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Physical characteristics of the Oport granite related to stone decay in monuments

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Abstract

Most of the Oporto monuments, were built with the Oporto granite, a two micas, medium-grained leucogranite.

With the purpose of showing that fast imbibitions are responsible for the development of stone deterioration in the monuments, polished thin sections of granite impregnated with coloured resins, and measurements of total porosity, 48 hours porosity, mercury porosimetry, capillarity and permeability to nitrogen were made in unweathered and weathered granites of the Trindade quarry and in granitic stones of the interior walls of the Hospital Santo António.Results show that total porosity and 48 hours porosity are very low in all samples. They are different in the unweathered and weathered granites of the quarry. The stones used in the monument had different degrees of weathering. Most of the porosity is invaded by the solutions. Imbibitions are, indeed, very fast in the weathered granites of the quarry and of the monument.

Keywords

Granite, hydrothermal alteration, weathering, plagioclase, deterioration, porosity, capillarity, permeability.

Introduction

Most of the Oporto monuments, namely the Hospital de Santo António, were built with the Oporto granite, a medium-grained leucogranite, sin-tectonic considering the third phase (F3) of the Hercynic deformation (Pereira et al. 1989) and exhibit severe stone decay features with the same morphologies and mechanisms that have been observed in monuments built with limestones, marbles or sandstones.

The situation of stones in each façade of the monument plays a decisive role in the crystallization mechanism of different soluble salts and, therefore, in the type of stone deterioration (Arnold and Zehnder 1989; Jeannette and Hammecker 1992).

Begonha and Sequeira Braga (1993) refer that in the Hospital de Santo António, granular disintegration is observed essentially in the lower areas of the façades due to the rising of soluble salt solutions by capillarity from the ground. It is also observed in stones involved by large amounts of recent Portland cement mortars, which are also a source of soluble salts. Basically, plates are formed in stones where the evaporation of soluble salt solutions is not realized on the surface of the stone but in a horizon of accumulation. Black crusts are associated to sheltered areas on walls not exposed to run-off. In these areas there is an accumulation of soluble salt solutions by capillary transfer that evaporate on the surface and there is a deposition of fly ashes and soot related to air pollution.

All these deteriorations result of the concentration of soluble salts (gypsum, halite and nitrates) on the surface or near it after the migration of the solutions across the weathered granite, which proves the existence of an internal porous network in the granitic stones that allows capillary transfer of the solutions.

The petrophysic characteristics are, indeed, the most important factor that enables stone decay. The fastness of capillary transfer of the soluble salt solutions depends on the porous network geometry and on the size of the pores of the rock (Merts 1991; Jeannette and Hammecker 1993).

Since there is a wide range of the size and geometry of the pores and their interconnections, a rock porosimetry study requires several techniques, each one with its precise application field (Meng 1993).

Earlier studies concerning capillary transfer of soluble salt solutions in granites and its influence in stone decay in the monuments have been accomplished by Alves et al. (1993) and by Vicente et al. (1993).

The purpose of this paper is to study some physical characteristics of the Oporto granite (porosity, capillarity and permeability) in order to achieve a better understanding of the processes of capillary transfer of the soluble salt solutions responsible for stone deterioration in the monuments.

Materials

The Oporto granite is a two micas medium grained leucogranite composed by quartz, plagioclase, microcline, muscovite and biotite. The molecular percentages of anorthite in the plagioclases (An6.9-An14.3) have been analysed by a scanning electron microscope (SEM) equiped with a X-ray microprobe (EDS-WDS). Apatite (as an inclusion in plagioclase, microcline and in biotite) and zircon (as an inclusion in biotite) are the accessory minerals.

Samples have been taken in three different areas in the Trindade quarry being two of fresh (unweathered) Oporto granite (F1 and F2) and one of weathered granite (T).

Two samples of stones (H1 and H2), not submited to any weathering or deterioration process after the building of the monument, have been taken in two interior walls of the Hospital de Santo António.

