EXPERIMENTAL PROPERTIES OF GRANITES

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ABSTRACT
In the present work, a study of the tensile mechanical behavior of a set of twelve selected granite lithotypes is carried out. Some petrographic aspects such as grain size and presence of planar anisotropy explain the variation on the parameters that characterize the tensile behavior, like the strength and fracture energy. Other factors that influence the tensile mechanical behavior, such as weathering degree and physical properties like porosity and density, are also analyzed. Statistical correlations between the ultrasonic pulse velocity and the mechanical and physical properties are proposed.

KEY WORDS
Granites, strength, fracture energy, physical properties, ultrasonic pulse velocity.

INTRODUCTION

Generally, natural stone represents the most widely used structural material in the past, whether in monumental or in more traditional constructions all over Portugal. The granite rocks, by their abundance in ancient buildings, assume an important role especially in Northern Portugal.
Any action related to the conservation and rehabilitation of an ancient construction needs the knowledge of the material that constitutes the structure, both in terms of mechanical and physical properties.
Granite rocks have a wide range of petrologic characteristics (namely, the mineralogical composition, texture – size grains – structure – arrangement of the minerals and voids) and weathering state. Thus, the main issue of the present study consists of a comprehensive characterization (both from mechanical and physical points of view) of a set of granite lithotypes selected taking into account these parameters. The granites are mostly originated from the Northern region of Portugal and can be related to the granites more frequently used in ancient constructions. As far as the mechanical characterization is concerned, the present study presents only direct tension tests results. Additionally the measuring of the ultrasonic pulse velocity is also performed and the possibility of using this property to determine the strength and other physical properties is addressed by means of statistical correlations.

DESCRIPTION OF THE SELECTED EXPERIMENTAL MATERIAL

The selection of the granite lithotypes was based on the mineralogical composition, size and shape of the grains. In addition to these criteria, the heterogeneity of the granites and the presentation of preferential orientation of the grains were also considered. In some cases, weathering effects were taken in account.
Thus, granites of fine, fine to medium, medium to coarse, and coarse grain were selected. Some of them present porphyroid structure. The variety of grain sizes allows the analysis of the influence of the microstructure on the mechanical behavior under tension.

The granites under study were mostly collected from the North of Portugal as shown in Figure 1. The summary of the petrologic description of the different lithotypes is presented in Table 1. The more weathered types of the same granite facies are designated with an asterisk (*).

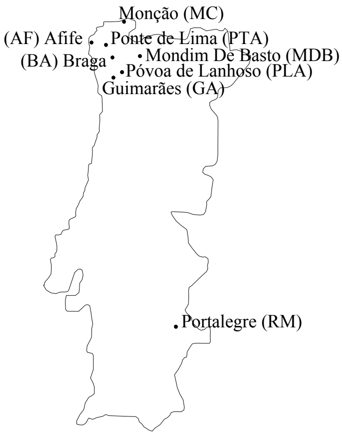


Figure 1 – Location map of the granites

Table 1 – Brief petrologic description

Granite	Petrologic Description
AF	Two micas, fine to medium grained granite
MC	Biotite-rich, coarse grained, porphyroid granite
MDB MDB*	Two mica, medium grained granite
RM	Biotite-rich, medium grained granite.
G, G*	Two mica, fine to medium grained, with porphyroid trend granite
BA	Biotite-rich, fine to medium grained, porphyroid granite
PTA PTA*	Two mica, fine to medium grained granite
PLA PLA*	Biotite-rich, medium to coarse grained, porphyroid granite

The specimens used for tensile tests, porosity tests and ultrasonic pulse velocity measurements, were extracted from blocks of different dimensions without apparent macroscopic cracks, since the presence of those cracks can significantly change the results [1]. In all blocks the orientation of quarry plans was carefully marked and in the case of granites that exhibit planar anisotropy the foliation plans were also considered.

EXPERIMENTAL CHARACTERIZATION OF GRANITES

The determination of the tension properties and the ultrasonic pulse velocities of granites that present planar anisotropy were carried out both parallel and perpendicular to the plan of foliation. The granites that exhibit significantly heterogeneity were tested also parallel and perpendicular to the rift plane (plane of easiest splitting). The other granites were assumed homogenous and only the direction of the rift plane was taken in account.

