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# Salt Weathering on Buildings and Stone Sculptures

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# Artificial Weathering of Portuguese Granites Exposed to Salt Atmosphere: Variations of Physico-Mechanical Properties

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ABSTRACT

*Five types of granites [SPI, Cinzento Santa Eulália (CE), Cinzento Arronches (CA), Rosa Santa Eulália (RE) and Rosa Arronches (RA)] from the Portalegre region (SE Portugal) have been extensively used as ornamental and building stones. Sound samples of these granite types were exposed to 150 cycles of sodium chloride atmosphere (SCA). Petrographic and major physico-mechanical properties (water absorption under vacuum, water absorption at atmospheric pressure and uniaxial compressive strength) were determined, before and after the SCA exposure, in order to observe variations in the characteristic values. The results revealed a decrease in the characteristics of all the properties evaluated. Although the data obtained so far suggests that variations in the mean values of physico-mechanical properties due to salt crystallization are smaller on fine to medium granites and larger on medium to coarse granites, the same can not be said about their chromatic changes.*

Keywords: granite, dimension stone, weathering, salt, physico-mechanical properties

## 1 INTRODUCTION

Granite is, among the different rock materials used in building construction, also susceptible to the action of soluble salts. The weathering caused by soluble salts is present in coastal areas (sodium chloride is the principal salt in maritime aerosols). Arenization caused by the sodium chloride crystallization-dissolution process results in the loss of grains leading to serious damage to architectural and historical buildings. Portugal has a long tradition in the use of granite as building material. Some Portuguese cities such as Oporto and Évora are good examples of this tradition and have been classified as cultural World Heritage Sites by UNESCO. There is also a considerable amount of granite masonry in residential buildings in rural areas.

In the literature, there are a large number of studies published on granite weathering by salt crystallization. Salt mist is an important rock weathering agent. Artificial weathering caused by soluble salts obtained during laboratory tests indicates that rock alterations are mainly due to a physical process originated by crystallization or hydration of the salts. This process leads to increasing pressures on the rock pores (Doehne 1994; Doehne & Selwitz 2002; Rivas et al. 1997; Rivas et al. 2002). Salt solution penetration in rock pores and further salt expansion cause the increase of voids, followed by the removal of soluble salts and secondary minerals (Silva & Simão 2009).

Mechanical and physical weathering has also been studied by several authors emphasizing the role of micro-cracking; the generation of new and the growth of pre-existing fissures; and the influence of rift and bedding planes on the physico-mechanical properties of granitic rocks (López-Arce et al. 2010).

Weathering and durability are difficult parameters to quantify in granites, since both are usually based in visual aspects or weight loss. As such, the study of the effect of salt crystallization in the main physico-mechanical properties of granites in terms of their use as dimension stone is scarce. The main goal of the present work is to analyze the extent of change in the physico-mechanical properties of the five studied lithologies and evaluate a possible relationship with their major petrographical characteristics.

## 2 MATERIALS

The granites under study [SPI, Cinzento Santa Eulália (CE), Cinzento Arronches (CA), Rosa Santa Eulália (RE) and Rosa Arronches (RA)] are primarily quarried in the southeast Portugal, Portalegre district (Fig. 1) and processed by Granitos de Maceira (located in Sintra, Lisbon), also responsible for its national and international marketing. These granites have been widely used as ornamental and building stones, in sculpture and other applications, both in Portugal and other countries.

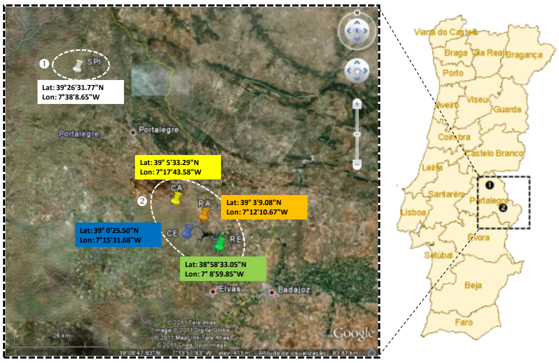


Figure 1. Geographic location of SPI (zone 1) and RA, CA, RE, CE (zone 2) granite quarries.