When unweathered, the Oporto granite is homogeneous light gray but in the weathered rock it is slightly yellow.

The Oporto granite, as well as, all the two micas granites and leucogranites of Northwestern Portugal were affected by tardi-post magmatic alteration phenomena related to the albitization and muscovitization phenomena of these rocks (Dias 1987; Sequeira Braga 1988; Brilha 1992). As a consequence, the most fresh samples collected in the Trindade quarry (F1 and F2) are not really fresh but unweathered. In fact, a hydrothermal alteration was responsible for the sericitization of the plagioclase, as well as, the albitization of the microcline in the fresh granite. Fresh rock is used in this paper in the context of parent rock in a weathering profile model. In this model the unweathered rock (fresh rock) evolves successively to weathered rock, (saprock) saprolite and finally to soil (Bisdom 1967; Meunier 1980; Sequeira Braga and Paquet 1987). Besides, the samples taken in the monument correspond to the weathered granite observed in the weathering profiles in the quarry (sample T).

Indeed, kaolinite and gibbsite have been identified by X-ray diffraction (XRD) in the <2µm fraction in samples of weathering profiles (either in the saprock or in the saprolites) and also in stones of the Hospital de Santo António (H1 and H2). Their presence has been corroborated in polished thin sections using a scanning electron microscope. These two secondary minerals are characteristic of a high degree of weathering in the perhumid and temperature climate of Southwestern Atlantic Europe (Sequeira Braga 1988; Sequeira Braga et al. 1990). Granitic stones already weathered by hydrolysis of the parent minerals were, therefore, used as building materials of the monuments (Sequeira Braga et al. 1993).

SAMPLE	DRILL SAMPLE	NT %	N48 %	S48	A g/cm2/(h1/2)	B cm/(h1/2)
T	T1	2,65	2,27	0,86	0,06489	3,319
	T2	3,03	2,55	0,84	0,09481	4,661
	T3	2,61	2,31	0,89	0,07041	3,545
	T4	2,62	2,26	0,86	0,05651	3,069
	T5	2,69	2,34	0,87	0,07565	3,504
	T6	2,9	2,39	0,82	0,06015	2,996
	T7	2,95	2,54	0,86	0,09838	4,604
	T8	2,77	2,36	0,85	0,07248	3,469
	T9	2,93	2,29	0,78	0,06913	3,655
	T10	2,63	2,27	0,86	0,06435	3,384
	T11	3,06	2,38	0,78	0,06986	3,451
	T12	2,78	2,41	0,87	0,07927	3,62
H1	H44	1,93	1,72	0,89	0,04974	3,473
	H45	1,91	1,7	0,89	0,04992	3,546
	H46	2,01	1,78	0,89	0,0589	4,003
	H47	1,82	1,63	0,9	0,03985	2,967
	H48	1,96	1,53	0,78	0,03149	2,361
	H49	1.78	1,6	0,9	0,04183	3,159
H2	H50	3,13	2,71	0,87	0,08095	3,349
	H51	3.15	2,73	0,87	0,08264	3,581
	H52	3,3	2,84	0,86	0,08462	3,502
	H53	3,33	2,85	0,86	0,08635	3,721
	H54	3,59	3	0,84	0,07753	2,746
	H55	3,34	2,91	0,87	0,07258	2.619
F1	F70	0,93	0,64	0,69	0,00958	1,12
	F71	0.93	0,63	0,68	0,00989	0.953
	F72	0,95	0,65	0,68	0,00953	1.24
	F73	0,92	0,68	0,74	0,00776	1.237
	F74	0,81	0,8	0,99	0,00776	0,984
	F75	0,72	0,66	0,92	0,00741	0,862
	F76	0,78	0,75	0,96	0,00869	0.99
F2	F77	0,88	0,77	0,88	0,00996	0,906
	F96	1,14	0,96	0,84	0,02514	1,935
	F97	0,96	0,86	0,9	0,01217	1,218
	F98	0,92	0,84	0,91	0,01168	1.139
	F99	1,09	0,96	0,88	0,02184	1,365
	F100	1,09	0,97	0,89	0,03176	1,823
	F101	1,13	1	0,88	0,03376	1,988
	F102	0,91	0,78	0,86	0,01003	1,107
	F103	0,96	0,87	0,91	0,01118	0,996
	F104	0,88	0,79	0,9	0,01065	0,797
	F105	0,87	0,75	0,86	0,00999	0,914

Table 1 - Results of the petrophysic caracteristic of the unweathere samples (F1; F2) and weathered samples (T) of the aquarry and of th stones of the Hospital de Santo António (H1; H2).

