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Mechanical behavior of high strength granite for new prestressed stone structures

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ABSTRACT

The present paper analyzes the internal destruction process of high strength granite under compression, focusing inconsistencies between some conventional theories and the observed reality. It is proposed that the crack progression is a result of the relative displacement of two fitted irregular faces, which implies an increase of the gap between them and tensile forces at the tips. This model explains some aspects of the mechanical behavior of granite: (a) Spalling of granite laminae without buckling processes; (b) Consequences of the destruction of crack face irregularities; (c) Effect of the grain size in the compressive strength. The paper also discusses some loading conditions effects in the compressive strength of granite: load distribution; constraints of transversal deformation on the loaded ends of specimens; long term loads; cyclic loads.

1. Introduction

To build innovative slender granite structures with high compression stress levels, a detailed analysis of the material mechanical behavior becomes necessary. The path for such analysis must be distinct to the conventional theories and models based on nonlinear mechanics, which cannot describe some experimentally observable phenomena like long cracks or spalling. Models consistent with the observed reality in experimental tests and technical applications as mining engineering [1] are required.

The need of more adequate models exists because the currently used theories fail in the description of some failure modes ([1,2], and [3]). The level of complexity of some models of nonlinear analysis is also not compatible to the needs of the practice in structural design. The models should be robust, without too many hypotheses and parameters of complicated control, to overpass limitations of the current knowledge and practice.

To develop consistent and safe methods for the design of innovative granite structures, exploring high strength, where the current approaches have limitations and inconsistencies, knowledge of the internal destruction processes of granite under compression is essential. A core aspect is the understanding of what causes tension forces at the crack tips and their consequent progression. This paper proposes a clear and mechanical explanation of those forces based on fundamental and simple experimental observations. The perspective is similar to the presented in [4], related to the real shape of cracks in structural concrete.

Strut-and-tie models [5] are currently powerful tools for the design of concrete structures, being consistent with the material behavior and the equilibrium of internal forces. The similarities of the mechanical behavior of granite and concrete, as shown in this paper, leads to the proposal to apply those models in the design of granite structures.

The referred models result from the integration of stress fields into axially loaded struts and ties, which compose an equilibrium system with the external forces. Such equilibrium is only possible if allowed by the strength of the model elements, on direct compression or tension, implying a safety condition for the resultant forces. The needed strength limits must consider the real structure conditions, as the loading duration, cyclic nature of loads, uniformity of the compression forces distribution, existence of transversal reinforcement and mortar in the joints. Based on experimental results, it was possible to understand those effects and to determine reduction factors, to obtain effective strength design limits f^{*}_{gd}, from the characteristic value of the compression strength f_{gk} measured in specimens.

The consideration of failure mechanisms consistent with experimental observations is an essential requirement to obtain strut-and-tie models with possible-effective conditions of equilibrium, otherwise the model is not adequate for the design of structures.

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The main contributions of the paper are the definition of (i) exploitable safe strength levels; and (ii) criteria for selecting design models and technological solutions consistent with observed granite mechanical behavior, avoiding early brittle failures.

2. Fundamental experimental observations

2.1. The internal destruction processes

It can be proved that internal destruction of granite results essentially from the formation and progression of cracks, which can only arise due to tension forces of some type.

According to [1,6], the destruction of granite and other rocks under compressive loading can be divided in two phases: (a) The primary phase, which corresponds essentially to the formation of cracks due to transversal tension forces; (b) The secondary phase, which leads to failure either by buckling of few slender pillars formed between cracks (Fig. 1) or by global deformation and simultaneous instability of series of micro-pillars along inclined ''sliding'' planes (Fig. 2).

During the primary phase, the longitudinal compression induces transversal tension forces near the ends of voids, pre-existing cracks or grains with heterogeneous stiffness.

The length of the cracks determines the occurrence of one or another variant of failure. Failure by buckling of slender pillars occurs when cracks have a long progression. The instability along inclined planes when crack length remains short. In this second case, the global ''sliding'' planes may divert the attention of the observer from the small size cracks that remain unconsidered [1].

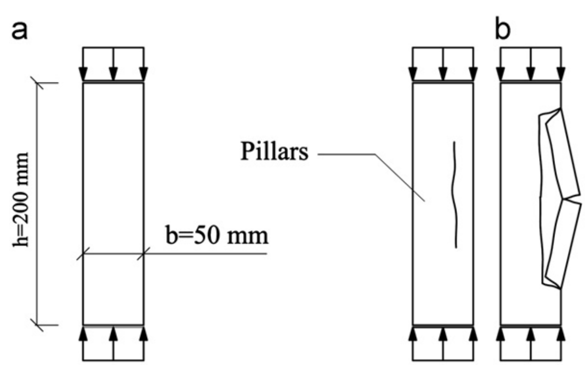

Fig. 1. (a) Failure of a granite prism ($h/b=4$); I—Progression of an axial macro-crack; II—Buckling of the resultant pillars. (b) Half of the prism after failure.