CHARACTERIZATION OF TENSILE BEHAVIOR

For the different granites under study, the properties that characterize the tensile behavior, tensile strength and fracture energy correspondent to mode I of failure were obtained from direct tensile tests, which should be the reference method to adopt [2,3]. With respect to this type of tests, several issues related to the specimens and the test procedures have been discussed in the literature. In particular, the testing equipment and control method, the size and shape effects of the specimens, the boundary conditions and the location of the LVDTs are aspects to be taken into account when stable softening behavior of quasi brittle materials, like the rock granites, is required [4,5,6].
In order to obtain the complete stress-displacement behavior of the granites, the direct tensile tests were carried out in a CS7400S servo-controlled universal testing machine with fixed loading platens. Due to the limited distance between the platens, the specimens were only 80mm height, 50 mm length and 40mm width. Such dimensions are particularly unfavorable in case of granites of coarse grain and porphyroid structure, since according to [2], the microstructure of rock materials, with variations in the grain sizes, grain shapes and interface

properties, is the main cause of the size effects. To overcome this difficulty, a high number of specimens was tested, so that the scatter in the results could be reduced, especially in the case of granites PLA and PLA*.
It is also noted that a notch with a depth of 5mm was introduced at mid height of the specimen, to localize the fracture surface. This procedure allows a suitable displacement control of the test through one of the four LVDTs located in the sides of the specimens. In order to enhance a controlled cracking propagation during fracture process the distance measured by the LVDTs is about 6mm, which also avoids any snap-back behavior, see [7] for details. Due to the brittle behavior of granite, direct tests had to be conducted using low values of the velocity, which varied between 0.08μm/s and 0.5μm/s.
Finally, for the selected MDB* granite both wet and dry conditions were considered in order to evaluate the influence of the moisture content on the fracture properties. All other specimens were tested in oven dry conditions.

PHYSICAL PROPERTIES

The tested physical properties of the granites, including porosity, bulk density and dry density, were determined in accordance with the procedures given in ISRM suggested methods [8]. In order to use representative samples of rock masses and taking into account the average dimension of the grains, cubic specimens of size approximately 15x15x15cm^3 were used in the porosity test. The ultrasonic pulse velocity of the granites was carried out on the same specimens, by the application of ultrasonic compression wave pulses according to ASTM D2845 [9]. In order to evaluate the influence of the moisture content on the values of the ultrasonic pulse velocity, the measurements were made using oven-dry conditions (0% saturation) and saturated conditions (100% saturation).

RESULTS

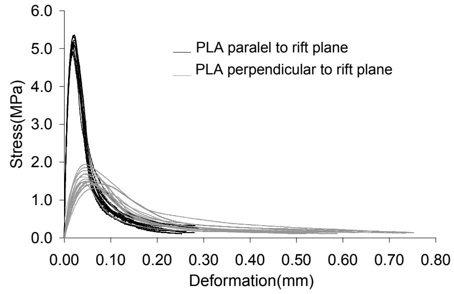
The complete stress-strain curves shown here adopt the average displacement measured by the four LVDTs placed in the sides of the specimen. From these curves the mean values of the fracture parameters, strength and fracture energy, as well as values of the initial tensile elastic modulus are calculated. The latter value is mostly qualitative because the notches introduce stress gradients that change the stress state of the specimens, see [2]. The fracture energy is calculated according to [5]. The results of the physical and mechanical properties are given in Table 2. Here, both the mean values of the properties and the variance (inside brackets) are shown.
It can be seen that, in general, granites present low porosity, even if weathered granites present higher values. It is also important to stress that the values of ultrasonic pulse velocity are strongly dependent of the moisture content, being higher values found on wet specimens.
The analysis of the values of fracture properties, indicated in Table 2, allows to conclude that strength and fracture energy vary with the direction of the applied load, the degree of weathering and the internal structure of the granites.
The degree of anisotropy (given by the ratio between the maximum and minimum strength values) of granites that presents foliation, MDB, MDB* and AF, is low to medium. Higher strength anisotropy occurs for the granites PLA and PLA*, being the degree of anisotropy equal to 2.25 and 2.02, respectively. Similar anisotropy was found in the fracture energy, parameter that seems to be directly related to the orientation and arrangement of the grains. Thus, in the granites PLA and PLA*, larger values of the fracture energy were obtained in the specimens tested in the parallel direction to the rift plane, for which the fracture surface presents higher roughness. The fracture surface in the perpendicular direction is almost flat. By visual observation of the fracture surfaces of all granites, the fracture energy seems to be correlated with the roughness of the fracture surface.

