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Brittle-to-ductile transition in Beaucaire marl from triaxial tests under the CT-scanner

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Abstract

This paper presents an experimental study of the deformation of Beaucaire marl subjected to drained triaxial tests under a wide range of confining pressure. Several methods of observation have been used: X-ray computed tomography, scanning electronic microscopy, quantitative image analysis of thin sections and mercury porosimetry. The analysis at the grain scale shows the existence of various deformation modes depending on the mean stress level. These modes are classified with reference to the brittle and ductile regimes. In specimens deformed under low confining pressure, macro-cracks are localised in a band more contracting than the rest of the specimen. In specimens deformed under moderate confining pressure, a series of micro-scale shear bands characterised by a grain re-orientation towards the direction of macro-shear is detected in the zones of localised deformation. The material in between the micro-scale shear bands is contracting more than the rest of the specimen in some cases; in other cases, a schistosity is detected also in the rest of the specimen outside the localisation zones. In the specimen deformed under high confining pressure, no localisation occurs, and a schistosity is observable throughout the specimen.

Keywords: Brittle; Shear bands; Cracks; Triaxial tests; Microstructure; Tomography

1. Introduction

Rock deformation is generally classified by a brittle regime, a ductile regime, and a transitional semi-brittle regime. Following Paterson [1, p. 16], the brittle regime is the case when fracture "*is not preceded by any appreciable permanent deformation, although the microscopic and other pre-failure observations* (…) *show that the behaviour is by no means purely elastic prior to the macroscopic failure*". Accordingly, the ductile regime may be defined as the regime when failure is preceded by a significant amount of permanent deformation, including the limit case when the material reaches failure by flowing under constant load (perfect plastic flow). For a given rock, the deformation regime depends on the pressure and temperature conditions. The deformation at failure, in both brittle and ductile regime, is most generally localised in narrow, sub-parallel-sided zones, which have been loosely termed shear zones in the nature like in the experimental tests [2,3]. Shear-enhanced compaction bands have been observed in porous sandstones [4,5], limestones [6] and clays [7–10]. The theory of bifurcation in shear band mode, developed by Rice and colleagues [11–13], considers shear bands as an alternative to the homogeneous strain in a process called *strain localisation*. In this theoretical framework, a shear band differs from a crack: it is a band of non-vanishing thickness in which the elementary deformation mechanisms are more intense, or possibly of different nature, than in the rest of the specimen, or structure. In such a band a discontinuity of the strain field is considered, not a displacement discontinuity. This theory is verified for a large class of materials including rocks, metals and sands.

In this work we study the brittle–ductile transition in a Plaisancian marl through a series of triaxial tests

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performed at different confining pressure [14,15]. This marl is a weak and porous clayey rock from near Beaucaire in the South-East of France (and thus is hereafter called the Beaucaire marl). Depending on the mean stress level, the Beaucaire marl shows both localised and diffuse deformation. The aim of the present paper is to present an overview of the deformation processes of the Beaucaire marl observed in a series of tests and at different scales of observation. As such, the results of three observation methods at different scales during and after the homogeneous laboratory tests are presented and compared: X-ray computerised tomography (CT); microstructural analysis using SEM; and volumetric porosimetry by mercury injection. From these data, the effects of the mean stress level on the deformation mechanisms, the texture evolution and the porosity of the material under mechanical loading are determined, which allows a classification of the different strain regimes for this soft rock to be proposed.

2. Materials and methods

2.1. Beaucaire marl

The material for the present study was extracted from a quarry at a depth of approximately 70 m below the natural ground surface. Block samples of $30 \times 30 \times 30\,cm^3$ were cut using a chainsaw from a freshly excavated wall and paraffin-coated to preserve the natural saturation of the material. In the field, clear bedding is observed. Within the layers, the marl is a grey, homogeneous, compact, fine-grained material and does not exhibit any cracks. A granulometric study of Beaucaire marl showed that it is a silty marl with 99% of its grains with a size below 80 μm, 72% below 20 μm and 20% below 2 μm. X-ray diffraction analyses indicated that Beaucaire marl is composed of 36% quartz, 31% calcium carbonate and 32% phyllosilicates. Furthermore, thermographic analyses revealed that the phyllosilicate fraction consists of 50% illite, 30% chlorite and 20% of a montmorillonite and chlorite mixture known to induce swelling. Fig. 1 presents the aspect of the material observed at two different scales. The porosity is mainly an intergranular porosity.

