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Weathering of the Oporto granite: geotechnical and physical properties

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Abstract

This paper characterizes the weathering products of the two-mica Oporto granite in terms of its mineralogical, chemical, geotechnical and physical properties. This information is used to identify a physical property that can be used as an index of the degree of weathering and to estimate other properties. In outcrop, the Oporto granite is always weathered and weathering profiles frequently exceed 20 m. Within these profiles, granitic saprolites are composed of quartz, feldspars and some mica with kaolinite and gibbsite as final weathering products. The average percentage of secondary minerals determined by bulk X-ray diffraction (XRD) is low in both weathered rock (2.4%) and saprolite (8.7%). Geotechnically, the saprolites exhibit no or low plasticity (plasticity index, $PI \leq 12\%$). The skeleton character of the saprolites is reflected in the significant proportion of fines ($29.5\% < 75$ μm) and low percentages in the <2 μm fraction (6.2%). According to the Unified Soil Classification System (ASTM D 2487-93), most saprolites are SM-silty sands, with some SW-SM-well graded sand with silt, SC-clayey sand, CL-lean clay and ML-silt. Total porosity, free porosity, dry bulk density, ultrasonic velocity and uniaxial compressive strength tests of fresh and weathered rock vary with the degree of granite weathering. This permits correlation between physical properties and the identification of free porosity as the property most strongly influenced by weathering. It is proposed that this could be used as a weathering index, and as the property, which correlates with the highest number of other physical properties; it might be used for their estimation. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Granite; Weathering; Granitic saprolite; Particle-size distribution; Plasticity; Physical properties

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1. Introduction

Oporto is located in Northwest Portugal and most of the city and surrounding areas are founded on the Oporto granite, a light grey, two mica, medium-grained, hypidiomorphic granite (Fig. 1). It belongs to the Central Iberian Zone and is located near the Oporto–Tomar wrench fault system. Ferreira et al. (1987) and Beetsma (1995) considered the Oporto granite as syntectonic with the third phase (F3) of Hercynian deformation, and its intra-Westphalian age of 318 million years was determined by Almeida (personal communication) using U–Pb zircon and monazite geochronology.

Weathering of granitic rocks in temperate climates is usually manifested as arenization and Sequeira Braga et al. (1989, 1990) have proposed that arenization should be considered as one of the major world weathering processes. Gaussen (1981) established a Quaternary age for the granitic saprolites in Northwest Portugal and Daveau (1977), Diniz (1984) and Pereira and Pais (1987) refer to the existence of a humid temperate climate in Portugal during the early Quaternary, not very different from the present-day climate. Field observation of numerous weathering profiles studied by Sequeira Braga (1988), Sequeira Braga et al. (1989) and Begonha (1997) in Northwest Portugal did not

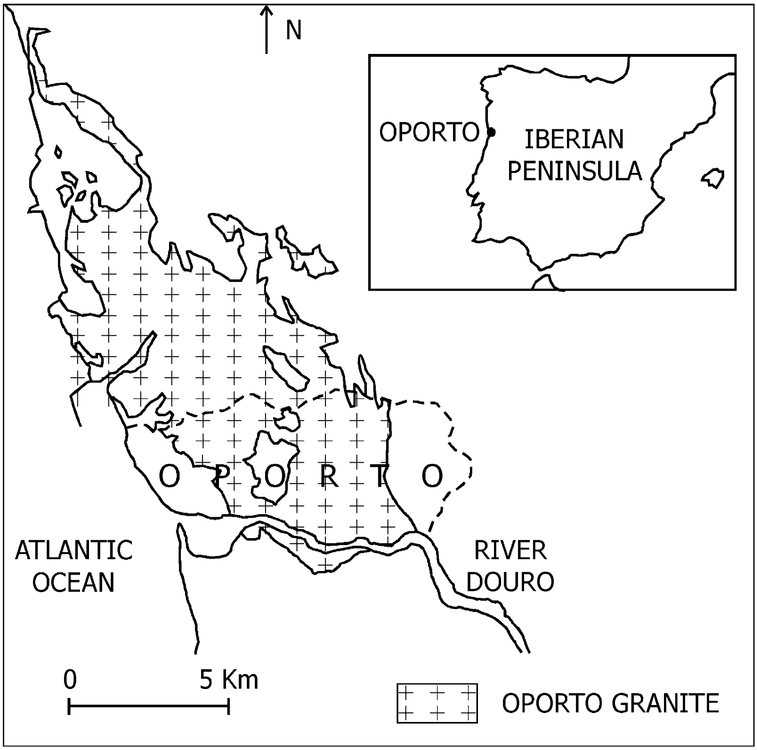

Fig. 1. Location of the outcrops of the Oporto granite.

show any modification in their normal evolution (for example, weathering profiles are not truncated). Weathering progresses through joint and fissure systems that are frequent in the granitic massifs and forms weathering rinds that develop into granitic saprolites. Mineralogical evidence of the weathering of biotite to gibbsite and/or kaolinite in the microenvironments of the weathering rinds of the granitic boulders suggest that weathering is continuing under present-day conditions as it had acted in the early Quaternary in Northwest Portugal (Sequeira Braga et al., 2002).

Sequeira Braga et al. (1989, 1990) and Pédro (1993) highlight the contradiction between the low quantity of secondary minerals produced and the high degree of mineralogical evolution in the arenization process in temperate climates, in contrast to the coherence between the type and degree of weathering in tropical regions. In Northwest Portugal, for example, granitic saprolites contain the final weathering products of the granitic rocks in temperate areas, but retain their original granitic structure and are therefore fabric skeleton materials, mainly composed of grains of quartz, feldspar and some mica. The content of secondary minerals or "plasma" is very low and from a geotechnical point of view, they should be classified as residual soils in which sand is the dominant granular fraction. These materials are in contrast to other components of weathering profiles that are more compact and show greater cohesion than saprolite, have a greater bulk density and can only be broken up with a hammer. These materials are best described as 'weathered rock'.

Mineralogical and chemical studies of the weathering of the Oporto granite have been carried out by Begonha and Sequeira Braga (1993, 1995), Santos (1995) and Begonha (1997). Silva Cardoso (1986), Begonha (1989, 1997), Viana da Fonseca (1989, 1993), Viana da Fonseca et al. (1994), Santos (1995), Santos and Silva Cardoso (1995), Begonha and Sequeira Braga (1995) and Cruz et al. (1997) have all examined the geotechnical properties of weathered Oporto granite. Similar studies of the physical properties of the Oporto granite and their correlations have been carried out by Santos (1995) and Begonha (1997). There is, however, a need to integrate these investigations and this study aims to address this through the comprehensive characterization of weathered rock, fresh rock and saprolite in terms of their geotechnical properties. Hopefully, this will permit correlation between physical properties and the identification of a property most strongly influenced by weathering. This might then be used as a weathering index and to estimate other physical properties.

