of the relationship between exfoliation microcracks and these properties, however. Exfoliation microcracks play a significant role in the hydraulic properties of granites (Maréchal et al., 2004). Capillary absorption favours salt crystallisation- or freeze-thaw-induced material decay in much granitic ancient monuments (Momeni et al., 2015). Alpedrete granite exhibited very low capillary absorption, although the capillarity coefficient was higher on the first day and subsequently declined. That finding may be attributed to the narrow opening and scant interconnection between the microcracks. They are larger and more interconnected in plane G (Figures 5 and 7), however.

Further to the micro-roughness findings, the unexposed plane parallel to R was the smoothest, followed by the plane parallel to G, while plane HW was the roughest. Jessel et al. (1995) and Fujii et al. (2007), using digital photogrammetric techniques, reported results consistent with the present findings. In traditional quarries splitting planes could consequently be identified by touch: plane R, the smoothest, was the easiest to hew and the one that delivered an essentially flat surface (Figure 4). Greater surface roughness yields a greater specific surface, favouring interaction with the agents of decay (Moses et al., 2014). The (rougher) surfaces perpendicular to R may be subject to more microbial colonisation and intense soiling.

Microcracks affect granite fragility (Přikryl, 2006; Wong and Einstein, 2009; Cuccuru et al., 2012) and even induce pathologies such as scaling or flaking, preferentially parallel to plane R in historic ashlars (Freire-Lista and Fort, 2016b).

Each petrophysical property in the Alpedrete granite studied here exhibited a different anisotropy index. Takemura et al. (2003) and Takemura and Oda (2004) studied the splitting planes of granite to determine how open microcracks affected anisotropy. Using ultrasonic wave velocity and uniaxial compression tests, they observed that anisotropy was caused by pre-existing open, not by pre-existing closed, microcracks. In ascending order of their anisotropy index, the properties analysed here can be ranked as follows: first day capillarity (dM=0.1%); surface hardness (dM=2.8 %); V_s (dM=3.7 %); V_p (dM=12.9 %); capillarity from day 2 to day 38 (dM=18 %); air permeability (dM=83 %).

Oriented microcracks affect ultrasound wave velocity (Siegesmund et al., 1993). Nonetheless, the anisotropy of ultrasound wave velocity in stone deep into the crust where confining pressure is high and no exfoliation microcracking is present is controlled by preferred mineral orientation (texture) and tectonic fractures.

The three planes exhibited similarly high surface hardness values. The low anisotropy of this property is due to the fact that the exfoliation microcracks are very narrow and not connected, the samples were unaltered and without textural orientation.

According to readings reported by Lin (2002) in a sound granite with characteristics similar to those of Alpedrete granite, the lowest V_p value was perpendicular to plane R, an indication that the many exfoliation microcracks parallel to plane R induced a decline in $V_{p.}$ Inasmuch as V_p is lowest in the direction perpendicular to plane R, granite used in building façades should be oriented with plane R parallel to the ground to enhance its durability. In such a position its mechanical strength is greater (Sajid and Arif, 2015) and capillary absorption lower. Although that arrangement lowers stone resistance to rainwater absorption, the result is much less aggressive than in the capillary suction of salt-bearing ground water.

The low air permeability observed in Alpedrete granite denotes high resistance to air pollution-induced decay. Polluted air penetration is confined to very shallow depths, affecting the surface only, provided the stone is positioned on plane R where permeability is lowest. The higher permeability in any other arrangement would intensify air pollution-induced decay.

Another consideration not addressed until recently in connection with granite exfoliation microcracks is the effect in cutting parameters of dimension granites (Yurdakul, 2015) graffiti cleaning (Pozo-Antonio et al., 2016) or damage by acidic chemical solutions (Miao et al., 2016). The microcrack-determined anisotropy of granite petrophysical properties also affects the readiness with which splitting planes can be damaged.

5 CONCLUSIONS

Requisite to an understanding of decay in ashlars and sculptures hewn from crystalline rock is the study of the orientation and distribution of exfoliation microcracks, which are determined by the position of the stone in the quarry. The microscopic techniques and petrophysical analysis show that exfoliation microcracks play a significant role in granite anisotropy and that the splitting planes are controlled by these types of microcracks. Fluorescence microscopy allowed the study of exfoliation microcrack characteristics. The thin section parallel to the rift plane showed an abundance of intercrystalline microcracks, whereas the thin sections parallel to grain and hardway planes most of such microcracks were intracrystalline, straight and parallel to the ground surface, which were exfoliation microcracks.