From the geological point of view, the SPI granite quarry is located near Alpalhão village (Portugal) in the granitic batholith of Nisa-Albuquerque (Spain), which outcrops in an area over 700 km$^2$, extending towards WNW-ESE. In the Portuguese sector, this tardi-Variscan batholith has 45 km length and a maximum width of 20 km (Borges 1994; Menéndez & Azor 2006), being discordant with the regional structures of Central Iberian Zone (ZCI) and Ossa-Morena Zone (ZOM). The SPI granite occurs in the batholith as discontinuous small patches (Fig. 2).

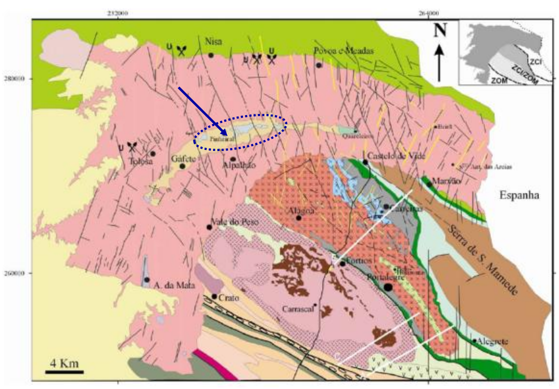


Figure 2. Geological map of the area surrounding the SPI quarry (adapted from Solá 2007).

The RA, RE, CA and CE granite quarries are located in Santa Eulália batholith. This is a plutonic complex of the late Variscan age (Menéndez et al. 2006), located in the NE part of the ZOM (Fig.3). This complex, which outcrops in an area over 300 $km^2$, displays granites which are grouped in two *facies*: an external one, showing a ring-type outcrop pattern (where RA and RE pink granites are located) and a central one (where CA and CE grey granites are located) that might have been intruded shortly after the external granite and forms a circular outcrop, being totally surrounded by the external granite (Menéndez et al. 2006).

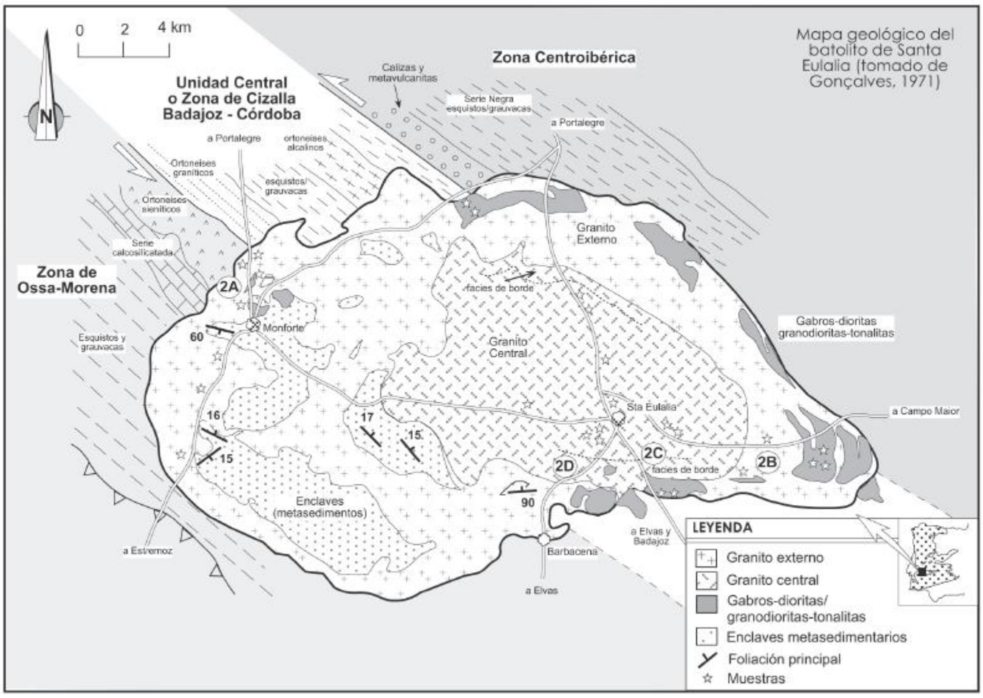


Figure 3. Santa Eulália batholith geological map (in Menéndez et al. 2006).

