DEFORMATION AND FAILURE MODES IN HIGH POROSITY CARBONATE ROCKS: MECHANICAL DATA AND MICROSTRUCTURAL OBSERVATIONS

[1] Institut de Physique du Globe
EOST (CNRS/ULP)
5 rue René Descartes
67084 Strasbourg Cedex, France
pbaud@eost.u-strasbg.fr

Patrick Baud[1], Sergio Vinciguerra[2], Andrea Cavallo[2], Thiérry Reuschlé[1]

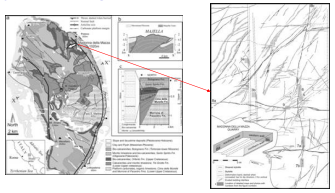
[3] INGV Rome

Introduction

The compactive and dilatant deformation in porous carbonate rocks is an important problem in fault development, geotechnical engineering and reservoir management. