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Citation: Fonseca, J., Bésuelle, P. and Viggiani, G. (2013). An experimental study of micro-scale deformation in a soft sandstone. Paper presented at the Proceedings of the 1st International Conference on Tomography of Materials and Structures (ICTMS2013), 01-07-2013 - 05-07-2013, Ghent, Belgium.

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An experimental study of micro-scale deformation in a soft sandstone

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Keywords: micro-structure, soft rock, laboratory tests, in-situ x-ray micro tomography

ABSTRACT

This study investigates the grain scale mechanisms that lead to failure by strain localisation in a slightly cemented sandstone. While the effects of interparticle bonding on the mechanical behaviour of granular geomaterials, including soft rocks, have been largely studied, the physical micro-scale mechanisms governing the material deformation are still poorly understood. In this study, laboratory techniques have been developed to allow a non-invasive investigation of the internal deformation of a soft sandstone during triaxial compression to failure. The material studied is Fontainebleau sandstone, a quartzite formation from the Paris Basin, with a porosity of 21 %. Fontainebleau sandstone is a uniformly graded material with a mean grain size of 260 μm . Triaxial compression tests at confining pressures of 2 MPa and 7 MPa were conducted on dry cylindrical specimens of 11 mm diameter by 22 mm height. Three-dimensional images of the full specimen were obtained by carrying out x-ray micro-tomography scans at key points throughout the test. The high-resolution tomographic images have a voxel size of 8.5 μm (0.033 d_{50}) allowing a clear identification of the grains. A preliminary analysis has suggested that the failure mechanisms can be different for the samples tested at different confining pressures, which has a direct implication on the permeability of the material.

1. INTRODUCTION

Predicting the occurrence of failure in cohesive geomaterials by strain localisation is a key aspect in many geotechnical applications, *e.g.*, drilling technology, nuclear waste disposal and sequestration of carbon dioxide. Previous studies have shown that the failure mechanisms in porous soft rocks are highly dependent on the stress level (*e.g.*, Sulem and Ouffroukh, 2006; Bésuelle et al., 2000). Deformation bands have mechanical and structural evolutions that distinguish them from fractures and slip surfaces and in the case of permeability reduction, these bands could act as barriers to fluid flow in otherwise more permeable rock, impacting extraction and storage of fluids (*e.g.*, Issen and Rudnicki, 2000; Fossen et al., 2007). This study investigates the deformation of a soft sandstone tested in triaxial compression at different confining pressures and the micro-scale mechanisms associated to the macroscopic behaviour.

2. EXPERIMENTAL METHOD

2.1. Material description and triaxial tests

The material investigated in the study is Fontainebleau sandstone from the Paris Basin in France. Silicification processes occurring after deposition of Fontainebleau sands, have developed grain cementation by quartz overgrowths (Grisoni and Thiry, 1988; Thiry et al., 1988). Sub angular grains with some very angular facets, occasional grain interpenetrations and an absence of matrix material characterise this shallowly buried sandstone (Thiry and Marechal, 2001).

The specimens were cored from large blocks retrieved from the site to approximately 11 mm diameter and the length of the cylindrical cores was reduced to approximately 22 mm using a

coarse sand paper. The ends of the cylinder were smoothed using a very thin layer of epoxy resin. This resin layer allowed smoothing the ends of the sample, avoiding leakage due to damage of the membrane, as well as helping to obtain flat and parallel ends.

The triaxial compression tests were carried out on dry specimens following isotropic compression at pressures of 2 MPa and 7 MPa. The tests were performed in a small high-pressure triaxial cell designed to operate inside the x-ray scanner, which allows *in-situ* scans to be carried out (*in-situ* meaning x-ray scanning at the same time as loading). Deviatoric loading was applied by an ascending piston at a rate of 21 $\mu\text{m}/\text{min}$. Between seven and eight loading stages were imaged during each test, as indicated in Figure 1. The scans were taken at a spatial resolution of 8.5 μm , which means that the diameter of a mean size grain is represented by approximately 30 pixels. Due to detector size limitations, the top and bottom parts of the sample were scanned separately and stitched together to obtain the full specimen.