2. Materials and methods

Two samples of fresh rock, 27 of weathered rock and 51 of granitic saprolite were obtained from 16 weathering profiles in the Oporto. These were examined by optical microscopy, X-ray diffraction (XRD) of the bulk rock and of the <63 and <2 μm fractions, scanning electron microscopy (SEM) and plasma spectrometry to characterize their mineralogy and chemistry. Estimations of the mineral quantities in the bulk rock and the <2 μm fraction were obtained by the relative intensity of diagnostic reflections of each mineral in the X-ray diffractograms. To assess the geotechnical properties of the granitic saprolites, particle-size analyses and Atterberg limits (the liquid limit (LL), the plastic limit (PL) and the plasticity index (PI)) tests were carried out for 48 samples of granitic saprolites of the Oporto granite according to E195 (LNEC, 1966a) and E196 (LNEC, 1966b) specifications and to Portuguese standards NP 83 (1965) and NP 143 (1969). The particle-size distribution, the percentage of fines (<75 μm fraction), the percentage of the <2 μm fraction and the coefficients of uniformity (Cu) and curvature (Cc) were determined according to ASTM D 2487-93 (1993). In this study, the weathering classification proposed by the ISRM (1978) was used which proposes five degrees of weathering: W1 (fresh rock with no signs of weathering), W2 (slightly weathered rock with discoloration in discontinuity surfaces), W3 (moderately weathered rock with less than half of the rock decomposed), W4 (highly weathered rock with more than half of the material transformed to a soil) and W5 (completely weathered rock with all the material transformed to a soil but the original mass structure still largely intact). Total porosity, free porosity, dry bulk density, ultrasonic velocity and uniaxial compressive strength tests were also performed on 167 drilled core specimens of fresh and weathered rock. Total porosity and free porosity tests were carried out in accordance to the methods described by Mertz (1991), Hammecker (1993) and Begonha (1997), dry bulk density and ultrasonic velocity tests in accordance with Begonha (1997) and uniaxial compressive strength tests in accordance with Portuguese standard NP 1040 (1974). The modulus of elasticity and strain in rupture were obtained from the uniaxial compressive strength tests.

3. Petrographic and chemical classification

Chemical characterization was performed on two polished thin sections of fresh and weathered rock by optical microscopy and SEM. These show that the Oporto granite is composed of quartz, microcline (Or, 92.8%; Ab, 5.7%; An, 1.5%), plagioclase (Or, 0.7%; Ab, 90.3%; An, 9.0%), muscovite and biotite. Muscovite is the dominant mica and microcline is frequently perthitic. Apatite, zircon and rutile are the accessory minerals. The fresh Oporto granite was submitted to a late post-magmatic alteration process, characterized by the muscovitization of the plagioclase crystals, by a second generation of plagioclase and by the presence of several generations of dioctahedral micas, chlorite, rare chorite/smectite mixed-layer minerals and a pure smectitic phase. Evidence of post-magmatic deformation is supported by the occurrence of beams of associated secondary micas and fibrolite crossing microcline and primary muscovite crystals, by the arching of the cleavage planes of the micas and by the undulous extinction exhibited by the quartz crystals and also displayed by some muscovite crystals.

Chemical analyses were performed on three specimens of fresh Oporto granite. This granite is peraluminous since the A/NKC ($A/NKC=Al_2O_3/(Na_2O+K_2O+CaO)$) molar ratio ranges from 1.19 to 1.25 and the CIPW normative corundum is comprised between 3.14% and 4.04%. According to the Debon and Le Fort (1983) classification, the Oporto granite is a leucogranite since the parameters A ($A=Al-(Na+K+2Ca)$), B ($B=Fe+Mg+Ti$), Q ($Q=Si/3-(Na+K+2Ca/3)$) and F ($F=K-(Na+Ca)$) are between $44\leq A\leq 60$, $22\leq B\leq 24$, $180\leq Q\leq 188$ and $-36.1\leq F\leq -28.4$. The amount of biotite, calculated from the parameter B, is very low, ranging from 4.0% to 4.3%.

4. Weathering of the Oporto granite

4.1. General characteristics of weathering profiles

The climate in the Oporto region is Mediterranean with a strong Atlantic influence, being characterized by the absence of significant precipitation in the summer months (June to September), a mean annual temperature of 14.5 °C and a mean annual rainfall of 1200 mm. A maximum temperature of 39.9 °C and a minimum of −4.1 °C were recorded between 1941 and 1980. The mean number of days per year with rainfall higher than 0.1 mm is 148.

The climatic characteristics associated with good drainage conditions favour the weathering and outcrops of Oporto granite often display different degrees of weathering. Total profile depths frequently exceed 20 or even 30 m and granitic saprolites can be more than 10 m thick. The original structure of the granite, including the joints, is preserved even in the granitic saprolites on the top of the profiles. The heterogeneity of the profiles is

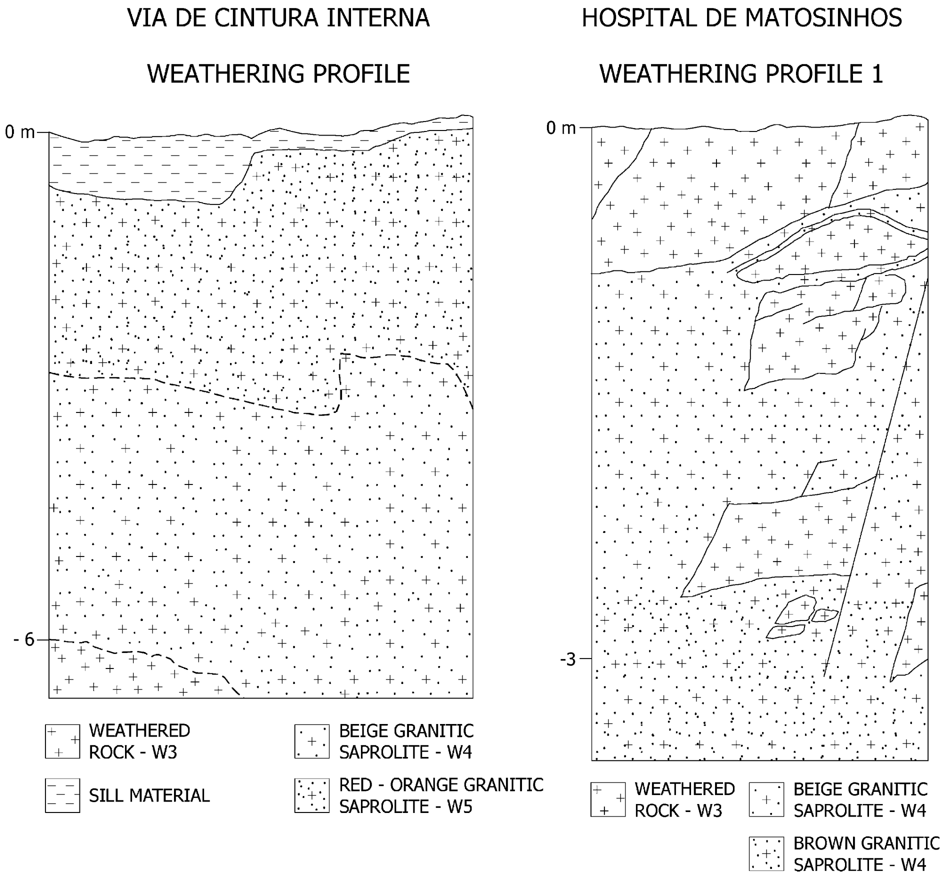

Fig. 2. Weathering profile of the Via de Cintura Interna and weathering profile 1 of the Hospital de Matosinhos.