Table 2 – Physical and mechanical properties

Granite	Ft_{med} (N/mm^2)	Strength Anisotropy	Gf(N/m)	UPVdry(m/s)	UPVwet(m/s)	Porosity(%)
AF // foliation	3.04 (2.9)	1.30	202.6 (17.7)	2572.1 (12.1)	4175.9 (4.9)	3.07 (16.8)
AF ⊥ foliation	2.34 (11.4)		178.7 (16.8)	2273.8 (6.3)	4410.2 (3.1)	
BA	8.08 (2.7)	-	181.0 (4.5)	4804.8 (1.4)	5527.4 (0.98)	0.41 (12.3)
GA	6.06 (11.2)	-	148.8 (17.1)	4593.0 (0.95)	5424.0 (1.2)	0.47 (5.8)
GM	3.52 (12.3)	-	200.5 (18.7)	3244.3 (2.0)	4597.9 (0.92)	3.54 (3.2)
MC	5.23 (6.1)	-	222.1 (19.7)	4083.3 (1.1)	5489.3 (0.64)	0.87 (4.1)
RM	4.51 (9.3)	-	153.5 (19.0)	4104.5 (0.04)	5368.5 (0.02)	0.80 (14.9)
MDB*// foliation	1.97 (5.2)	1.08	248.8 (13.7)	2341.5 (0.62)	3959.8 (0.25)	7.24 (3.1)
MDB*⊥ foliation	1.81 (5.4)		263.4 (18.9)	2340.5 (0.03)	4025.1 (0.02)	
MDB // foliation	2.21 (4.8)	1.04	249.8 (16.9)	2241.1 (2.6)	3994.1 (3.3)	5.06 (7.3)
MDB ⊥ foliation	2.30 (11.8)		256.3 (17.0)	2488.9 (1.6)	4041.0 (1.2)	
PTA* // rift plane	2.12 (4.0)	1.35	254.8 (14.2)	2544.5 (11.8)	4042.2 (3.9)	5.19 (11.8)
PTA* ⊥ rift plane	1.56 (11.0)		228.2 (20.4)	2154.6 (20.2)	3937.9 (10.5)	
PTA // rift plane	4.16 (14.2)	1.18	184.3 (17.6)	3277.7 (2.1)	4722.9 (3.4)	1.17 (2.8)
PTA ⊥ rift plane	4.90 (15.1)		208.5 (13.0)	3584.9 (1.2)	4873.4 (2.5)	
PLA* // rift plane	3.86 (4.93)	2.02	246.2 (12.0)	3725.4 (2.0)	4967.1 (2.5)	1.55 (7.7)
PLA* ⊥ rift plane	1.91 (10.9)		160.8 (19.9)	2715.9 (6.9)	4507.3 (5.1)	
PLA // rift plane	6.31 (12.7)	2.25	270.9 (24.6)	2743.4 (2.0)	4705.8 (2.7)	0.84 (5.7)
PLA ⊥ rift plane	2.80 (10.5)		145.5 (19.2)	4161.9 (1.7)	5421.1 (4.8)	

