Formation of extension fractures as constitutive instabilities: Physical experiment

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Summary

Extension fractures/discontinuities perpendicular to the least stress σ_3 were generated in a synthetic physical rock analogue material (granular, frictional, cohesive and dilatant) in axisymmetric extension tests. These fractures are of two types defined by the mean stress σ. When σ is very small, the fractures form through mode I cracking at σ_3 equal to the material tensile strength. The fracture walls have smooth surfaces. With σ increase the surface becomes progressively rougher and has plumose topography very similar to that in geological joints. These fractures were shown to be initiated as propagating localization bands characterized by the porosity increase due to dilatancy. As evidenced on MEB images, the dilation bands are not opened and are not fractures. They are generated even at slightly compressive σ_3 and become fractures with plumose fractography after the separation of the sample parts along the band. These results as well as MEB images of incipient natural joints suggest that most of them could have been formed (initiated) as dilation bands.

1. Introduction

The mechanism of quasi-brittle fracture/rupture remains one of the central problems in different domains of material science/mechanics including geomechanics. There are basically two approaches to this problem. One is the fracture mechanics approach stemming from the Griffith energy balance theory. It considers conditions of stability of cracks characterized by strong stress concentration at the tips that causes the crack propagation in a very heterogeneous stress field.

The other approach to the failure of materials is the formation of deformation localization bands as constitutive instabilities [*Rice*, 1973, 1976; *Rudnicki and Rice*, 1975] whose mechanism is far from being totally understood The instability can result from the smooth evolution of the constitutive parameters (such as cohesion and internal friction) with deformation or their abrupt change at some point. The latter leads to the formation of the localization band networks with the material outside the bands undergoing elastic unloading [*Chemenda*, 2007, 2009].

The most difficult and probably important area for applications is a transition between both mentioned above end-member approaches to the mechanics of quasi-brittle rupture. Understanding of this process is impeded by a critical lack of sufficiently precise and detailed experimental information (including mechanical, microstructural and fractographic data).

The present paper is a contribution to reduce this lack. It reports results and analysis of axisymmetric extension tests on an "ideal" synthetic granular, frictional, cohesive and dilatant physical rock analogue material GRAM1.

2. GRAM1 material, experimental setup and procedure

GRAM1 (Granular Rock Analogue Material 1) is made from a finely ground powder of TiO_2 with well sorted grains treated with polyacrylic acid in order to reduce the grain surface energy. The average grain size is of ~0.3 µm. The powder is subjected to the hydrostatic pressure of $P^{fabr} = 2$ MPa at which the grains are bonded one to another by the Van der Waals-type molecular forces defining the cohesion of the resulting material. The strength of the created bonds and their “brittleness” depend on the contact surface, the fabrication pressure, the form of the grains and the surface energy of the granular material. These parameters were chosen so that the synthetic material has the internal friction coefficient, the dilatancy factor, the Poisson ratio, the compression and tensile strengths values approximately to scale with real rocks in the brittle field (but about two orders of magnitude less strong).

The dog-bone-shape GRAM1 samples were instrumented with the LVDT strain (displacement) sensors (two axial and four radial), jacketed and subjected to the confining pressure *P* in the pressure cell filled with mineral oil. Then the samples were progressively unloaded in the axial direction at *P*

= *const*, which resulted in its deformation and fracturing. Finally these samples were totally hydrostatically unloaded. The formed fractures/discontinuities were studied both visually and using SEM (Scanning Electron Microscope).

3. Results

Fig. 1a shows a typical aspect of a fractured sample. One can see a discontinuity (in the sample middle) that corresponds to the extension fracture formed. The surfaces of the borders of such discontinuities generated at different P are shown in Figs. 1b to d. All are orthogonal to the sample axes, hence to σ_3, which in Figs. 1b and c is tensile and in Fig. 1d, compressive. At higher P, the fractures become oblique to σ_3, with the obliquity angle growing with P or σ.