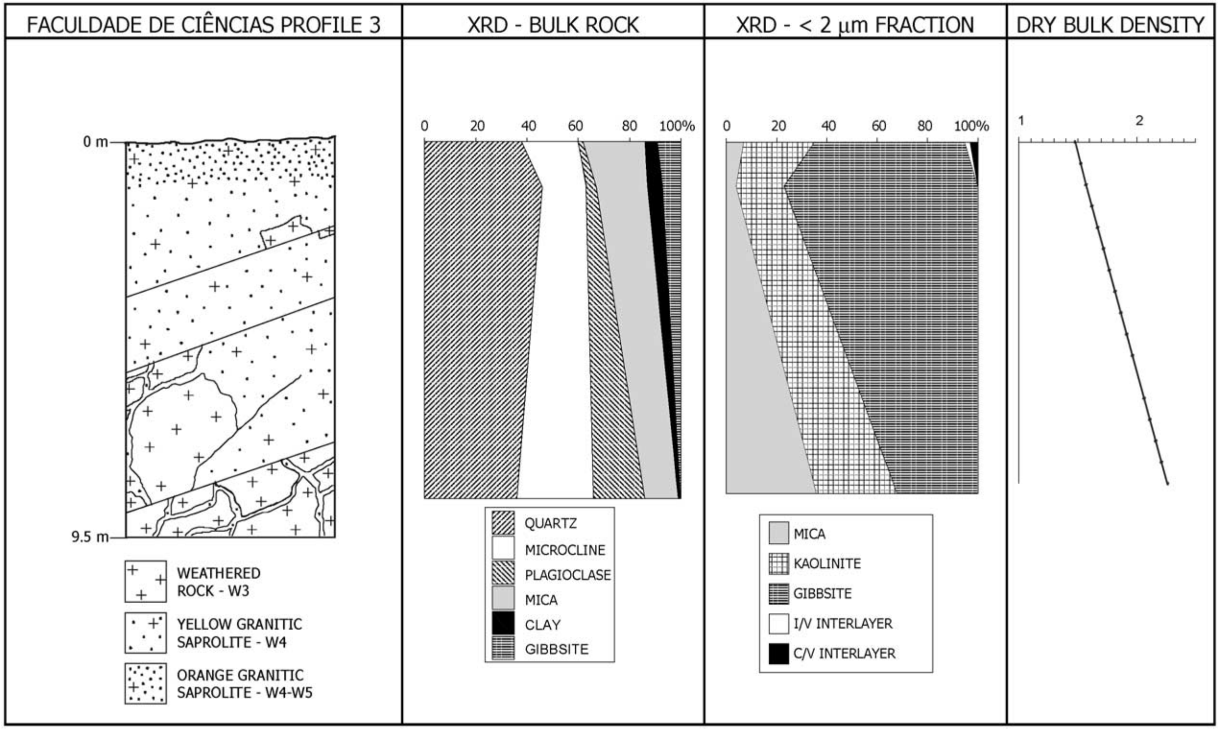

Fig. 3. Weathering profile 3 of the Faculdade de Ciências-estimation by X-ray diffraction of the mineralogical composition of the bulk rock and the <2 μm fraction.

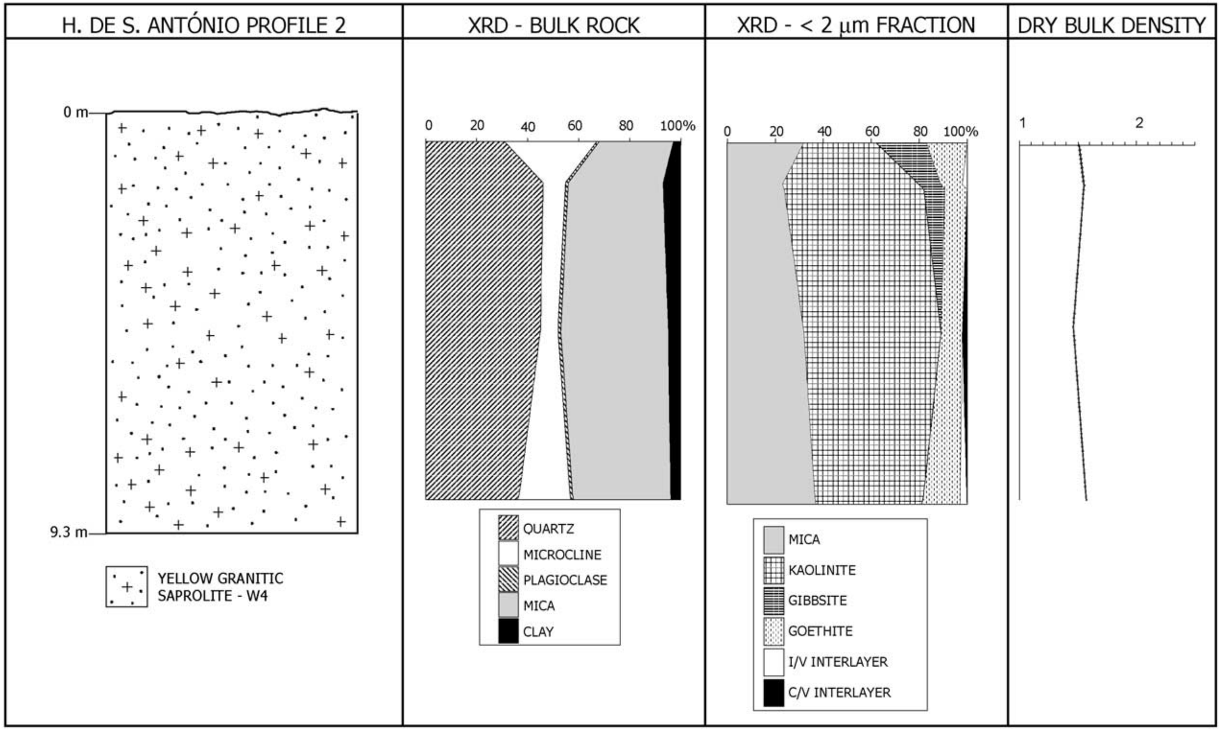

Fig. 4. Weathering profile 2 of the Hospital de Santo António-estimation by X-ray diffraction of the mineralogical composition of the bulk rock and the <2 μm fraction.

clearly shown by the variation in the degree of weathering from the bottom to the top. There are several types of weathering profiles, such as: with weathered rock at the bottom and saprolite at the top (Figs. 2 and 3), weathered rock at the top and saprolite at the base (Fig. 2) and thick layers of saprolite with or without corestones of weathered rock in their midst (Fig. 4).