Furthermore, the values of the fracture energy are also dependent on the internal structure of the granites regarding the size and shape of the grains. In general, the dissipated energy in the fracture process presents increasing values with the increase of the size grain and when the granites have porphyroid trend, for which bridging effects are also more severe, see also[10].
As far as weathering of the granites is concerned, it can be seen that there is a considerable decrease on the values of the strength and an increase of the fracture energy. By examining the shape of the complete stress-deformation curves for granites (e.g. granites PTA and PTA* as it is shown in Figure 2), it is possible to observe that larger values of the pre-peak and post-peak deformations were found out in case of the more weathered granite (PTA*). In fact, larger values of porosity are associated to more weathered granites, which are the result of the bond interface weakness between the grains and the matrix. On the other hand, the changing of the internal structure results in an increase of the dissipated energy during the post-peak cracking.
Figure 3 shows the complete tensile behavior of the granite MDB* under dry and wet (100% saturated) conditions. Even though the shape of the curves is similar, the values of strength present a decrease of approximately 25% with the change from dry to saturated conditions. On the other hand almost no change of the fracture energy mean value is verified, as the mean value presents an increase of approximately 5%.
According to the values obtained of ultrasonic pulse velocity, both the degree of anisotropy and weathering are well described by the UPV. In order to evaluate the dependence of the tension strength on the other mechanical and physical properties a set of statistical correlations were defined. The physical and mechanical properties were plotted against each other in order to evaluate a possible correlation. The best fit curves and correlation coefficient, r-squared, which measures the statistical correlation between each two variables was obtained by a least squares curve fit.
A non-linear correlation exists between the ultrasonic pulse velocity measured on dry specimens and the strength, as is shown in the Figure 4a. The r-squared value obtained for this correlation enables to conclude about the validity of ultrasonic pulse velocity as a non-destructive technique to predict and estimate the strength of granites that are present in ancient constructions. Similar non-linear trend between porosity and density was also obtained, see

Figure 4b. It is noted that the volumetric weight decreases as the porosity increases, see also [11,12].



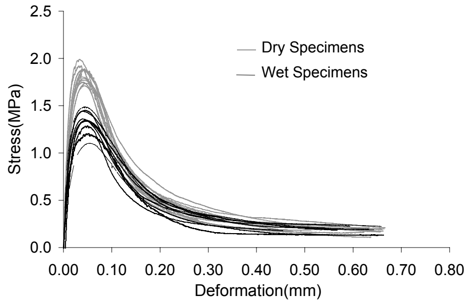
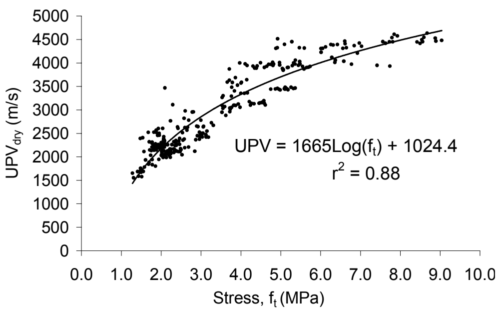


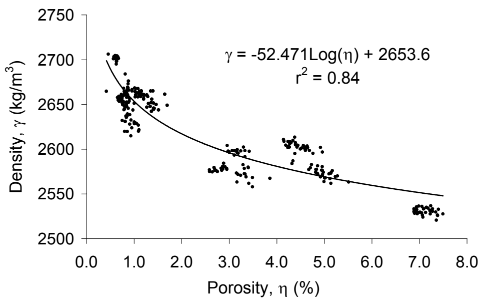
Figure 2 - Stress-deformation diagrams of granites PTA and PTA*

Figure 3 - Stress-deformation diagrams of granites MDM_{dry} and MDM_{wet}

A non-linear statistical correlation between the porosity and the ultrasonic pulse velocity, as well as the strength, is observed, see Figure 4c,d. The correlations obtained allow concluding that a statistical correlation between the variables does exist, though it can be affected by the high degree of anisotropy exhibited by some granites. It is stressed that the porosity is not a directional property, unlike the strength and the ultrasonic pulse velocity.