Figure 1 shows the mechanical response of the three specimens tested. The three samples exhibit brittle behaviour when subjected to an increase in deviatoric stress with the specimens tested at 7 MPa showing a higher peak stress. The drop in stress in the strain softening regime was more pronounced for the 7 MPa specimens while for the 2 MPa sample the reduction towards a residual stress level was more gradual.

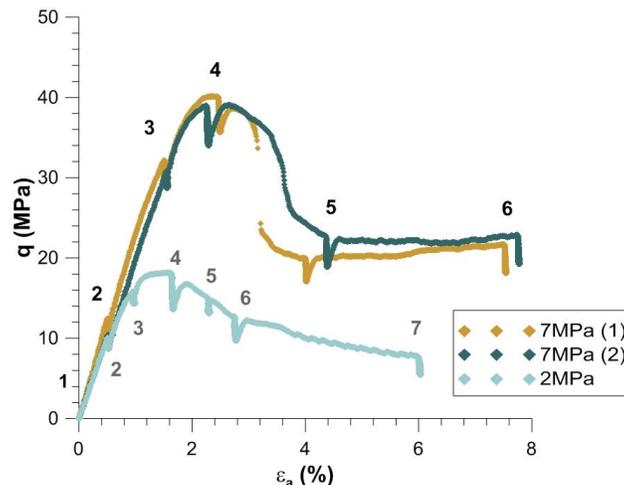


Figure 1: Stress:strain curve for the specimens tested with indication of the loading stages chosen for imaging (marked by small relaxations in the stress deviator)

3. OBSERVATIONS

The failure mechanisms observed for the specimens tested at different confining pressures were slightly different. For the specimen tested at confining pressure of 2 MPa, multiple shear bands of localized strain were identified. As shown in Figure 2(b) a large region of high dilation can be identified in the sample at the end of the test for an axial shortening of 6 % (load stage 7). A detailed view of Figure 2(b) shows large voids and occasional grain fractures in the dilatant shear bands. Significant barrelling was observed at the last loading stage for an axial shortening of 6 %.

For the specimen tested at 7 MPa confining pressure, a well-defined shear band was formed during the strain softening regime. As shown in Figure 3(b), this band can be clearly identified as a region of intense grain crushing with a thickness of approximately $4-6d_{50}$ (1.5 mm) and with an orientation angle of 48° (measured to the horizontal plane). A detailed view of the shear band shows that the void space is filled with crushed material while some grains remain apparently intact. Outside the shear band, grain fracturing can be observed throughout the specimen with a significant number of fractures showing an orientation close to the vertical direction, *i.e.* parallel to

the orientation of the major stress. These fractures appear to initiate at grain contacts.