4.2. Secondary minerals in weathered rock and in granitic saprolites

The average percentage of secondary minerals in the bulk weathered rock by XRD is very low (2.4%, ranging from 1% to 4%). Kaolinite, gibbsite and chlorite/vermiculite (C/V) irregular mixed-layer minerals were the secondary minerals identified by XRD in the <2 μm fraction. In some samples, gibbsite is the dominant mineral in this fraction. The almost complete absence of chlorite in the weathered rock and the complete absence of smectite and of the chlorite/smectite (C/Sm) mixed-layer minerals, which are both present in the fresh rock, prove the instability of these late post-magmatic alteration minerals at the very beginning of the weathering process.

The average percentage of secondary minerals determined in the bulk saprolite (8.7%, ranging from 2% to 24%) by XRD is significantly higher than that of the weathered rock. Gibbsite, kaolinite, goethite, illite/vermiculite (I/V) and chlorite/vermiculite irregular mixed-layer minerals were the secondary minerals identified by XRD in the <2 μm fraction. Gibbsite or kaolinite are the dominant minerals in all samples. Table 1 shows the average percentages, the interval of variation and the number of samples (*n*) for identified minerals in the <2 μm fraction in the weathered rock and the saprolite. Mica is the most abundant mineral in the <2 μm fraction of the weathered rock, followed by kaolinite and gibbsite. In the granitic saprolites, gibbsite and kaolinite are the most common minerals, followed by mica and goethite. From the weathered rock to the saprolite, there is a significant decrease in the mean percentage of mica (31%) and an increase in the mean amounts of gibbsite (16%), kaolinite (9%) and goethite (8%). The illite/vermiculite and chlorite/vermiculite irregular mixed-layer minerals correspond to intermediate phases in

Table 1
Semi-quantification of the minerals of the weathered rock and of the granitic saprolites identified by XRD of the <2 μm fraction

	Weathered rock (f<2 μm) n=18			Granitic saprolites (f<2 μm) n=39		
	Average (%)	Interval of variation (%)	*n*	Average (%)	Interval of variation (%)	*n*
Gibbsite	26	0–61	11	42	0–93	31
Kaolinite	31	17–53	18	40	5–81	39
Mica	41	11–72	18	10	0–37	37
Goethite	0	0–0	0	8	0–35	24
I/V mixed layers	0[a]	0–0	0	0	0–3	11
C/V mixed layers	1	0–8	2	0	0–3	9
Chlorite	1	0–9	3	0	0–0	0
Gibbsite+kaolinite	57	21–89	18	82	44–100	39

[a] Identified in the three samples by XRD in the bulk rock.

the mineralogical evolution that occurs during the weathering process and always appear in very low quantities.

The semi-quantification obtained from the XRD in the bulk rock shows that the amount of plagioclase is significantly reduced at the very beginning of the weathering process (weathered rock) (Fig. 3) almost disappearing in the granitic saprolites at the top of the profiles (Fig. 3). Quartz, microcline and mica show distinct tendencies in each profile. Usually the relative amounts of quartz and mica increase from the bottom to the top of the profiles (Fig. 4). However, they can display no significant change through all the profile (Fig. 4) or may even diminish from the bottom to the top. The relative increase in microcline at the earlier stages of the weathering process and the decrease in later stages, indicate its higher resistance to weathering compared to plagioclase. Microcline can also have an irregular behaviour throughout the weathering profile (Fig. 4), decreasing at the bottom of the profile, showing no variation in the middle and increasing at the top.

5. Geotechnical characteristics of granitic saprolites

Table 2 shows the particle-size distribution, the percentage of fines (<75 μm fraction), the percentage of the <2 μm fraction, the coefficients of uniformity (Cu) and curvature (Cc), the Atterberg limits—the liquid limit (LL) and the plastic limit (PL), the plasticity index (PI)—and dry bulk density (d) determined for 48 samples of saprolite of the Oporto granite according to ASTM D 2487-93 (1993). Table 3 shows for all the samples of saprolite and for the saprolites classified as SM-silty sands: the averages, intervals of variation of the <75 and <2 μm fractions; the number of saprolites with no plasticity (IP=0%) or low plasticity ($0\% \leq IP \leq 12\%$); and the number of well graded ($Cu \geq 6$ and $1 \leq Cc \leq 3$) or poorly graded soils ($Cu<6$ and/or $1 > Cc > 3$).

Sand and silt are the dominant fractions in all samples. Most saprolites are classified as SM-silty sands. The mean percentage of fines in all samples is significant: 29.5%. The mean percentage of the <2 μm fraction is very low, 6.2%, and confirms the mean value obtained by XRD in the bulk rock (8.7%). All these values are in accordance with those published by Silva Cardoso (1986), Viana da Fonseca (1989, 1993), Viana da Fonseca et al. (1994), Santos (1995), Santos and Silva Cardoso (1995), Carta Geotécnica do Porto (1995) and Cruz et al. (1997). Particle-size distribution in the saprolites shows great variability and heterogeneity in the 16 weathering profiles. There are profiles with particle-size distributions increasing from bottom to top, profiles displaying exactly the opposite, profiles with similar particle-size distributions from bottom to top and profiles with irregular particle-size distributions. In spite of the significance of the fine fraction (mean value of 29.5%) plasticity indices are very low. This can be explained by the skeleton nature of the saprolites and the low mean value of the <2 μm fraction and its mineralogy (gibbsite and kaolinite), minerals that do not provide any or significant plasticity. Usually the samples classified as SM-silty sands and SW-SM-well graded sand with silt have lower values of the <2 μm fraction and lower plasticity indices and the coefficients of uniformity than the samples classified as SC-clayey sand, CL-lean clay and ML-silt. The percentage of the <75 μm fraction, the value of the coefficient of curvature and the value of dry bulk density are similar in all types of the Oporto granite saprolites.