Table 1 displays the major petrological and mineralogical characteristics of the materials under study. The granites differ macroscopically due to their color (pinkish or grey) and also in respect to the grain size and the presence or absence of a porphyritic texture. The mineralogical composition is also different, namely the predominance of K-feldspar and plagioclase over the quartz.

Table 1. Petrographical characterization of the selected granites (Borges 1994; Moura & Leite 2010)

| Granite | Petrologic description | Mineralogy |
|---|---|---|
| RA | Coarse-grained porphyritic granite slightly pink K-feldspar in a white-grey matrix | Microcline (40%); Plagioclase (30%); Quartz (20%); Biotite (8%); Zircon, Apatite and Opaques (2%) |
| CA | Medium grained blue-grey biotite granite, slightly porphyritic | Microcline (26%); Plagioclase (33%); Quartz (35%); Biotite (5%); Muscovite, Zircon, Apatite and Sphene (1%) |
| RE | Medium to coarse biotite granite with an homogeneous pinkish color K-feldspar | Microcline (35%); Plagioclase (25%); Quartz (30%); Biotite (8%); Zircon, Apatite, Sphene, Allanite and Opaques (2%) |
| CE | Medium to fine grained biotite granite with an homogeneous grey color | Microcline (25%); Plagioclase (30%); Quartz (35%); Biotite (9%); Muscovite, Zircon, Apatite, Sphene and Opaques (1%) |
| SPI | Fine grained monzonitic biotite granite with an homogeneous bluish grey color | Microcline (25%); Plagioclase (33%); Quartz (33%); Biotite (6%); Muscovite, Zircon, Apatite, Sphene and Opaques (3%) |

## 3 METHODOLOGY, EXPERIMENTAL TESTS AND PROPERTIES

The five granite types under study have been characterized in relation to their petrographical characteristics and major physico-mechanical properties (apparent density, water absorption at atmospheric pressure, open porosity and uniaxial compressive strength), before and after the exposure to 150 cycles of an atmosphere of sodium chloride (SCA). Table 2 presents the experimental tests performed (according to European Standards for Natural Stone), for each type of rock, on 46 cubic samples (50 ± 5) mm.

Table 2. Tests performed and respective standards

| Natural Stone Test | European Standard |
|---|---|
| Determination of Uniaxial Compressive Strength | EN 1926:2006 |
| Determination of Real and Apparent Density and of Total and Open Porosity | NPEN 1936:2001 |
| Determination of Water Absorption at Atmospheric Pressure | NPEN 13755:2005 |
| Determination of Resistance to Ageing by Salt Mist | EN 14147:2003 |

### *3.1 Resistance to Ageing by Salt Mist*

According to the European Standard EN 14147:2003, seven cubic samples of each granite were placed in a controlled atmosphere salt spray chamber (Ascot S120T), electronically scheduled to produce cycles comprising 4 h of saline spray followed by 8 h of drying at (35 ± 5) ºC. The salt solution was prepared in order to obtain a concentration of (100 ± 10) $g.l^{-1}$. Every 15 cycles the samples were removed from the chamber and immersed in deionized water for a period of 5 days and then dried, weighed (in order to determine the mass variation) and visually inspected (observation of their surfaces using a binocular stereoscope Olympus SZ and documentation with photos using a Olympus SP - 500 UZ). For the purpose of this work a total of 150 cycles (75 days) were performed.