(a)



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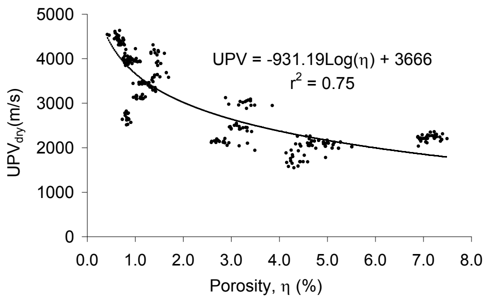
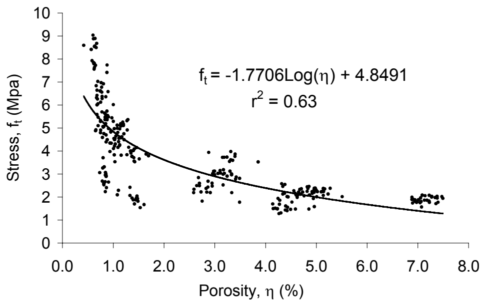


(c)



(d)

Figure 4 – Statistical correlations between: a) UPV_{dry} and Stress; b) Density and Porosity; c) UPV_{dry} and Porosity; d) Stress and Porosity

FINAL REMARKS

In the present work a mechanical and physical characterization of different granite lithotypes was carried out. This study provides fracture properties, from complete stress-deformation curves that resulted from a suitable controlled direct tension tests. The characterization of the tension behavior allowed to conclude that the fracture parameters, not only depend on the textural and structural characteristics of the material, but also on the weathering state, moisture content, and physical properties. With respect to structural issues it is important to highlight the high degree of anisotropy exhibited by some granites. Moreover, it can be seen that the correlation obtained between the strength and ultrasonic pulse velocity leads to the possibility of using this technique in practice, as an alternative to the removal of cores in the construction of for qualitative assessment.

Additional uniaxial compression tests are being carried out, from which the elastic and fracture properties in compression will be established. Furthermore, in order to clarify the influence of the microstructure on the fracture properties both in tension and compression a deeper research is required. For this purpose, a 3D laser scan of the fracture surface will be carried out.

BIBLIOGRAPHIC REFERENCES

1.GOODMAN, R.E - *Introduction to Rock Mechanics*, 2nd edition, Wiley and sons, New York, 1998. ISBN 84-376-0219-X.

2.VAN MIER, J.G.M. e VAN VLIET, M.R.A - *Uniaxial Tension Test for the Determination of Fracture Parameters of Concrete: State of the Art*, Engineering Fracture Mechanics, 69, 235-247, 2002.

3.VAN MIER, J.G.M. e SHI. C. - *Stability issues in uniaxial tensile tests on brittle disordered materials*, International Journal of Solids and Structures 39, 3359-3372, 2002.

4.VAN MIER, J.G.M.et al. - *Tensile cracking in concrete and sandstone – Part 2 – Effect of boundary rotations*, Materials and Structures, 29 87-96, 1996.

5.VAN VLIET, M.R.A - *Size effect In Tensile Fracture of Concrete and Rock*, PhD thesis, Delft University of Technology, 2000. ISBN 90-407-1994-2.

6.CARPINTERI A., e FERRO G. - *Size effects on Tensile fracture properties: a unified explanation based on disorder and fractality of concrete microstructur*e, Materials and Structures, 27 563-571, 1994.

7.VONK, R.A. - *A micromechanical investigation of softening of concrete loaded in compression*, volume 38, nº3 Heron, pp.94 1993.

8.International Society for Rock Mechanics, Rock Characterization, *Testing and Monitoring*. In: Brown E.T. - ISRM Suggested Methods. Pergamon, Oxford, 1981.

9.ASTM (American Society Testing Materials), *Standard Test Method for the Laboratory Determination of Pulse velocities and Ultrasonic Elastic Constants of Rock*, 1995.

10.GUPTA, A.S. e SESHAGIRI RAO, K. - Weathering effects on the strength and deformational behavior of crystalline rocks under uniaxial compression, Engineering Geology, 56 257-274, 2000.

11.TUĞRUL A., ZARIF, I.H. - *Correlation of mineralogical and textural characteristics with engineering properties of selected granites rocks from Turkey*, Engineering Geology, 51 303-317, 1999

12.PŘIKRYL R. - *Some microstructural aspects of strength variation in rocks*, International Journal of Rock Mechanics and Mining Sciences, 38 671-682, 2001