Table 2
Granular characteristics, Atterberg limits and classification of the Oporto granitic saprolites

Sample	LL (%)	PL (%)	PI (%)	*f*<75 μm (%)	*f*<2 μm (%)	Cu	Cc	*d*	Classification (ASTM D 2487-93, 1993)
FC-G1	NP	NP	0	41.4	4.3	55.79	1.26	1.39	SM-silty sand
FC-G2	NP	NP	0	19.1	3	50.67	3.64	nd	SM-silty sand
FC-G3	NP	NP	0	15.4	2	25.48	2.64	1.96	SM-silty sand
FC-G5	NP	NP	0	26.6	5.2	59.27	1.63	nd	SM-silty sand
FC-G9	37	25	12	51.4	22.6	193.37	0.24	1.59	ML-silt
FC-G12	NP	NP	0	18	1.7	21.28	1.42	1.67	SM-silty sand
FC-G13	37	26	11	39.4	7.4	147.84	0.74	1.45	SM-silty sand
FC-G14	NP	NP	0	33.4	6.5	101.76	2.57	1.39	SM-silty sand
FC-G15	NP	NP	0	43	6.8	72.96	0.61	1.28	SM-silty sand
FC-G16	NP	NP	0	37.1	4.8	70.14	0.39	1.49	SM-silty sand
FC-G17	33	30	3	29.5	10.6	382.33	6.79	nd	SM-silty sand
FC-G20	30	21	9	52.4	20.2	160.67	0.21	1.81	CL-lean clay
FC-G21	32	21	11	46.4	23.2	267.25	0.23	1.48	SC-clayey sand
FC-G22	30	22	8	32.3	12.3	618.30	6.43	1.57	SC-clayey sand
P3.1	NP	NP	0	29.4	3.7	74.30	1.55	1.47	SM-silty sand
P3.2	NP	NP	0	14.1	2.1	34.69	1.86	1.62	SM-silty sand
P3.3	NP	NP	0	13.9	2.5	24.80	1.94	1.8	SM-silty sand
P3.4	NP	NP	0	11.2	2.7	19.19	2.18	1.34	SW-SM-well graded sand with silt
P3.6	NP	NP	0	20.7	2.2	55.26	2.72	1.57	SM-silty sand
P3.7	NP	NP	0	26.7	2.4	74.30	1.65	1.46	SM-silty sand
P3.8	NP	NP	0	27.8	3.7	82.33	1.49	1.55	SM-silty sand
P3.9	NP	NP	0	20.5	2.9	47.93	2.01	1.51	SM-silty sand
P4.10	NP	NP	0	17.3	1.6	37.32	0.68	1.93	SM-silty sand
P4.11	NP	NP	0	14.4	2.1	54.06	1.53	1.86	SM-silty sand
SH5	NP	NP	0	34.3	7.2	86.23	2.45	1.72	SM-silty sand
SH7	NP	NP	0	31.8	5.2	78.38	2.10	1.54	SM-silty sand
SH9	36	33	3	38	8.7	104.24	2.19	1.53	SM-silty sand
SH10	NP	NP	0	24.2	3.1	66.38	2.85	1.67	SM-silty sand
SH11	NP	NP	0	16.8	3.4	35.90	2.29	2.02	SM-silty sand
SH12	29	26	3	28.9	3.3	57.59	1.38	1.7	SM-silty sand
SH13	NP	NP	0	23.6	3	37.08	1.71	1.89	SM-silty sand
SH14	27	24	3	36.6	6.8	90.40	1.49	1.61	SM-silty sand
SH15	NP	NP	0	32.7	3.3	61.32	1.45	1.48	SM-silty sand
SH16	36	33	3	39	6.2	60.06	1.61	1.45	SM-silty sand
VCI-A2	NP	NP	0	20.8	3.1	53.02	2.25	1.49	SM-silty sand
VCI-A3	NP	NP	0	24	6	126.85	3.95	1.53	SM-silty sand
VCI-A4	32	26	6	40.3	18.5	394.33	2.43	1.58	SM-silty sand
C1	NP	NP	0	30.7	nd	nd	nd	nd	SM-silty sand
C2	48	40	8	39.1	3.7	63.33	1.76	nd	SM-silty sand
C3	54	42	12	42.8	5.4	92.36	2.63	nd	SM-silty sand
VCI 1	35	32	3	23.6	nd	nd	nd	nd	SM-silty sand
VCI 2	34	26	8	25.2	4.7	118.29	3.80	nd	SM-silty sand
VCI 4	30	26	4	21.2	nd	nd	nd	nd	SM-silty sand
VCI 5	32	30	2	33.9	5.9	103.91	2.96	nd	SM-silty sand
VCI 6	35	27	8	26.4	nd	nd	nd	nd	SM-silty sand
VNG 4	NP	NP	0	31.2	4.1	30.99	4.29	nd	SM-silty sand
VNG 5	33	26	7	30.9	5.8	96.27	3.12	nd	SM-silty sand
VNG 6	37	30	7	37.6	6.7	120.33	1.29	nd	SM-silty sand

NP—no plasticity; nd—not determined.

Table 3

Granitic saprolites: averages and intervals of variation of the <75 and <2 μm fractions, number of samples with no or low plasticity and number of well or poorly graded soils

	Number of samples	<75 μm fraction			<2 μm fraction			Plasticity		Well-graded soils	Poorly graded soils
		Average	Interval of variation		Average	Interval of variation		PI=0%	0%≤PI≤12%		
	(*n*)	(%)	(%)	*n*	(%)	(%)	*n*	*n*	*n*	*n*	*n*
All samples of granitic saprolites	48	29.5±10.0	11.2–52.4	48	6.2±5.3	1.6–23.2	44	28	20	30	14
SM-silty sand granitic saprolites	43	28.4±8.5	13.9–43.0	43	4.9±3.0	1.6–18.5	39	27	16	29	10

Table 4
Results of the tests performed on 167 drilled core specimens of Oporto granite