The orientation of exfoliation microcracks determines the granite ashlars durability. The angle between the splitting plane and the exfoliation microcracks defines the surface micro-roughness in granite. The grain and hardway planes are rougher than the rift plane and hence more vulnerable to soiling and microbial colonisation. The ultrasonic P-wave velocity, air permeability as well as capillary water absorption is lower in the perpendicular direction to the rift plane. The penetration of conservation treatments consequently varies depending on whether they are applied to the rift or the other two planes.

Samples of crystalline rocks without texture orientation should be cut according to exfoliation microcracks, especially when ageing tests are to be conducted to reproduce the orientation of historic ashlars used in built heritage. Also, the direction of exfoliation microcracks should be taken into consideration when granite cladding slabs are cut and polished. The face side must be the surface parallel to such microcracks. If the face side is perpendicular to the exfoliation microcracks, the cladding slab will be more brittle and polishing will be worse.

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REFERENCES

Aoki, H., Matsukura, Y., 2007. A new technique for non–destructive field measurement of rock–surface strength: an application of the Equotip hardness tester to weathering studies. Earth Surface Processes and Landforms. 32, 1759–1769.

Baltuille, J.M, Alfonso de Molina, F., Gazapo, C., Vivar, V., 2004. Primeros resultados de una nueva lanza térmica de gas (gas flame–jet) de cara a sus aplicaciones en canteras de granito. Ventajas medioambientales. Geotemas (Madrid). 6 (1), 247–250.

Bromblet, P., Bernabé, E., Vergès–Belmin, V., 1996. Petrophysical investigation on the origin of scaling of a microgranular magmatic rock associated to granite in the monuments from Brittany (France)–Environmental Protection and Conservation of the European Cultural Heritage– Degradation and Conservation of Granitic Rocks, European Commission. 73–78.

Catlos, E., Baker, C., Sorensen, S., Jacob, L., Çemen, I., 2011. Linking microcracks and mineral zoning of detachment–exhumed granites to their tectonomagmatic history: Evidence from the Salihli and Turgutlu plutons in western Turkey (Menderes Mass). Journal of Structural Geology. 33, 951–969.

Chen, Y., Nishiyama, T., Kusuda, H., Kita, H., Sato, T., 1999. Correlation between microcrack distribution patterns and granitic rock splitting planes. International Journal of Rock Mechanics and Mining Sciences. 36, 535–541.

Chigira, M., 2001. Micro–sheeting of granite and its relationship with landsliding specifically after the heavy rainstorm in June 1999, Hiroshima Prefecture, Japan. Engineering Geology. 59, 219–231.

Cuccuru, S., Casini, L., Oggiano, G., Cherchi, G.P., 2012. Can weathering improve the toughness of a fractured rock? A case study using the San Giacomo granite. Bulletin of Engineering Geology and the Environment. 71, 557–567.

DIN EN ISO., 4287., 1984. International Organization for Standardization. Surface roughness terminology: Part 1. Surface and its parameters.

Fort, R., Alvarez de Buergo, M., Perez-Monserrat, E.M., Varas, M.J., 2010. Characterisation of monzogranitic batholiths as a supply source for heritage construction in the northwest of Madrid: Engineering Geology. 115, 149–157.

Fort, R., Varas, M.J., Alvarez de Buergo, M., Freire-Lista, D.M., 2011. Determination of anisotropy to enhance the durability of natural stone: Journal of Geophysics and Engineering. 8, 132–144.

Fort, R., Alvarez de Buergo, M., Pérez-Monserrat, E.M., Gómez-Heras, M., Varas-Muriel, M.J., Freire-Lista, D.M., 2013. Evolution in the use of natural building stone in Madrid, Spain: Quarterly Journal of Engineering Geology and Hydrogeology. 46, 421–429.

Freire-Lista, D.M., Fort, R., Varas-Muriel, M.J., 2015a. Freeze–thaw fracturing in building granites. Cold Regions Science and Technology. 113, 40–51.

Freire-Lista, D.M., Fort, R., Varas-Muriel, M.J., 2015b. Alpedrete granite (Spain). A nomination for the "Global Heritage Stone Resource" designation. Episodes. 38 (2), 106–113.

Freire-Lista, D.M, Fort, R., 2016a. The Piedra Berroqueña region: candidacy for Global Heritage Stone Province status. Geoscience Canada. 43 (1), 43–52.

Freire-Lista, D.M., Fort, R., 2016b. Causes of scaling on brush hammered heritage ashlars. A case study: Plaza Mayor of Madrid (Spain). Environmental Earth Sciences. 75, 932.

