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Shear-enhanced compaction band identification at the laboratory scale using acoustic and full-field methods

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ABSTRACT

This paper presents results from the analysis of shear-enhanced compaction bands that developed in a porous sandstone during triaxial compression tests at high confining pressures. The analysis uses non-destructive full-field experimental methods: X-ray tomography, 3D-volumetric digital image correlation (DIC) and acoustic emission (AE) monitoring including source mechanisms analysis. The 3D-volumetric DIC measurements reveal that these bands are zones with: a small component of band-parallel slip; a larger component of vertical shortening; compactant volumetric strains; and high maximum shear strains. Low X-ray tomography gray-scale standard deviation values within the bands indicate regions of grain size reduction and grain fragmentation. AE hypocenters detected during loading were concentrated inside these narrow bands and showed predominantly pure and hybrid collapse mechanisms; the latter implies some shear strain and is consistent with the oblique geometry of these bands. The experimental results in general support the hypothesis that laboratory developed shear-enhanced compaction bands, at least those studied here, share more characteristics with compaction bands than with compactant shear-bands; these latter deformation features differ from shear-enhanced compaction bands not only in the mechanical behavior, but also in the kinematics and the grain-scale deformation mechanisms.

1. Introduction

Compaction bands, a subset of deformation bands, have only recently been widely recognized in geological outcrops. Published documentation of naturally occurring compaction bands are confined to studies of two Jurassic Aeolian sandstones (see [1] for a review); the Navajo sandstone at the East Kaibab Monocline, Utah [2] and the Aztec sandstone at the Valley of Fire, Nevada [3–5]. The deformation features observed by these authors have been identified as either sets of *pure compaction bands* or as *shear-enhanced compaction band sets*. Pure compaction bands are characterized as narrow tabular zones of inelastic deformation, which have accommodated pure compaction (volume loss) with no evidence of shear and according to these authors, have formed normal to the major principal stress direction [2]. Shear-enhanced compaction bands are inferred to form at 38 to 53° relative to the maximum principal stress direction and thus, to accommodate localized compaction oblique to the loading direction [5]. Field observations have demonstrated that shear-enhanced compaction bands are longer than pure compaction bands but their shortening normal to the band width and offset along the band length are similar. Although more intense grain crushing has been documented in shear-enhanced compaction bands, grain fragmentation and grain size reduction exist in both types of compaction bands [6]. Furthermore, both bands are characterized by reduced porosity and permeability [1,7]. The latter observation strongly suggests that compaction bands could act as baffles to fluid flow and thus have significant implications for hydrocarbon production in subsurface geologic reservoirs and CO_2 disposal into aquifers.

Initial geological outcrop observations of compaction bands have been followed by many experimental investigations at the laboratory scale. Compaction band formation and propagation have been studied experimentally in a variety of porous sandstones, with porosities ranging from 13 [8] to 28% [9], different mineralogical compositions (among others[8,10–12]) and a range of grain sizes [12,13], deformed under triaxial compression at high confining pressures. Baud et al. [13] suggested a classification of

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these laboratory-generated deformation bands based on their width. Discrete compaction bands, with a width equal to three intact grain-sizes, have been described in [11–15], while diffuse compaction bands, with a width of more than three grain-sizes, have been presented in [12–14]. All of these bands are characterized by porosity reduction, intense grain fragmentation and permeability decrease.

Several theoretical frameworks, based on both field and experimental observations, have been applied to understand the formation and propagation of compaction bands in porous rocks. Compaction bands in rock can be understood as a bifurcation of the inelastic response, and thus their occurrence can be predicted by using the tools of bifurcation analysis [16–20]. Although bifurcation analysis appears to be a good theoretical framework for the compaction band study, it is limited in that continuum analysis deals solely with the onset of the constitutive instability in the initially homogeneous material. Therefore, bifurcation theory cannot explain compaction bands or predict their geometrical complexities, including any further micro-scale deformation. Field observations of long linear natural compaction bands suggested the idealized penny shape geometry, which has motivated different micro-mechanical models (anti-crack and inclusion models) analyzed in the framework of linear elastic fracture mechanics [4,21,22]. Such models indicate the ways in which the microstructural heterogeneities affect the compaction band initiation and propagation. A combination of processes described both by the bifurcation theory and an anti-crack model has been applied by Chemenda [23] to reproduce tabular compaction bands using finite-difference simulations. Micromechanical parameters related to the formation of compaction bands, such as initial porosity, crushing strength and variability of grain size shape and mineralogy, have been taken into account in discrete element approaches to describe their propagation [24–26].