The formation of long cracks may result from the coalescence of shorter cracks practically aligned or slightly offset, by the breaking of the weak connection zones between the crack tips [6]. In low strength granites with bigger grains, the coalescence is more difficult due to the unfavorable relative position of the cracks. The micro-pillars collapse before the cracks can coalesce or significantly progress. As shown in Section 4, the crack progression is more difficult than in high strength granites.

The progression and opening of a crack implies transversal compression of the lateral zones, which inhibits the opening of other adjacent cracks (Fig. 2). In high strength granite, the long cracks produce an enlarged confinement, which reduces the number of cracks and increases their spacing (Fig. 3). Under uniform compression, there is a tendency for symmetric transversal deformations that creates a lower state of confinement in the central region. The progression of cracks becomes easier in that zone.

Failure by buckling of pillars is a characteristic of high strength granites. Fig. 1 describes the failure of a granite prism with dimensions ratio $h/b=4$ in uniaxial compression test performed by the authors ($f_{gk}=140$ MPa). The progression of a central macro-crack originates two pillars, whose buckling leads to failure as shown in Fig. 1b. The material destruction by cracking before buckling is local and the main part of the specimen maintains the capacity to transfer loads.

The relation h/d of the tested specimens is higher than the generally used in the compression tests ($h/d=2$). With higher relations h/d the confinement effect of the loading plates becomes local, which has effects in the failure mode, including the reduced number of macro-cracks. The compressive strength values used in the design of slender granite structures should result from compression tests on slender specimens with relations h/d higher than 4, because lower ratios may be influenced by confinement effects.

Failure along inclined planes occurs when crack progression is limited. It is the characteristic failure mode of low strength granite. It may also be found in very slow tests and in compression tests with transversal confinement. Failure occurs by global deformation and simultaneous instability of many micro-pillars placed along inclined bands (in an echelon formation of cracks) dependent from the kinematics of the whole body parts. This type of failure is only possible if the two parts posteriorly separated by the inclined plane can have a relative displacement.

The relative position of the micro-pillars in echelon is a consequence of the impossibility to significant progression of

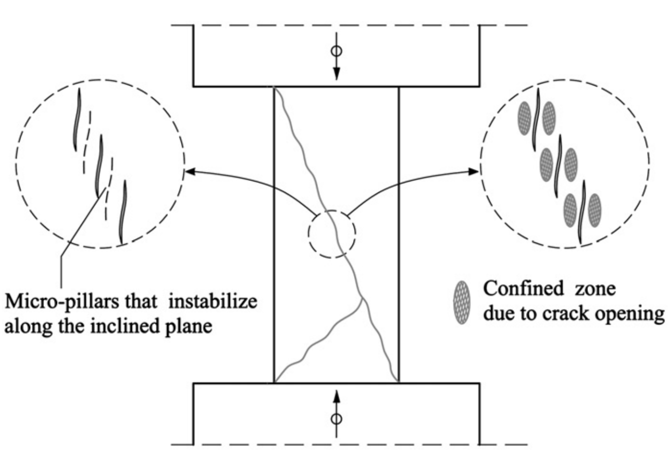

Fig. 2. Failure by global deformation and simultaneous instability of micro-pillars forming inclined ''sliding'' planes.

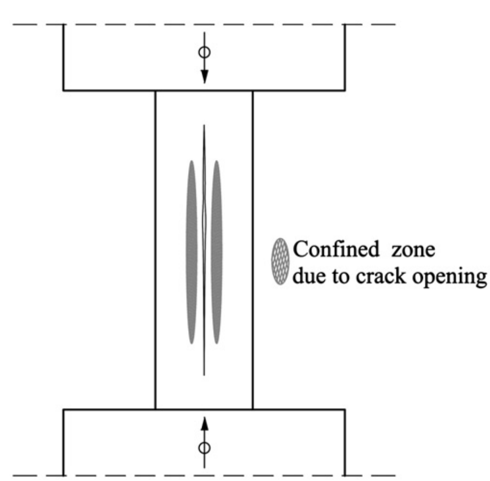

Fig. 3. Progression of a long crack inhibiting adjacent cracks.