Freire-Lista, D.M., Fort, R., Varas-Muriel, M.J., 2016. Thermal effects–induced microcracking in building granite. Engineering Geology. 206, 83–93.

Fujii, Y., Takahashi, M., Hori, S., 2007. Three–dimensional topography of fracture surfaces obtained by a digital photogrammetric technique. International Journal of the Japanese Committee for Rock Mechanics. 3 (1), 31–36.

García-Rodríguez, M., 2015. Erosión y exhumación de bloques graníticos en La Pedriza del Manzanares, España. Evolución histórica a partir de dataciones relativas. Revista Mexicana de ciencias geológicas. 32 (3), 492–500.

Goodman, R.E., 1993. Engineering Geology. New York: John Wiley and Sons.

Gómez-Heras, M., McCabe, S., Smith, B.J., Fort, R., 2009. Impacts of Fire on Stone–Built Heritage: an Overview. Journal of Architectural Conservation. 15 (2), 47–58.

Gorbatsevich, F.F., 2003. Decompaction mechanism of deep crystalline rocks under stress relief. Tectonophysics. 370, 121–128.

Guydader, J., Denis, A., 1986. Propagation des ondes dans les roches anisotropes sous contrainté evaluation de la qualité des schistes ardoisiers, Bulletin of Engineering Geology and the Environment. 33, 49–55.

Hooker, J.N., Larson, T.E., Eakin, A., Laubach, S.E., Eichhubl, P., Fall, A., Marrett R., 2015. Fracturing and fluid flow in a sub–décollement sandstone; or, a leak in the basement Journal of the Geological Society. 172, 428–442.

Jessell, M.W., Cox, S.J.D., Schwarze, P., Power, W.L., 1995. The anisotropy of surface roughness measured using a digital photogrammetric technique, Special Publication of Geological Society, London. 92, 27–37.

Jyh-Chau Liou, J.C., Tien, N.C., 2016. Estimation of the thermal conductivity of granite using a combination of experiments and numerical simulation. International Journal of Rock Mechanics and Mining Sciences. 81, 39–46.

Kawasaki, S., Tanimoto, C., Koizumi, K., Ishikawa, M., 2002. An attempt to estimate mechanical properties of rocks using the Equotip Hardness tester. Journal of Japan Society of Engineering Geology. 43, 244–248.

Lin, W., 2002. Permanent strain of thermal expansion and thermally induced microcracking in Inada granite. Journal of geophysical research. 107 (B10), 2215.

Liu, Q., Huang, S., Kang, Y., Liu, X., 2015. A prediction model for uniaxial compressive strength of deteriorated rocks due to freeze–thaw. Cold Regions Science and Technology. 120, 96–107.

Maréchal, J.M., Wyns, R., Lachassagne, P., Subrahmanyam, K., 2004. Vertical anisotropy of hydraulic conductivity in the fissured layer of hard–rock aquifers due to the geological structure of weathering profiles. Journal of the Geological Society of India. 63 (5), 545–550.

Miao, S., Cai, M., Guo, Q., Wang, P., Liang, M., 2016. Damage effects and mechanisms in granite treated with acidic chemical solutions. International Journal of Rock Mechanics & Mining Sciences. 88, 77–86.

Momeni, A., Khanlari, G.R., Heidari, M., Bagheri, R., Bazvand, E., 2015. Assessment of physical weathering effects on granitic ancient monuments, Hamedan, Iran. Environmental Earth Sciences. 74, 5181–5190.

Moses, C., Robinson, D., Barlow, J., 2014. Methods for measuring rock surface weathering and erosion: A critical review. Earth–Science Reviews. 135, 141–161.

Pérez-Monserrat, E.M., Alvarez de Buergo, M., Gómez-Heras, M., Varas-Muriel, M.J., Fort, R., 2013. An urban geomonumental route focusing on the petrological and decay features of traditional building stones used in Madrid, Spain: Environmental Earth Sciences. 69, 1071–1084.

Porsani, J.L., Sauck, W.A., Júnior, A.O.S., 2006. GPR for mapping fractures and as a guide for the extraction of ornamental granite from a quarry: A case study from southern Brazil. Journal of Applied Geophysics. 58, 177–187.

Pozo-Antonio, J.S, Rivas, T., Fiorucci, M.P., López, A.J., Ramil, A., 2016. Effectiveness and harmfulness evaluation of graffiti cleaning by mechanical, chemical and laser procedures on granite. Microchemical Journal. 125, 1–9.