The different mineral phases are randomly distributed. Grain orientations of elongated grains with respect to the axis of the cylindrical specimen are more or less equally distributed in all directions (mean value 5.6% of grains per direction over 18 bins of 10°, standard deviation 3.0%, the complete profile is shown later in the paper). This organisation is defined as an irregular aggregate [16].

Cores subjected to triaxial testing were cut perpendicular to the stratification. The loading was also applied in the direction perpendicular to the stratification and thin sections were cut parallel to the loading axis.

Table 1 summarises the geotechnical properties of the material. Beaucaire marl has wet and dry unit weights

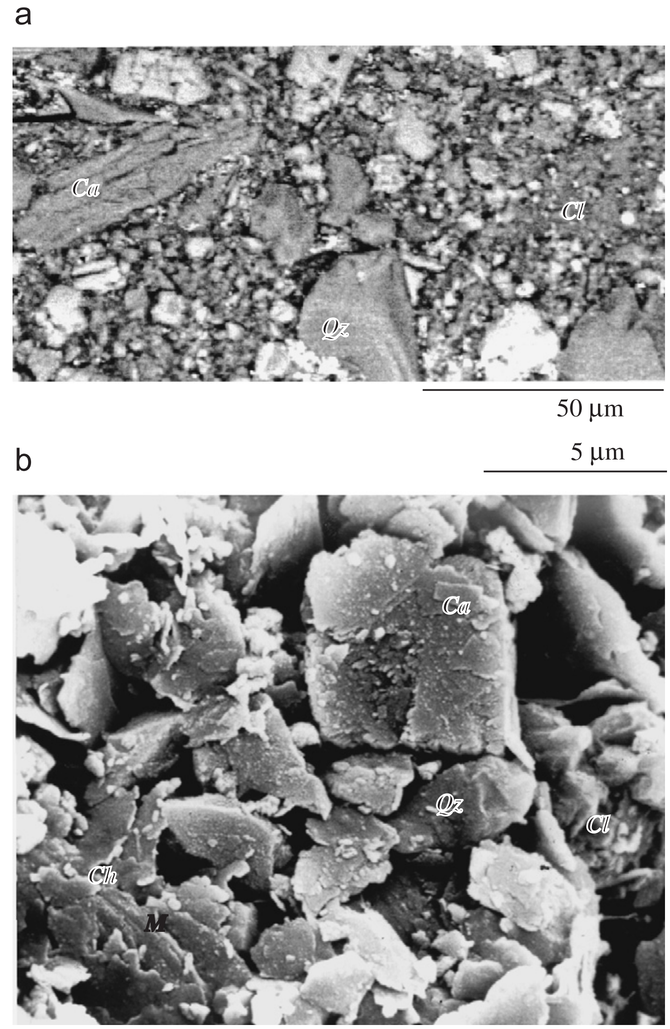

Fig. 1. Topographic SEM images showing: (a) the aspect of the undeformed Beaucaire marl and (b) its intergranular porosity. Qz: quartz, Ca: calcite; Cl: clay, Ch: chlorite.

Table 1
Geotechnical properties of Beaucaire marl

Wet volumetric weight (kN/m^3)	19.7
Dry volumetric weight (kN/m^3)	15.8
Natural water content (%)	24.5
Porosity (%)	39
Plastic limit (%)	25
Liquid limit (%)	40
Plasticity index (%)	15
Liquidity index (–)	−0.03
Activity ratio (–)	0.83
Natural saturation (%)	100

of 19.7 and $15.8\,kN/m^3$, respectively, a water content of 24.5% and a porosity of 39%. With a plastic limit of 25% and a liquid limit of 40%, it is classified as a moderately plastic clay in the Casagrande chart. Its activity ratio, defined as the ratio between the plastic index and the clay fraction (i.e., the percentage of grains with diameters less than 2 μm) is 0.83 and does not indicate a susceptibility to