### *3.2 Water Absorption at Atmospheric Pressure*

This test was performed on twelve cubic samples of each lithology according to the European Standard NPEN 13755:2005 in order to determine the water absorption at atmospheric pressure. In this test, the samples were dried until constant mass and then the weight was recorded. After this, they were immersed in water for 48 h; after, they were removed and cleaned with a damp cloth and weighed again. Every 24 h the same procedure was repeated until constant saturated mass was reached. Following the same procedure, the test has been also performed on seven cubic samples, again for each type of granite, after 150 cycles of exposure to salt mist. The water absorption was determined and compared with the values obtained for the samples before the SCA test.

### *3.3 Apparent Density and Open Porosity*

Twelve cubic samples of each lithology were tested according to the European Standard NPEN 1936:2001. The samples, dried until they reached constant weight, were placed in a vacuum chamber and kept at 2 kPa depression for 24 h. They were then immersed in deionized water and remained depressed for over 24 h. After this time, the pressure has been increased to normal atmospheric pressure and the samples remained immersed for another 24 h. Later on, their weights were recorded, immersed and saturated, in order to determine the values of the properties mentioned above. This test was also accomplished on seven cubic samples, for each lithology under study, after the exposure to 150 cycles of salt mist, in order to compare the results with those obtained for the samples before the SCA test.

### *3.4 Uniaxial Compressive Strength*

In order to evaluate the resistance to the uniaxial compressive strength in the granites under study, fifteen samples of each granite type were subjected to uniaxial compressive strength test according to the European Standard EN 1926:2006. This test was also performed on seven samples, for each type of granite, after the exposure to 150 cycles of salt mist, in order to evaluate any variation of this property due to the artificial weathering. In this work, the five types of granites were assumed to be homogeneous, with random orientation of the minerals; because of this, only the direction parallel to rift plane was considered. The samples, after being dried to constant mass, were loaded continuously at a constant rate of stress of (1 ± 0.5) $MPa.s^{-1}$ up to failure; the maximum load was then recorded to the nearest 10 kN.

## 4 RESULTS AND DISCUSSION

The results obtained are expressed in Table 3 and represent the mean values obtained for the apparent density, water absorption, open porosity and uniaxial compressive strength before (B) and after (A) the SCA test, as well as the mass variation of the five types of granites after the exposure to 60 cycles and 150 cycles of salt mist.

The apparent density values of the five granites are very similar, corresponding to typical values of sound granites, ranging from 2632 $kg.m^{-3}$ for RE up to 2655 $kg.m^{-3}$ for CE. After the realization of the SCA test, a slight decrease in the values of apparent density could be observed for all the granites.

The values of water absorption at atmospheric pressure, ranging from 0.13% for RA granite up to 0.31% for RE granite, are also usual in sound granites. However, after the SCA test, there was a very significant increase in these values, especially for the coarse-grained porphyritic RA (77% increase) and for the medium grained slightly porphyritic CA (39% increase) granites.

The open porosity before the SCA test ranges from 0.4% (for RA and RE granites) up to 0.8% (in SPI and CA granites). All the granites increased their values of open porosity after the SCA test, with the exception of the fine grained SPI. The values increased from 25% for CA and RE granites to 50% for the coarse-grained porphyritic RA granite.

The values obtained before the SCA test for the uniaxial compressive strength were higher for the medium to fine grained RE, CE and SPI granites than for the coarse to medium grained RA and CA granites. After the SCA test, there was a sharp decrease in the values of uniaxial compressive strength, which corresponded to very significant levels of resistance loss. A particular resistance loss of 62% was observed for the coarse-grained porphyritic RA granite and a decrease of 41% was observed for medium to fine grained CE and SPI granites. In spite of the high resistance loss observed in the medium to fine grained granites, the worst result was observed for the RA granite, which is quite consistent with the variations obtained for this granite in some of the other accomplished tests, like the water absorption at atmospheric pressure and the open porosity.