Přikryl, R., 2006. Assessment of rock geomechanical quality by quantitative rock fabric coefficients: Limitations and possible source of misinterpretations. Engineering geology. 87, 149–162.

Sajid, M., Arif, M., 2015. Reliance of physico–mechanical properties on petrographic characteristics: consequences from the study of Utla granites, north–west Pakistan. Bulletin of Engineering Geology and Environment. 74 (4), 1321–1330.

Sajid, M., Coggan, J., Arif, M., Andersen, J., Rollinson, G., 2016. Petrographic features as an effective indicator for the variation in strength of granites. Engineering Geology. 202, 44–54.

Siegesmund, S., Kern, H., Vollbrecht, A., 1991. The effect of oriented microcracks on seismic velocities in an ultramylonite. Tectonophysics. 186 (3–4), 241–251.

Siegesmund, S., Vollbrecht, A., Pros, Z., 1993. Fabric changes and their influence on P–wave velocity patterns–examples from a polyphase deformed orthogneiss. Tectonophysics. 225 (4–30), 477–492.

Siegesmund, S., 1996. The significance of rock fabrics for the geological interpretation of geophysical anisotropies. Geotekton. Forsch. 85, 1–123.

Sousa, L.M.O., 2007. Granite fracture index to check suitability of granite outcrops for quarrying. Engineering Geology. 92 (3–4), 146–159.

Sousa, L.M.O., 2010. Evaluation of joints in granitic outcrops for dimension stone exploitation. Quarterly Journal of Engineering Geology and Hydrogeology. 42, 85–94.

Sousa, L.M.O., 2014. Petrophysical properties and durability of granites employed as building stone: a comprehensive evaluation. Bulletin of Engineering Geology and the Environment. 73, 569–588.

Sousa, L.M.O., Oliveira, A.S., Alves, I.M.C., 2016. Influence of fracture system on the exploitation of building stones: the case of the Mondim de Basto granite (north Portugal). Environmental Earth Sciences. 75, 39.

Takemura, T., Golshani, A., Oda, M., Suzuki, K., 2003. Preferred orientations of open microcracks in granite and their relation with anisotropic elasticity. International Journal of Rock Mechanics & Mining Sciences. 40, 443–454.

Takemura, T, Oda, M., 2004. Stereology–based fabric analysis of microcracks in damaged granite. Tectonophysics. 387, 131–150.

UNE–EN, 1925, 1999. Natural stone test method. Determination of water absorption coefficient by capillarity.

UNE–EN, 14579, 2007. Natural Stone Test Methods–Determination of Sound Speed Propagation. AENOR, Madrid.

Vasconcelos, G., Lourenço, P.B., Alves, C.A.S., Pamplona, J., 2009. Compressive Behavior of Granite: Experimental Approach. Journal of Materials in Civil Engineering. 21(9), 502–511.

Vázquez, P., Shushakova, V., Gómez-Heras, M., 2015. Influence of mineralogy on granite decay induced by temperature increase: Experimental observations and stress simulation. Engineering Geology. 189, 58–67.

Viles, H., Goudie, A., Grab, S., Lalley, J., 2011. The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. Earth Surface Processes and Landforms. 36, 320–333.

Villaseca, C., Bellido, F., Perez-Soba, C., Billstrom, K., 2009. Multiple crustal sources for posttectonic I–type granites in the Hercynian Iberian Belt: Mineralogy and Petrology. 96, 197–211.

Wong, L.N.Y., Einstein, H.H., 2009. Systematic evaluation of cracking behavior in specimens containing single flaws under uniaxial compression. International Journal of Rock Mechanics & Mining Sciences. 46, 239–249.

Yarahmadi, R., Baghepour, R., Sousa, L.M.O., Taherian, S.G., 2015. How to determine the appropriate methods to identify the geometry of in situ rock blocks in dimension stones. Environmental Earth Sciences. 74(9), 6779–6790.

Yin, P., Wong Chau, K.T., 2014. Coalescence of two parallel pre-existing surface cracks in granite. International Journal of Rock Mechanics & Sciences. 686, 6–84.

Yurdakul, M., 2015. Effect of cutting parameters on consumed power in industrial granite cutting processes performed with the multi-disc block cutter. International Journal of Rock Mechanics & Mining Sciences. 76, 104–111.

Ziegler, M., Loew, S., Bahat, D., 2014. Growth of exfoliation joins and near–surface stress orientations inferred from fractographic markings observed in the upper Aar valley (Swiss Alps). Tectonophysics. 626, 1–20.