After impregnation with coloured resins, polished thin sections have been executed in all samples, in order to be studied in the optical microscope and in the scanning electron microscope (SEM). The impregnation method and the coloured resins employed have been described by Mertz (1991).

All samples have been drilled with the purpose of obtaining cylindric samples of 4 cm diameter and 6 cm high to perform the porosity, capillarity and permeability tests (table I).

According to the techniques developed in the Laboratoire de Pétrophysique in the Centre de Géochimie de la Surface de Strasbourg (Mertz 1991), following tests have been executed in the cylindric samples: total porosity to water by imbibition under vacuum (N_T), 48 hours porosity by water imbibition under air and atmospheric pressure (N_{48}), capillarity - water absorption and permeability to the nitrogen under different fluid and confinement pressures. Mercury porosimetry tests have been executed in some fragments.

Microscopic studies

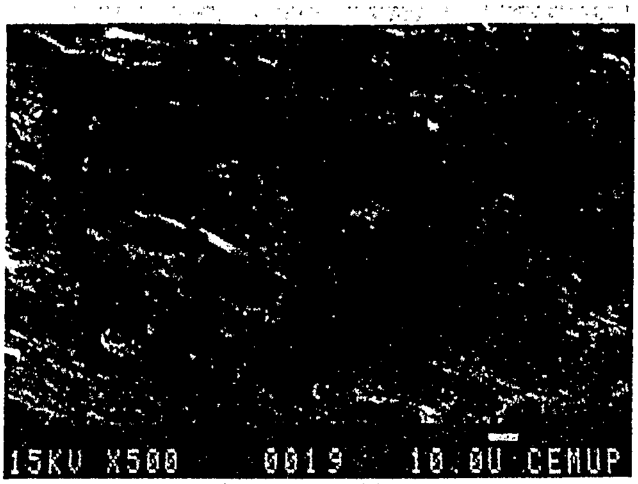
In the fresh samples, most of the porosity is a microporosity associated to the sericitization of the plagioclase, which is, indeed, crossed by a porous network impregnated with red resin, mainly fulfilling the twinned and cleavage planes. Inter and intragranular microfractures are not in a high number but are also impregnated with red resin. Macropores and thicker fractures associated to trapped porosity (fulfilled with blue resin) have not been detected.

Free porosity represents, consequently, almost all total porosity in the unweathered samples.

In the weathered samples of the quarry and of the monument, new minerals like kaolinite and gibbsite have been formed in the porous network of the plagioclases, increasing free porosity. Red resin not only fulfils the twinned and cleavage planes but also new microfractures developed by weathering of the plagioclase. The plagioclase porous network becomes denser during the weathering process (fig. 1.a). Inter and intragranular microfractures become more numerous and thicker, allowing, in some of them, the impregnation of red and blue resins.

In absolute terms trapped porosity is significant in the weathered samples but free porosity is also higher in the weathered samples than in the fresh rock. The relation between 48 hours porosity and total porosity is, therefore, almost constant in all unweathered and weathered samples.