Sample	N_T	N_{48}	d	v	Sample	N_{48}	d	v	Sample	N_{48}	d	v	σ	ε	E
Degree of weathering	(%)	(%)		(m s^{-1})	Degree of weathering	(%)		(m s^{-1})	Degree of weathering	(%)		(m s^{-1})	(MPa)	($\times 10^{-3}$)	(GPa)
W3	2.65	2.27	2.59	4030	W3	4.40	2.51	2660	W3	2.75	2.57	2960	78.8	11.2	8.41
W3	3.03	2.55	2.57	3740	W3	4.23	2.53	2990	W3	2.45	2.58	3030	103.9	12.3	9.81
W3	2.61	2.31	2.58	4190	W3	4.05	2.54	3110	W3	2.59	2.57	3320	87.6	12.2	8.77
W3	2.62	2.26	2.60	4140	W3	3.93	2.54	3340	W3	3.10	2.56	2090	97.3	12.8	9.48
W3	2.69	2.34	2.58	4600	W3	4.12	2.53	3240	W3	3.00	2.57	2360	95.0	13.4	8.37
W3	2.90	2.39	2.58	4530	W3	4.19	2.53	2650	W3	2.98	2.55	2310	98.4	14.2	8.51
W3	2.95	2.54	2.58	4740	W3–W4	9.02	2.39	1550	W3	4.33	2.52	2550	77.5	14.8	6.30
W3	2.77	2.36	2.58	4240	W3–W4	8.31	2.41	1720	W3	3.60	2.54	2800	105.7	14.4	9.11
W3	2.93	2.29	2.58	4190	W3–W4	8.80	2.40	1880	W3	3.68	2.55	2870	86.8	13.1	7.53
W3	2.63	2.27	2.58	4010	W3–W4	9.46	2.37	1440	W3	4.18	2.52	2730	79.8	13.5	6.85
W3	3.06	2.38	2.58	4400	W3–W4	10.77	2.34	1300	W3–W4	8.37	2.39	1420			
W3	2.78	2.41	2.57	4490	W3	4.48	2.52	3050	W3–W4	9.11	2.37	1400	20.2	15.2	1.04
W2	1.93	1.72	2.61	5010	W3	4.94	2.50	2420	W3–W4	8.46	2.39	1540	23.7	16.9	1.35
W2	1.91	1.70	2.61	4500	W3	4.44	2.51	2620	W3–W4	8.92	2.37	1390	22.4	13.9	1.15
W2	2.01	1.78	2.61	4570	W3	4.43	2.51	2990	W3–W4	8.34	2.40	1500	23.3	15.9	1.28
W2	1.82	1.63	2.62	4670	W3	5.72	2.49	2330	W3–W4	9.20	2.37	1340	21.3	17.1	1.10
W2	1.96	1.53	2.62	4870	W3	4.68	2.52	2990	W3–W4	7.79	2.41	1690	29.4	16.4	1.74
W2	1.78	1.60	2.61	4490	W3	5.84	2.48	2480	W3–W4	7.93	2.41	1640	29.0	16.7	1.68
W3	3.13	2.71	2.58	3420	W3	5.33	2.50	2460	W3	4.60	2.50	2460	60.0	13.7	6.01
W3	3.15	2.73	2.57	2780	W3	5.20	2.50	2810	W3	4.85	2.50	2260	61.5	13.9	5.03
W3	3.30	2.84	2.56	2920	W3	6.09	2.47	2210	W3	4.38	2.51	2590	71.8	12.6	6.81
W3	3.33	2.85	2.57	3350	W3	5.91	2.48	2230	W3	3.89	2.53	2780	73.2	11.1	7.49
W3	3.59	3.00	2.56	3440	W3	6.26	2.47	2200	W3	4.47	2.51	2520	78.5	12.5	7.55
W3	3.34	2.91	2.56	2640	W3	5.99	2.48	1880	W3	4.64	2.49	2400	72.7	12.2	6.88
W1	0.93	0.64	2.64	6420	W3	3.10	2.55	3620	W3	2.99	2.56	3570	108.0	11.1	11.16
W1	0.93	0.63	2.63	6000	W3	3.18	2.56	3750	W3	2.89	2.55	3760	92.6	12.0	10.11
W1	0.95	0.65	2.63	5780	W3	3.15	2.56	4080	W3	2.94	2.56	3750	111.2	11.2	10.83

W1	0.92	0.68	2.65	6200	W3	3.71	2.54	2960	W3	2.95	2.56	3610	118.1	12.1	10.46
W1	0.81	0.80	2.63	6140	W3	3.64	2.55	3220	W3	3.27	2.54	3460	107.0	11.9	10.45
W1	0.72	0.66	2.64	6010	W3	3.75	2.55	2680	W3	3.01	2.56	3530	90.9	11.6	9.07
W1	0.78	0.75	2.64	6130	W3	3.88	2.54	3000	W3	3.69	2.54	2680	75.6	11.6	7.77
W1	0.88	0.77	2.64	6120	W3	3.88	2.54	2870	W3	3.61	2.55	2310	83.5	13.3	7.90
W3	3.26	2.89	2.56		W3	3.83	2.54	3060	W3	3.43	2.55	2450	89.7	12.5	8.88
W2	1.59	1.48	2.62	5300	W3	3.49	2.55	3190	W3	3.65	2.55	2550	89.3	12.4	8.96
W3	3.36	2.96	2.57		W3	4.04	2.53	3380	W3	3.40	2.55	2160	90.4	13.9	7.96
W2	2.07	1.90	2.60	4550	W3	3.96	2.54	3160	W3	2.41	2.58	3980	123.2	12.5	12.05
W3	3.94	3.45	2.54		W3	2.81	2.57	3580	W3	2.72	2.56	3610	120.9	11.8	11.81
W2	1.93	1.75	2.60	5120	W3	6.47	2.45		W3	2.64	2.57	3750	135.2	12.1	12.89
W3	3.83	3.33	2.55		W3	5.27	2.48	2060	W3	3.78	2.53	3080	90.7	13.1	8.66
W2	1.63	1.48	2.61	5450	W3	7.46	2.42	1600	W3	2.36	2.59	3600	101.0	11.2	10.79
W3	3.70	3.26	2.55		W3	6.29	2.46	2030	W3	2.32	2.58	3590	75.6	9.9	9.17
W3	3.62	3.22	2.56		W3	4.48	2.52		W3	2.49	2.59	3700	90.3	11.2	9.48
W3	2.88	2.52	2.58		W3	3.38	2.56	3840	W3	2.12	2.58	3620	113.6	12.6	10.35
W3	2.74	2.44	2.58	3710	W3	3.64	2.54	4270	W3	2.32	2.58	3370	109.5	11.8	10.95
W3	2.62	2.33	2.59		W3	3.96	2.53		W3	2.32	2.59	3590	105.8	11.8	11.05
W3	2.41	2.18	2.60		W3	4.27	2.52	3530	W1	0.62	2.63	5700			17.23
W3	2.86	2.56	2.58		W3	4.29	2.53	3450	W1	0.61	2.62	5740	157.0	11.2	16.94
W3	2.56	2.29	2.59		W3	4.07	2.52		W1	0.61	2.64	5610	141.7	12.0	16.73
W3	2.71	2.46	2.59		W3	4.23	2.53	3570	W1	0.61	2.63	5700	153.5	11.6	16.77
W3	2.66	2.41	2.59						W1	0.52	2.65	5690	130.6	11.5	14.67
W1	1.14	0.96	2.63	5550					W1	0.61	2.63	5690			22.90
W1	0.96	0.86	2.64	5850					W1	0.63	2.63	5370	153.0	11.9	16.05
W1	0.92	0.84	2.64	5850					W3	2.24	2.58	3400	103.5	13.2	10.37
W1	1.09	0.96	2.63	5600					W3	2.19	2.59	3540	104.0	12.7	10.12
W1	1.09	0.97	2.63	5600					W3	2.21	2.59	3440	110.3	12.1	11.24
W1	1.13	1.00	2.63	5540					W2	1.60	2.61	3670	96.6	11.5	10.38
W1	0.91	0.78	2.63	5750					W2	1.62	2.61	3680	100.3	12.7	9.96
W1	0.96	0.87	2.63	5300					W2	1.60	2.61	3810	132.7	13.0	12.45
W1	0.88	0.79	2.64	5950											
W1	0.87	0.75	2.63	5910											

6. Physical properties of the Oporto granite

Table 4 shows the results of the tests performed on 167 drilled core specimens obtained from samples of fresh rock (W1) and weathered rock exhibiting different degrees of weathering (W2, W3, W3–W4) (ISRM, 1978). The following physical properties and parameters were determined: total porosity (N_T), free porosity (N_{48}), Hirschwald coefficient (S_{48}=N_{48}/N_T), dry bulk density (d), ultrasonic velocity (v), uniaxial compressive strength (σ), modulus of elasticity (E) and strain in rupture (ε).