The mass variation results, obtained during the salt mist ageing test, are similar for all five types of granites. The mass loss varies between 0.12% for SPI granite and 0.17% for CA granite, after the exposure to 60 cycles of salt mist. When the number of salt mist cycles reaches 150, percentage mass loss is more significant. In that case, values of mass loss could increase from 35% to 50%, compared to the values reached after 60 cycles.

Table 3. Mean values of mass loss (after 60 cycles and 150 cycles of salt mist), apparent density, water absorption, open porosity and uniaxial compressive strength, before (B) and after (A) the SCA test; Δ (%) is the property percentage variation (considering the results B and A), V (%) is the percentage variation coefficient and [x] is the number of samples tested

| Properties (mean values) / Lithology | | RA | CA | RE | CE | SPI |
|---|---|---|---|---|---|---|
| Apparent Density (kg.m$^{-3}$) | B | 2644 [12] V (%) = 1 | 2643 [12] V (%) = 2 | 2632 [12] V (%) = 2 | 2655 [12] V (%) = 1 | 2653 [12] V (%) = 2 |
| | A | 2627 [7] V (%) = 1 | 2626 [7] V (%) = 1 | 2613 [7] V (%) = 1 | 2632 [7] V (%) = 1 | 2651 [7] V (%) = 2 |
| | \|Δ (%)\| | 0.6 | 0.6 | 0.7 | 0.9 | 0.1 |
| Water Absorption at Atmospheric Pressure (%) | B | 0.13 [12] V (%) = 5 | 0.28 [12] V (%) = 10 | 0.31 [12] V (%) = 3 | 0.19 [12] V (%) = 1 | 0.24 [12] V (%) = 4 |
| | A | 0.23 [7] V (%) = 3 | 0.38 [7] V (%) = 17 | 0.39 [7] V (%) = 5 | 0.23 [7] V (%) = 29 | 0.27 [7] V (%) = 12 |
| | Δ (%) | 77 | 39 | 26 | 21 | 12 |
| Open Porosity (%) | B | 0.4 [12] V (%) = 30 | 0.8 [12] V(%) = 12 | 0.4 [12] V (%) = 3 | 0.5 [12] V (%) = 1 | 0.8 [12] V (%) = 2 |
| | A | 0.6 [7] V (%) = 34 | 1.0 [7] V (%) = 19 | 0.5 [7] V (%) = 7 | 0.6 [7] V (%) = 3 | 0.8 [7] V (%) = 6 |
| | Δ (%) | 50 | 25 | 25 | 20 | 0 |
| Uniaxial Compressive Strength (MPa) | B | 131 [15] V (%) = 19 | 144 [15] V (%) = 25 | 167 [15] V (%) = 30 | 175 [15] V (%) = 31 | 248 [15] V (%) = 15 |
| | A | 50 [7] V (%) = 18 | 119 [7] V (%) = 22 | 155 [7] V (%) = 35 | 103 [7] V (%) = 30 | 147 [7] V (%) = 17 |
| | \|Δ (%)\| | 62 | 17 | 7 | 41 | 41 |
| Resistance to Ageing Mass Loss (%) after 60 cycles | n.a. | 0.14 [7] V (%) = 3 | 0.17 [7] V (%) = 21 | 0.14 [7] V (%) = 7 | 0.14 [7] V (%) = 4 | 0.12 [7] V (%) = 12 |
| Resistance to Ageing Mass Loss (%) after 150 cycles | n.a. | 0.21 [7] V (%) = 3 | 0.23 [7] V (%) = 20 | 0.21 [7] V (%) = 22 | 0.20 [7] V (%) = 7 | 0.18 [7] V (%) = 17 |

In order to evaluate the petrographic changes occurred on the sample surfaces of the granites, during the exposure to 150 cycles of salt mist, a visual inspection was carried out every 15 cycles, which was also documented taking photographs under binocular stereoscope. It was possible to observe that grain contour limits, micro-fractures and cleavage traces in feldspar and biotite grains on the rock surfaces were privileged sites for salt local deposition and, as the test proceeded, expansion leading to flaking, micro-fissuring and loss of these minerals.