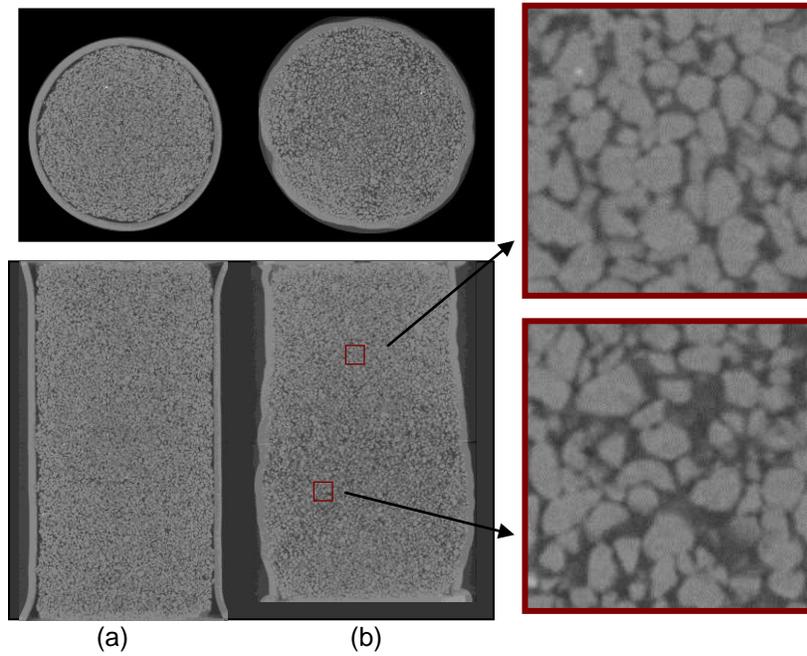


Figure 2: (a) Cross section (top) and vertical section (bottom) of the sample tested at 2 MPa prior to loading. (b) Sections of the sample tested at 2 MPa at the load stage 7 with a detailed view of material outside (top) and inside the dilatant shear band (bottom).

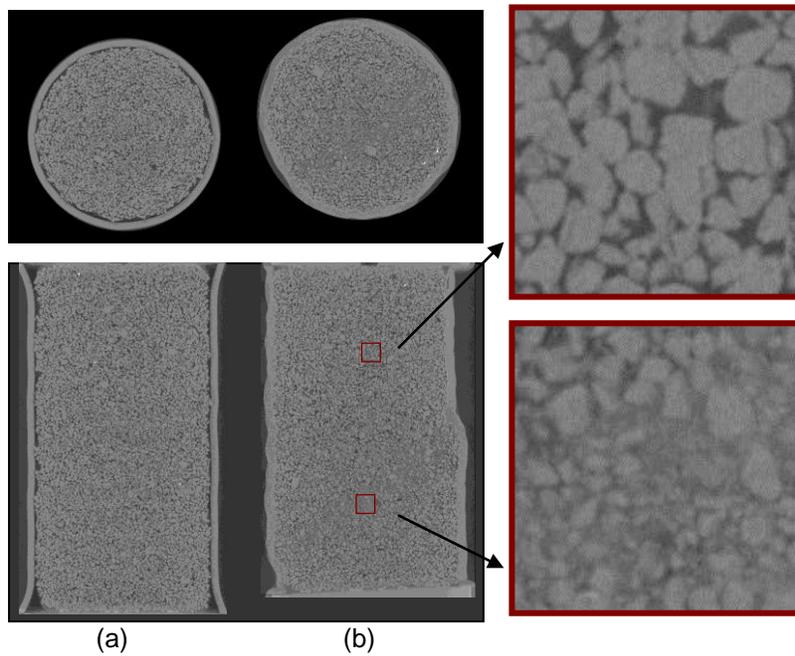


Figure 3: (a) Sections of the sample tested at 7 MPa (2) at the stage prior to loading. (b) Sections of the sample tested at 7 MPa(2) at the stage 6, a detailed view of the grain fracturing outside the shear band (top) and a detail of grain crushing inside the shear band (bottom)

4. DISCUSSION

A preliminary visual inspection of the images through the different loading stages suggests that there is no significant grain fracture before the peak stress. This is in agreement with previous studies, e.g. Menéndez et al. (1996), who suggested that the micro-scale arrangements in the pre-failure regime are likely to be associated to inter-granular cracking due to shear rupture of cemented grain contacts. The formation and evolution of a deformation band involves, generally, grain rotation and translation. The two examples shown in this study indicate that these bands can include grain crushing or merely rotation and frictional sliding along grain boundaries. The inherent heterogeneity of this porous rock can be observed for the images acquired prior to loading (Figures 2(a) and 3(a)) with a large variability of the particles morphology (size and shape) and the geometrical distribution and consequently the pore space. These complex pore geometries can significantly influence the stress concentration and heterogeneity in response to an applied stress (Wong et al., 2004).

This preliminary analysis has shown that important insights into the micro-scale deformation of a cohesive material can be gained using 3D images acquired during loading. A quantitative description into the mechanisms that underlie the complexity of the material response is however non-trivial and requires the development of new tools, which is in process.

5. ACKNOWLEDGEMENTS

This work was carried out within the framework of the project GEOBRIDGE funded by the French research agency, ANR (contract number: ANR-09-BLAN-0096).

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