The interval of variation and the number of tested specimen (n) for each degree of weathering are presented in Table 5. This shows that dry bulk density, ultrasonic velocity, uniaxial compressive strength and modulus of elasticity decrease during the weathering process and the values of total porosity, free porosity and strain in rupture increase. All the physical parameters, with the exception of the Hirschwald coefficient and strain in rupture, display continuous and significant variation with the degree of weathering of the specimen. Table 5 also shows the absence of any gap or pronounced decreases between the results of σ and E in the W1 and W2 specimen, contrary to studies by Christaras (1991), Baudracco et al. (1982) and Dobereiner et al. (1993) in the Sithonia, Xanthi, Vroutou, Arnea, Kavala and Fanos granites in Greece, in the granite from Sidobre in France and in the Massiac gneiss in France, respectively. According to these authors, these important decreases were associated with the appearance of microcracks at the beginning of weathering. The absence of pronounced decreases of σ and E between the fresh (W1) and the slightly weathered rock (W2) in the Oporto granite are probably related to the presence of a porous network already present in the fresh rock, referred to by Begonha et al. (1994). This network is composed of microcracks resulting from the late post-magmatic alteration process to which this granite was submitted.

With respect to the mean values of the fresh (W1) and most weathered rock (W3–W4), all parameters were classified as strongly, moderately and weakly influenced by weathering in agreement with Iliev (1966). The mean values of d, v, σ and E in the fresh rock are

Table 5
Variation of some physical properties and parameters with the degree of weathering

	Units	Properties and parameters							
		Fresh rock		Weathered rock					
		W1		W2		W3		W3–W4	
		Interval of variation	n	Interval of variation	n	Interval of variation	n	Interval of variation	n
N_T	%	0.72–1.14	18	1.59–2.07	10	2.41–3.94	32		
N_{48}	%	0.52–1.00	25	1.48–1.90	13	2.12–7.46	116	7.79–10.77	13
S_{48}	%	68–99	18	78–93	10	78–91	32		
d		2.62–2.65	25	2.60–2.62	13	2.42–2.60	116	2.34–2.41	13
v	m s^{-1}	5370–6420	25	3670–5450	13	1600–4740	99	1300–1880	13
σ	MPa	130.6–157.0	5	96.6–132.7	3	60.0–135.2	40	20.2–29.4	7
E	GPa	14.67–22.90	7	9.96–12.45	3	5.03–12.89	40	1.04–1.74	7
ε	$\times 10^{-3}$	11.2–12.0	5	11.5–13.0	3	9.9–14.8	40	13.9–17.1	7

(n)—Number of tested specimens for each degree of weathering.

respectively 1.1, 3.9, 6.1 and 13.0 times lower than the mean values for the most weathered rock. On the other hand, the mean values of N_{48} and ε for the most weathered rock are, respectively, 13.6 and 1.4 times greater than those for the fresh rock. The results suggest that the physical parameters N_{48}, v, σ and E are strongly influenced by weathering whereas ε is only moderately influenced and d is weakly influenced by the degree of weathering.

The behaviour of the physical parameters seems to be essentially controlled by the leaching of chemical elements during the weathering process. In fact, Begonha (1997) obtained an average material loss of 41% in the saprolites of the Oporto granite in comparison to the fresh rock. Voids resulting from leaching are the most important factor responsible for variations in physical parameters. Dry bulk density can be strongly influenced by the amount of secondary minerals but, in the case of the Oporto granite, the low amount of secondary minerals produced in the weathering process should not affect significantly the behaviour of dry bulk density and the physical parameters.

Table 6 shows the correlations between several of the physical parameters, their coefficient of correlation (r) and the number of specimen (n) used in each correlation. Only the correlations considered significant (with r higher than 0.900) are presented.

- N_T with N_{48}, d and v;
- N_{48} with d, v, σ and E;
- d with v, σ and E;
- v with σ and E;
- σ with E.

Figs. 5–7 show the variations and correlations between d and N_{48}, v and N_{48}, and E and σ. Knowledge of these correlations is very useful in estimating the values of other physical properties and parameters based upon the results of a test of an index property. The strong linear correlation between total and free porosity shows that the percentage of the voids accessible to water is more or less constant and, consequently, the Hirschwald coefficient

Table 6
Correlations between the physical parameters

Correlations	r	n
$N_{48}=0.001940+0.8669N_T$	+0.995	60
$d=2.6635-0.0293N_T$	−0.980	60
$d=2.6562-0.0309N_{48}$	−0.994	167
$v=6819.3507-101.1176N_T$	−0.934	47
$v=5282.6800-1713.0167\times\ln N_{48}$	−0.944	150
$v=4.3527\times202.5238^{d}$	+0.932	150
$\sigma=184.9028\times0.7952^{N_{48}}$	−0.965	55
$\sigma=4.2830\times10^{-6}\times d^{17.9721}$	+0.954	55
$\sigma=-594.7097+85.8524\times\ln v$	+0.914	55
$E=23.2826\times0.7262^{N_{48}}$	−0.976	57
$E=4.5065\times10^{-10}\times d^{25.2266}$	+0.966	57
$E=-78.9227+11.0114\times\ln v$	+0.938	57
$E=0.0183\sigma^{1.3646}$	+0.991	55

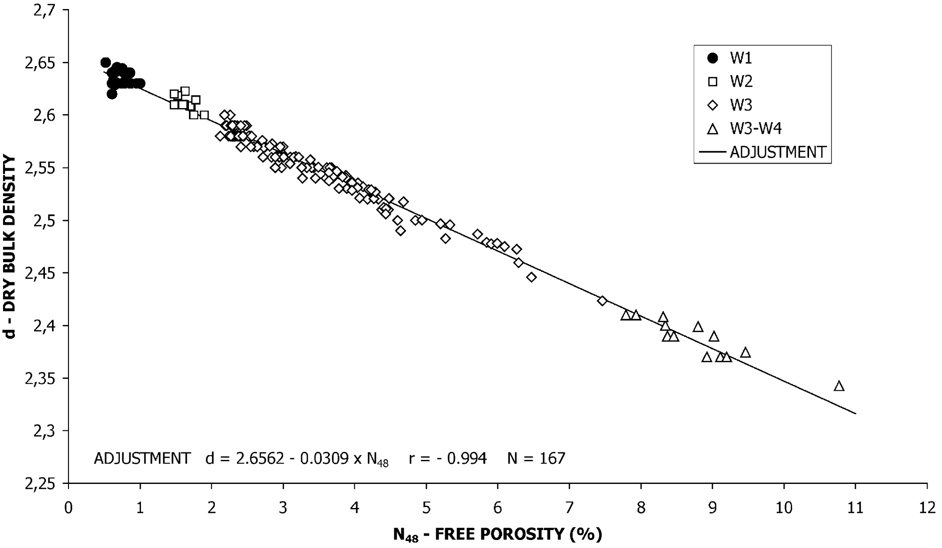

Fig. 5. Linear correlation between dry bulk density (d) and free porosity (N_{48}).

does not display significant variation during the weathering process. The strong linear correlation obtained between free porosity and dry bulk density confirms that the quantity of voids due to leaching of chemical elements in the weathering process controls the values of both parameters.