A B C

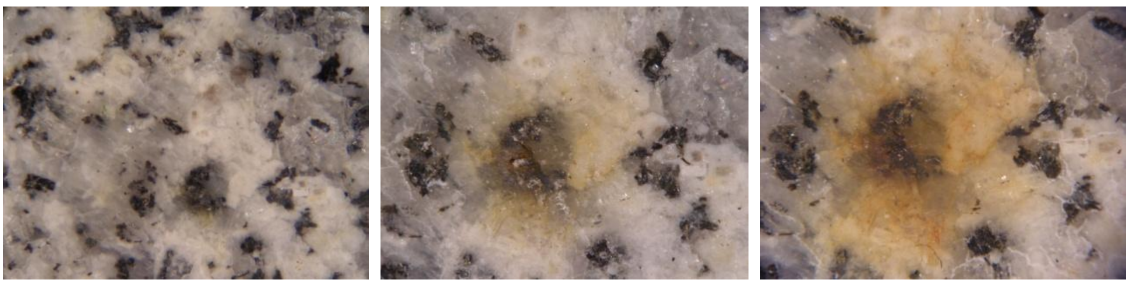

Figure 4. Photos from the same sample surface of the CE granite (x10 magnification): A) Before the SCA test; B) After 75 cycles; C) After 150 cycles.

Some major signs of corrosion and weathering observed on the sample surfaces were common for all the granites: loss of brightness, yellow tarnishing of the white minerals and oxidation presented in the form of brownish spots around the biotite grains. The pink granites (RA and RE) become less colorful due to the alteration of the K-feldspar, probably by the leaching of K. The CE granite presented the most severe change in color due to the extent of alteration in the biotite grains while a significant loss of quartz and biotite grains was also visible (Fig. 4).

## 5 CONCLUSIONS

The SCA ageing test performed on the five granites under study lead to a decrease in the granites major physico-mechanical properties. However, it can be seen that granites with medium to fine grain size exhibit lower variations in physical properties than the medium to coarse ones. Furthermore, among the medium to coarse granites, the porphyritic or slightly porphyritic ones present higher variations in physical properties. The results obtained in the uniaxial compressive strength test revealed a different behavior after the ageing by salt mist test for the medium to fine grained granites, where the variations seem to be relatively high.

The CE and SPI granites presented an unexpected decrease of 41% in the uniaxial compressive strength test. This behavior has no correlation either with the values of open porosity (after or before the SCA test) or the values of mass loss in the SCA test. The RE granite, for instance, had a mass loss increase of 50% after the SCA ageing test (like the SPI and RA granites) but had the minor variation of all the granites under study in the uniaxial compressive strength test (7% decrease). This might be related with some other petrographical characteristics not yet evaluated such as preferential crack and/or the shape of the pores.

According to some authors, the weathering process increases the width of micro-fractures and the amount of pore-shaped voids, particularly in feldspars (Sousa et al. 2005). Other authors have pointed that the crystallization pressure is higher in materials with small pores than larger pores. In addition, for stones containing small pores, mineral precipitation tends to occur preferentially in the interior of the stone rather than on the surface, leading to a decrease of internal cohesion (Rivas et al. 2010).

The higher decrease in the uniaxial compressive strength observed for RA granite may be due to the characteristics of the voids, the grain size and the texture. The prevalence of micro-fractures over the pores (concerning the type of voids), the coarse grain size and the porphyritic texture due to the K-feldspar phenocrystals may contribute to the obtained results.

The unexpected decrease in the uniaxial compressive strength observed for CE and SPI granites can be accounted for the decrease of their internal cohesion and/or possibly to preferential crack, as well as the shape of the pores. A new series of uniaxial compressive strength tests after the SCA ageing test is being performed in order to confirm these previous results.

The results of this study evidenced the importance to take into account the mineral composition, texture and structure, as well as the physical properties and performance during artificial ageing tests before applying them as dimension stones; thus, a holistic approach of the behavior of such materials will contribute to avoid unsafe constructions with negative economic and aesthetic impacts.

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