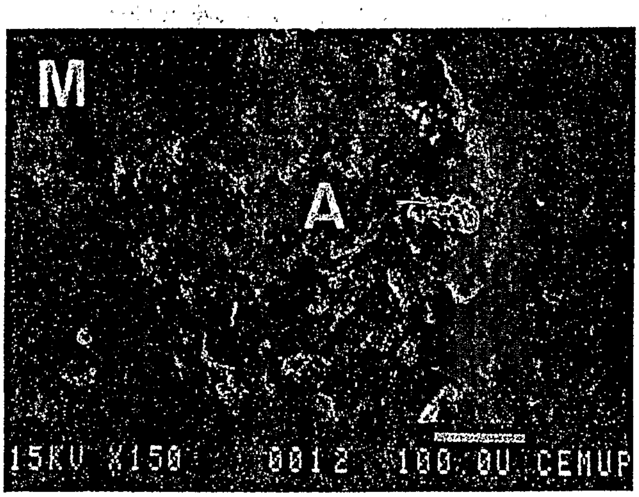
Macropores, inexistent in the unweathering granite, are not numerous in the weathered granite. These macropores (25 µm - 160 µm) are fulfilled with red or red and blue resins and they are mainly located in the core of weathered apatite crystals (fig. 1.b) and in some cases in plagioclase.



a)

fig. 1.a. SEM image of the porous network in a plagioclase crystal of the weathered granite of the Hospital de Santo António; b. SEM image of a macropore located in the core of a weathered apatite crystal (A) as an inclusion in microcline (M) in the weathered granite of the quarry.

b)



Porosity tests

Total porosity and 48 hours porosity are very low in all the 42 drilled core specimens. The results are presented in table I and plotted in fig. 2. They are different in the unweathered (F1 and F2) and weathered (T) granites of the quarry. In fact, the T cylindric samples are three times more porous (N_T=2.80%; N_{48}=2.36%) than the F1 and F2 cylindric samples (N_T=0.86% and 1.00%; N_{48}=0.70% and 0.80% respectively). The stones used in the Hospital (H1 and H2) had already different porosities before the building. The values of H1 (N_T=1.90%; N_{48}=1.66%) are, indeed, inferior to those of the T cylindric samples and the H2 values

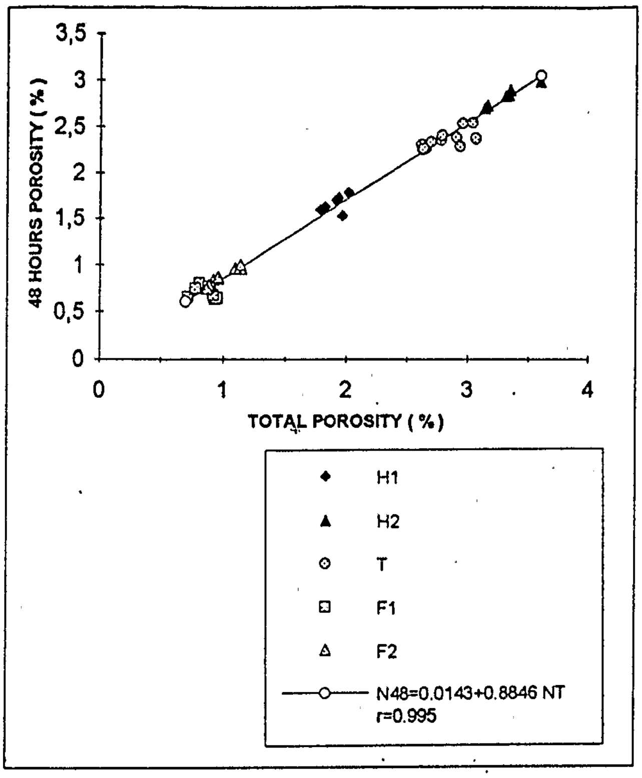


fig.2. Porosity results of the unweathered granite (F1; F2) and weathered granite (T) of the Trindade quarry and of the stones of the Hospital de Santo António (H1; H2).