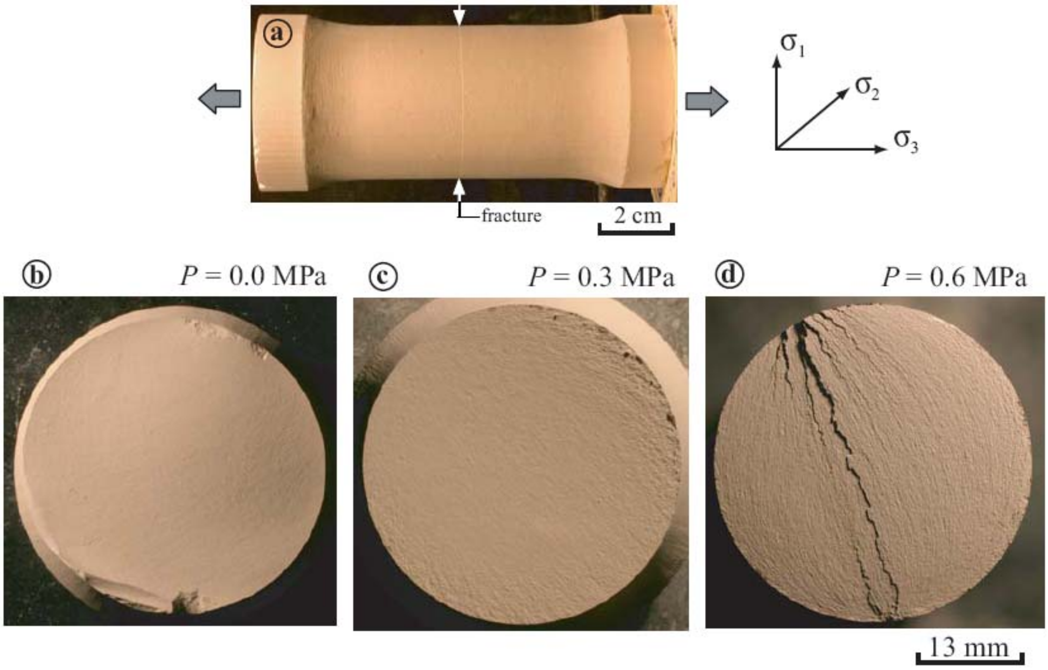

Fig.1. (a) General view of the fractured GRAM1 sample. Surfaces of the σ_3-orthogonal fractures generated in GRAM1 at different P.

The surfaces of σ_3-orthogonal fractures exhibit faint and delicate ridges and troughs forming a plumose topography, which becomes less expressed with P reduction (Fig. 1) and disappears completely at $P < \sim 0.2$ MPa.

Fig. 2a shows the SEM section of the not yet opened discontinuity (fracture) formed at $P = 0.6$ MPa. At SEM scale, the discontinuity represents a non planar, several grain-thick band of heterogeneously damaged material. The band consists of a quite irregular alignment of voids of different shapes and sizes, zones of loose grains indicating decompaction/dilation, and bridges of apparently intact material. There is clearly neither an along-band progressive/monotonous evolution of the deformation/damage, nor a progressive separation of the band (future fracture) walls. There is no separation at all. The material within the band underwent partial heterogeneous decohesion and dilatancy. Therefore the obtained bands are dilation bands. Because of the non planar geometry of the bands at this scale, micro-shearing accommodated by grain sliding, translation and rotation are certainly present as well. All are distributed in a complex manner in three dimensions and result in the volume/porosity increase.