The goal of this work is to advance our understanding of the micro-processes that may occur during the formation and evolution of compaction bands in porous sandstone subjected to triaxial compression at the laboratory scale, which is a crucial step in expanding knowledge of the larger scale natural systems. We first present the material used and the experimental procedure followed within this study. Results are discussed in terms of a combination of experimental methods, which captured different aspects of the observed deformation features and the deformation mechanisms that occurred.

2. Material and experimental procedure

The experiments presented here were carried out on a sandstone from the Woustviller quarry, in the Vosges Mountains, France, which comprises approximately 93% quartz, 5% microcline, 1% kaolinite, 1% micas, a few oxides, and has an average porosity of 22% [19,27,28]. Grains, mean diameter 300 μm, are moderately sorted and have a sub-angular to round shape. The sandstone's pore network tends to be rather heterogeneous, *i.e.*, some of the pores are rather small in certain regions while, less commonly, in other regions the pores have a shape and a size resembling grains. Observations of these grain-shaped pores suggest weathering out of feldspar grains, potentially by chemical alteration to clays and subsequent transported removal. This assumption is supported by observations of chemically altered feldspars, seen in thin sections [29]. The cement, which binds the grains together, appears mostly as quartz overgrowths.

Five cylindrical specimens with diameters of 40 mm and height of 80 mm were cored normal to the sedimentary bedding plane. Specimens had two opposite flattened surfaces along their height, which facilitated the pre- and post-deformation ultrasonic wave measurements [30]. A Teflon interface was used at the top and bottom of some samples acting as lubricant during the triaxial loading. A circumferential rounded notch (4 mm in depth and 0.8 mm in height) was machined at the mid-height of four out of the five tested specimens. The circumferential notch was filled with a 0.7 mm thickness Teflon O-ring (following [15]), which prevented the neoprene membrane (that jacketed the specimens during loading) from entering the notch and, thus, reduced the risk of failure of the experiment due to oil leakage through the membrane. In addition, two extra Teflon pieces were used to fill the space around the flattened surfaces of the specimens and so maintain the cylindrical geometry during the triaxial loading.

Triaxial compression experiments under dry conditions were performed on these Vosges sandstone specimens using a triaxial deformation apparatus. This system consists of a servo-hydraulic loading frame from Material Testing Systems (MTS) with a load capacity of 4600 kN and a triaxial cell sustaining a confining pressure up to 200 MPa. An important characteristic of this system is the ability to record acoustic emissions and ultrasonic transmission signals at a number of different positions during the loading of specimens. During the initial phase of isotropic compression, the confining pressure on the specimens was increased from zero to the highest pressure for each given experiment at a constant rate of 1 MPa/min. The subsequent phase of deviatoric loading was performed under constant displacement control at a rate of 20 μm/min (corresponding to a nominal axial strain rate of $2.5 \times 10^{-4}\ \text{min}^{-1}$). The axial loading during the latter phase was stopped at different axial strain levels for each sample, after which the specimens were fully unloaded. 3D X-ray tomography images were acquired for all the specimens before and after the triaxial compression experiments.

3. Experimental methods

With the occurrence of localized deformation during a loading experiment, such as compaction bands, standard experimental measures during triaxial testing, which obtain a bulk value for the whole sample, are insufficient to characterize the mechanisms and structural evolution of the material. For this reason there has been an increasing interest in using full-field methods [30–34,7] and acoustic methods [11,15,35,36] that permit analysis of the spatio-temporal distribution of mechanical evolution. However, individually such techniques still cannot answer all the questions being posed; therefore in this work a combination of techniques is employed to provide a powerful experimental tool that can capture the onset, evolution and resultant microstructure of localized deformation and to aid in the understanding of the underlying deformation mechanisms. The main advantage of such a combined experimental analysis approach is connected with the different sensitivities and resolutions of each method. In this paper, we show results on acoustic emission (AE) monitoring and source mechanisms analysis together with X-ray tomography and digital image correlation (DIC) from Vosges sandstones specimens.

3.1. Acoustic emission measurements

AEs, produced by the rock specimens as they deformed, were recorded during the triaxial compression experiments (syn-deformation measurements). Fourteen P-wave sensors were glued on the cylindrical surface of each specimen and sealed into the neoprene jacket using a two-component epoxy. These sensors were composed of PZT disks of 5 mm diameter and 1 mm thickness placed in brass housings; the PZT elements had a thickness-related resonant frequency of 1 MHz. Two P-wave sensors, of