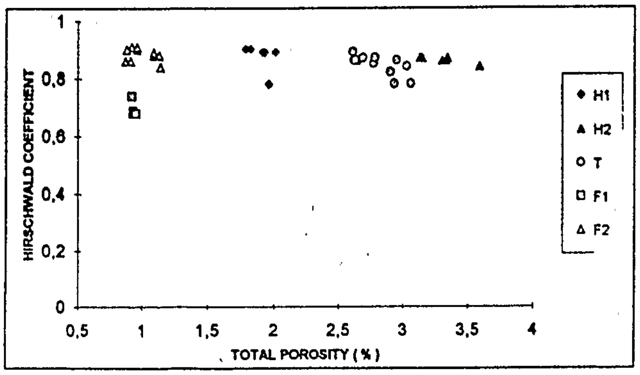


fig.3. Total porosity versus the Hirschwald coefficient results.

(N_T=3.31%; N_{48}=2.84%) are superior to them.

These results are quite inferior to those obtained by Alves et al. (1993) in the weathered biotite-rich granite of Braga (N_T=6.38% and 8.04%) and, according to Kobranova (1989), they are included in the mean porosity values (0.3%<N_T<4%) of the unweathered granites.

A linear equation has been statistically adjusted to the N_T and N_{48} results.

The obtained equation N_{48}=0.0143+0.846N_T with a coefficient of correlation r =0.995 has been plotted in fig. 2, allowing a very good adjustment to the results.

The stones of the monument were already weathered and had distinctive degrees of porosity and, consequently, different degrees of weathering. Basically this means that stones submited to the same physical and environmental conditions (crystallization of the same soluble salts, same exposure to rain and solar radiation, as an example) but with different porosities before the building of the monument, can present now different degrees or even types of stone decay. This may explain why in a façade a stone exhibits strong stone decay while the next stone does not show significant deterioration.

In all drilled samples the Hirschwald coefficient (S_{48}=N_{48}/N_T) is high (fig. 3) and does not present significant variation between the unweathered (F1 and F2) and the weathered (T, H1 and H2) samples. This means that most of the porosity may be invaded by the solutions, confirming the optical microscope observations of the polished thin sections impregnated by coloured resins.

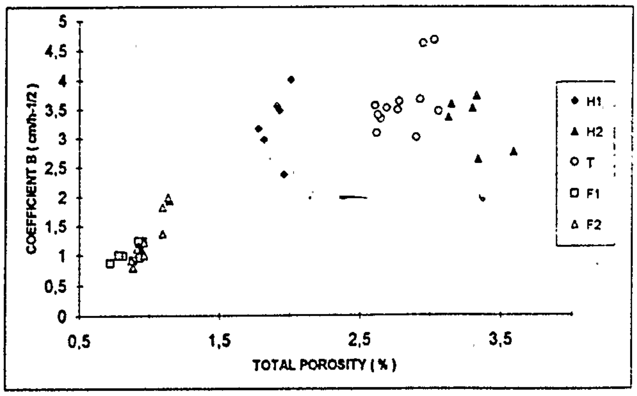


fig.4. Total porosity versus the capillarity coefficient B

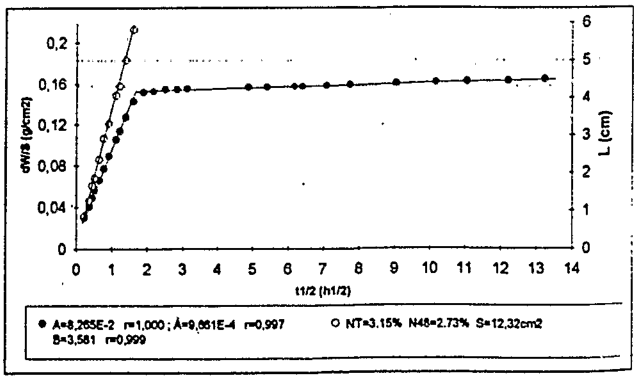


fig.5. Results of the capillarity-water absorption test of the H51 sample (weathered granite of the monument).

Capillarity - water absorption test

Capillarity - water absorption tests have been carried out in the 42 drilled samples (table I).