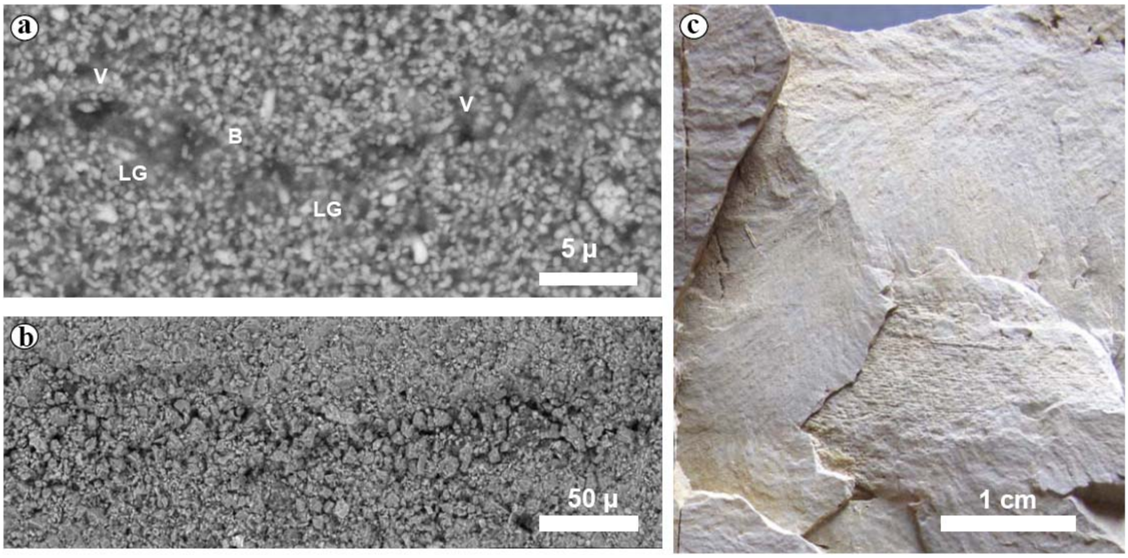

Fig. 2. Aspects of experimental (a) and natural (b) dilation bands. (a) SEM photomozaics (backscattered electrons micrographies) of the band in GRAM1 sample fractured at $P = 0.6$ MPa. The band area was impregnated with a low-viscosity epoxy resin which penetrated the pores both inside and outside the band. After the polymerization (solidification) of the resin, the sample was cut perpendicularly to the band and the section was carefully polished before observation. The structures are typical and cannot be induced by cutting/polishing procedure. At the scale shown the band displayed is formed by an alignment of voids (V), loose grain zones (LG) where the decompacted grains are surrounded by the resin (blurred grey background around the grains), and by zones (bridges (B)) of apparently intact material. (b) SEM image of a fine discontinuity (incipient joint) parallel to a dense joint set in dolomicrites ("cubic dolomite") of the tabular Hettangian layers of the Larzac Plateau border (South France). It shows a band with loose/dislocated grains and increased porosity (compared to the host rock). In both SEM images, the thickness of the band is a few to several grain diameters. (c) Aspect of plumose features on an open joint limiting the dolomicrite sample from which the SEM image in (b) was obtained (the fine discontinuity whose zoomed trace is shown in (b) is parallel to the surface shown).

4. Formation mechanisms

The data presented and those on the GRAM1 samples mechanical response during fracturing suggest that what is called in literature "extension fractures" includes fractures of two types corresponding to different formation mechanisms.

Smooth-surface fractures forming at very low σ are simply mode I (or opening mode) cracks that are generated when tensile σ_3 reaches the material tensile strength.

Plumose-surface fractures are not simple/isolated cracks but result from the interaction of grains, pores, and microcracks localized in a narrow dilation band with the internal structure bearing traces of these interactions (Fig. 2a). Although dilatant, the band is initially closed. Therefore it is not a fracture. After its opening, no direct traces of the band remain (except maybe some undetectable amount of the powder shed on the table) whose thickness in GRAM1 does not exceed a few microns. The indirect trace of the band is the plumose relief of its boundaries (fracture walls), which is defined by the geometry of the decohesion pattern of the material and suggests that the band is a propagating feature (the propagation/failure is dynamic). This would suggest the mode I-type crack mechanism, but this is false, as the band was never opened before its separation and is not yet a fracture. We argue that the most likely mechanism of band formation is a kind of constitutive instability resulting from the deformation bifurcation. The bifurcation is theoretically predicted and should occur at very small inelastic deformation (damage). What we were able to observe in the laboratory experiments is the result of post-bifurcation evolution of band deformation when it was finite and not homogeneous. This deformation can be modeled in dynamic numerical models. Such models [*Chemenda*, 2007, 2009] confirm on the one hand the predictions of the bifurcation theory regarding the conditions of the bifurcation onset, orientation and average spacing of the bands. On the other hand, they show that the deformation bands are not continuous even at the onset in the homogeneous stress-strain field and that they can propagate with the increasing deformation. Further progress in understanding of this process can be achieved only by combined laboratory and numerical experimentation and theoretical analysis of the results.

5. Comparison with geological joints

The fractures of the second type (dilation bands) obtained in the presented experiments are very similar to geological joints. The similarity is expressed first of all in the plumose topography (Figs. 1 and 2c) and the orientation of experimental and geological joints (both are orthogonal to σ_3). This similarity suggests that the natural joints with plumose fractography have been initiated as dilation bands and not as mode I fractures as is commonly considered in geological literature.

Research of the hitherto never described dilation band structure in natural joints certainly needs specific observations. It must be impeded by the very common aperture of joints and subsequent diagenesis (especially in carbonates) which transforms the internal structure. Fig. 2b shows a SEM image of a joint-parallel discontinuity from densely jointed Jurassic dolomicrites (fine grained carbonate rock) of Languedoc, where joints exhibit fine plumose features (Fig. 2c). Decohesion with porosity increase revealed by SEM observations is similar to what is observed in GRAM1 (Fig. 2a), strongly suggesting a dilation band structure. There is some similarity with the structure of dilation (disaggregation) band images of *Fossen et al.* [2007] from the Nubian Sandstone of Sinaï, and of *Du Bernard et al.*, [2002] in poorly consolidated sands of California. These observations reinforce the conclusion that the formation mechanism of plumose-bearing natural joints is similar to that in GRAM1, i.e., is the running dilation banding. The mechanism suggests the name of this type of joints, dilation joints, whereas joints forming through mode I mechanism (hence with smooth surfaces) can be called mode I joints.

A major impact of jointing mechanisms (propagating dilation band *vs*. mode I crack) refers to the prediction of spacing λ between joints, which is very important for reservoir modeling. For mode I, λ is controlled by the stress shadow effect resulting in the concept of fracture saturation according to which λ cannot be smaller than a certain value comparable to the layer thickness [*Rives et al.*, 1992 ; *Bai and Pollard*, 2000]. For localization bands, λ is defined by the stress-state type, all constitutive parameters (especially by the hardening modulus), and can vary from infinity to band thickness independently of layer thickness [*Chemenda*, 2007; 2009]. Very dense joint sets with λ much smaller than is "allowed" by the simple fracture saturation concept are frequently observed in the field.

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