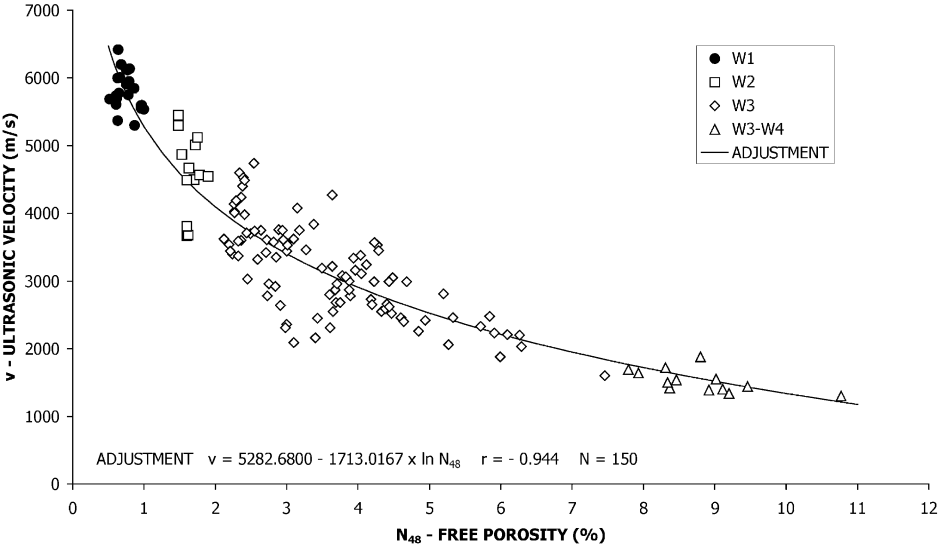

Fig. 6. Logarithmic correlation between the ultrasonic velocity (v) and free porosity (N_{48}).

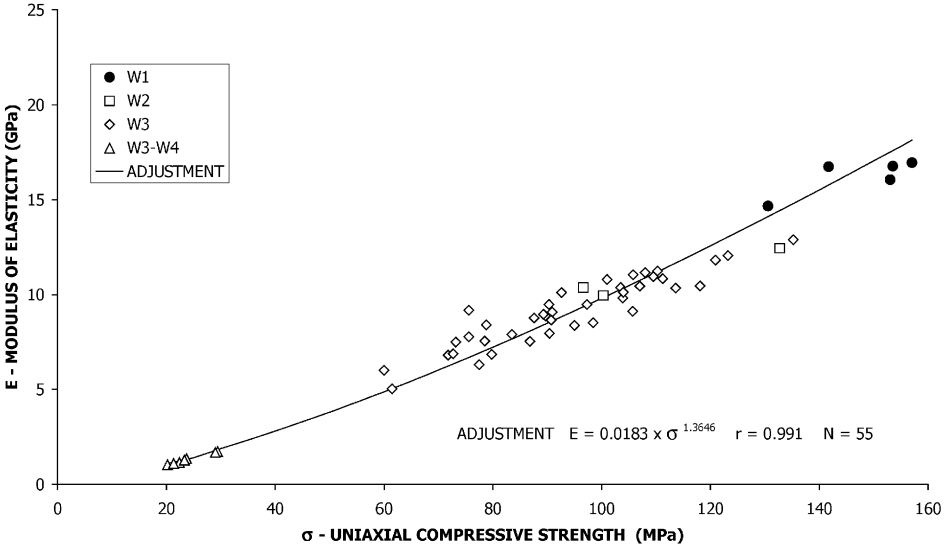

Fig. 7. Potential correlation between the modulus of elasticity (E) and the uniaxial compressive strength (σ).

The correlations v–N_{48}, v–d, σ–N_{48}, σ–d, E–N_{48} and E–d show that the most important variations in the values of ultrasonic velocity, uniaxial compressive strength and modulus of elasticity with free porosity or dry bulk density are exhibited at the very beginning of the weathering process (between fresh rock and slightly weathered rock). The sensitivity of v, σ and E at the beginning of weathering could be associated with the emergence of dendritic microcracks described by Begonha (1997) in slightly weathered Oporto granite. Free porosity should therefore be considered as the most important index property for several reasons: it is easy to determine, it has the highest interval of variation with weathering, and it is the property that correlates with the highest number of other physical parameters. Dry bulk density should be used as the second index property to confirm estimations achieved using free porosity.

7. Conclusions

The Oporto granite is a two-mica, medium-grained leucogranite, composed of quartz, microcline, plagioclase, muscovite and biotite. It was subjected to late post-magmatic alteration characterized by muscovitization of plagioclase crystals, by a second generation of plagioclase and by the presence of several generations of dioctahedral micas, chlorite, rare chorite-smectite mixed layer minerals and a pure smectitic phase in the fresh rock.

Complete weathering profiles of the Oporto granite are often 20 and up to 30 m deep. Each profile can be very heterogeneous and very different from nearby ones exhibiting contrasting degrees of weathering. The skeleton character of the saprolites is reflected in the particle-size analyses of these residual soils, principally the low percentage of the <2 μm fraction (6.2%). The saprolites preserve the original structures of the granite and can be more than 10 m thick. Gibbsite and kaolinite are the final weathering products. The skeleton character and the low quantity and mineralogy of the secondary minerals in the <2 μm fraction do not engender significant plasticity in the saprolites and geotechnically they exhibit no or low plasticity. According to the Unified Soil Classification System, most of them are SM-silty sands.

Results suggest that free porosity, ultrasonic velocity, uniaxial compressive strength and modulus of elasticity are strongly influenced by weathering; strain in rupture is moderately influenced; and dry bulk density is weakly influenced. Dry bulk density, ultrasonic velocity, uniaxial compressive strength and modulus of elasticity decrease during the weathering process of the Oporto granite whereas total porosity, free porosity and strain in rupture increase.

The data presented here suggest that free porosity should be considered as the most important index property for estimating other physical parameters. Dry bulk density could possibly be used as the second index property to confirm estimations made using free porosity.

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