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Technical note

Experimental characterization of the tensile behaviour of granites

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1. Introduction

Granitic rocks have been widely investigated in rock mechanics but there is a significant lack of information about their complete tensile fracture behaviour. Rock failure in tension results from the propagation of one or more cracks and thus can be studied under the fracture mechanics domain.

The tensile behaviour of granitic rocks, similarly to concrete and other quasi-brittle materials that have a disordered internal structure can be well described by the cohesive crack model proposed initially by Hillerborg et al. [1]. Although with some limitations, the cohesive crack model has been widely used as the fundamental model that describes the nonlinear fracture mechanics of quasi-brittle materials [2,3]. Due to cracking localization, the tensile behaviour is characterized by two constitutive laws associated with different zones of the material during the loading process. The elastic–plastic stress–strain relationship is valid until the peak load is reached. The stress–crack opening displacement relationship describes the strain softening behaviour at the fracture process zone, after peak. The softening diagram assumes a fundamental role in the description of the fracture process and is characterized by the tensile strength and the fracture energy, which is given by the area under the softening branch of the stress vs. crack opening diagram.

There are several experimental methods that have been used to measure the fracture properties of quasi-brittle materials: tensile strength, fracture energy and the critical crack opening. The methods that allow the definition of constitutive laws of the material are the direct tensile tests and the indirect tensile tests, such as the three-point load test or the Brazilian splitting test. Direct tensile tests have been adopted in the present testing program, as the most appropriate test to characterize the basic failure mechanism (mode I) of quasi-brittle materials [4]. The lack of results in the literature from direct tensile tests on rocks can be attributed to the difficulties that are involved in the execution of this type of tests.

Concerning direct tensile tests, different issues related to the specimens and the testing procedures have been discussed in the past [4,5]. The heterogeneity of the material can assume an important role on secondary flexure, which can be increased by initial eccentricities caused by the imperfect alignment of the specimen. Furthermore, the attachment of specimens to the steel platens, the testing equipment, the control method and the location of the LVDTs are factors that have to be taken into account when stable softening behaviour of quasi-brittle materials is addressed. In order to reach reliable experimental results, a final issue is the need of obtaining representative volumes of material. Although the tensile strength and fracture energy are considered intrinsic properties of the material, it is well known that fracture properties are size and scale dependent. Experimental investigations [6,7] have revealed that tensile strength decreases with specimen size, whereas, fracture energy presents higher values for larger structures. Apart from size effects induced by stress and strain gradients [8], the variation on the fracture properties can be explained by the heterogeneity of the material [9]. In short, the challenge of obtaining mode I fracture properties by direct tensile tests consists of reducing the structural effects and of obtaining parameters exclusively determined by the material microstructure features.

The present work intends to represent a step forward in the knowledge about the tensile fracture behaviour of the granitic rocks. For this purpose, a set of distinct granitic

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types were selected, based on texture, internal structure and weathering degree, representative of natural stone from Portuguese ancient buildings. The accomplishment of this goal is based on the experimental study dealing with the obtaining of the complete tensile behaviour, from which it is possible to derive the fracture parameters.

In addition, the weathering state and microstructural aspects related to the arrangement of minerals are also considered, namely, the anisotropy associated with foliation and orientation of the rift quarry plane (plane of easiest splitting). Finally, in order to provide a better insight on the variation of the fracture parameters in distinct granites, statistical correlations are discussed.

2. Brief description of the material

Granite is the most used stone in the construction of ancient buildings located in the North of Portugal, either in monumental or vernacular architecture. A wide range of granitic rocks is present in masonry constructions, depending on their petrographic features, such as grain size and internal texture. Therefore, the mechanical characterization of only one type of granite would be rather limitative. In addition, the weathering processes, to which granites are subjected through years, lead to changes on the mechanical properties that require characterization. The granitic types considered in the present study were mostly collected from the Northern region of Portugal. The selection of the granite types was based on mineralogical, textural and structural characteristics. Thus, fine to medium, medium to coarse, and coarse-grained granites were selected (some of them with porphyritic textures). In addition to this criterion, the presence of planar anisotropies and the weathering condition (assessment based on macroscopic characteristics, namely colour) were also considered. The natural orientation planes of granitic rocks or preferred orientation of minerals (foliation) can be relevant for further analysis of the variation of the mechanical properties [10]. Three orthogonal planes can be identified with rock splitting planes (quarry planes) defined as planes of preferred rupture. The rift plane is the plane corresponding to the easiest splitting in the quarry being easily recognized by the quarryman since it is further associated to the plane of easiest finishing. The foliation was marked, when macroscopically discernible. The orientation of the quarry rift planes was marked with the help of the quarryman.

A brief description of the different types studied here is presented in Table 1. The more weathered types of the same granite facies are designated with an asterisk (*). Additionally, the loading directions considered for each granite type are also indicated. It should be noted that the fresh granite PTA exhibits a clear preferential planar orientation but this feature was not visible, macroscopically, on the weathered type PTA*.

Table 1
Brief description of granites and loading directions

Granite designation	Description	Loading directions
AF	Fine to medium-grained two-mica granite	Parallel and perpendicular to the foliation plane
MC	Coarse-grained porphyritic biotite granite	Parallel to the rift plane
MDB MDB*	Medium-grained two- mica granite	Parallel and perpendicular to the foliation plane
RM	Medium-grained biotite granite	Parallel to the rift plane
GA, GA*	Fine to medium-grained, with porphyritic trend, two mica granite	Parallel to the rift plane
BA	Fine to medium-grained porphyritic biotite granite	Parallel to the rift plane
PTA PTA*	Fine to medium-grained two-mica granite	Parallel and perpendicular to the foliation and rift plane
PLA PLA*	Medium to coarse-grained porphyritic biotite granite	Parallel and perpendicular to the rift plane

3. Specimens and testing procedure

The direct tensile tests were performed using a James Cox CS7400S servo-controlled universal testing machine with fixed end platens. This equipment has a load cell connected to the vertical actuator with a maximum capacity of 22 kN, being particularly suitable for small specimens.

It is well known that the shape of the softening branch depends on the boundary conditions, which have been indicated to affect slightly the values of the fracture energy [11]. Nevertheless, all tests in this research program were performed under the same boundary conditions, allowing further comparative analysis of the results.

The size of the specimens was defined taking into consideration the restrictions of the testing equipment and the limitations for manufacturing the rock specimens. Due to the maximum distance available between the platens, prismatic specimens of 80 mm height, 50 mm length and 40 mm width were considered [12,13]. The microstructure of rock materials, which exhibits variations in the grain sizes, grain shapes and interface properties, and possible pre-existent microcracks and flaws, is responsible for size and scale effects [4,9]. The ISRM recommendations [14] indicate that the diameter of the tested specimen should be related to the size of the maximum grain in rock by a ratio of, at least, 10:1. For granite specimens with fine to medium grain size, the latter condition is followed here, but for coarse-grained granites the dimensions adopted for the specimens are insufficient, since larger representative material volume would be required. To overcome this limitation, a higher number of specimens were tested in order to evaluate the scatter in the results and the usefulness of the average values for the characterization of the macroscopic properties. On average, fifteen