In the fresh samples, capillarity rise reached the top only in the most porous F2 samples (F96, F99, F100 and F101). The capillarity coefficient B is much lower in the unweathered F1 and F2 samples of the quarry (1.04cm/ h and 1.33 cm respectively) than in the weathered samples of the quarry (3.61 cm/) and of the monument (3.25 cm/ for both H1 and H2 samples) (fig. 4). This shows that imbibitions are very fast in the weathered granites (fig. 5). These results are similar to those presented by Alves et al. (1993) in the weathered Braga granite (2.69 cm / $\sqrt{h}$ and 4.58 cm / $\sqrt{h}$).

The fastness of capillary transfer justifies the important deteriorations in the Oporto monuments built with this quite low porous weathered granite.

In the F1, F2, H1, T and H2 samples, water absorption coefficient A is respectively equal to 0.009, 0.018, 0.045, 0.073 and 0.081 g/cm2/. The results confirm the different degrees of weathering of the H1 and H2 samples and characterize the weathering degree of the Oporto granite.

Permeability to nitrogen test

Permeability to nitrogen has been measured in 16 fresh and weathered samples under several different confinement and fluid pressures.

The differences between the confinement pressure and the fluid pressure have been always equal to 0.2 bar. All samples present low permeability. Permeability results of six samples representative of unweathered and weathered granite have been plotted in fig. 6.

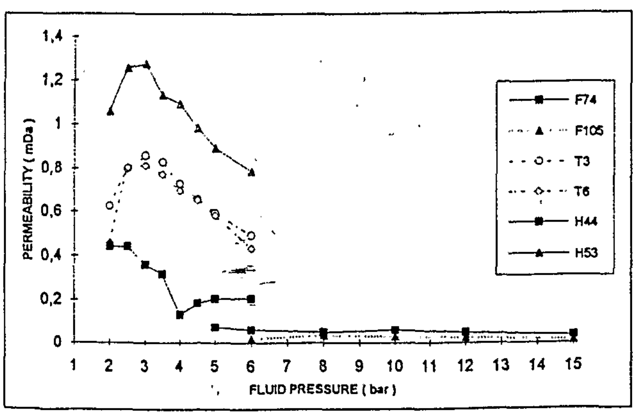


fig 6. Permeability results of the unweathered granite (F74; F105) and weathered granite (T3; T6) of the quarry and of the stones of the monument (H44; H53).

The weathered samples of the Trindade quarry (T3 and T6) are in an intermediate position relatively to the H1 and H2 samples (H44 and H53). The permeabilities of the fresh granite of the quarry (F74 and F105) are lower than those of the weathered samples of the quarry and of the monument. The H2 samples are more permeable to the nitrogen than the H1 samples.

These results corroborate the previous results concerning porosity and capillarity-water absorption tests.

Mercury porosimetry

Mercury porosimetry results show that the most frequent access radii to the pores are 0.20μm in two fresh samples of the quarry, 0.65μm in one weathered sample of the quarry, and 0.40μm in two weathered samples of the monument.

There is a great homogeneity of the access radii to the pores in the weathered samples. Indeed, all free porosity of these granites is invaded by the interconnections between 0.40μm and 0.65μm. The fastness of capillary transfer of the solutions is a consequence of the homogeneity of the access radii to the pores in the weathered granites.

In spite of the small number of the studied samples it seems that the access radii to the pores (0.20μm to 0.65μm) depend on the weathering degree of the granite.

Conclusions

The deterioration of the Oporto granite in the monuments is observed in stones previously involved in a hydrothermal alteration (muscovitization of the plagioclase) and later submited to weathering, being these two processes responsible for the internal microporosity of the plagioclase.

The physical characteristics of the Oporto granite allowed the following conclusions:

a. the weathering degree of the granitic stones can be characterized by porosity, capillarity, permeability and mercury porosimetry;

b. microporosity of the plagioclase is responsible for most of the total porosity and free porosity accessible to water by capillarity almost corresponds to total porosity;

c. in spite of the low porosity, the porous network is very homogeneous, allowing a fast capillary transfer of the solutions, which favours salt concentrations and, therefore, stone decay.

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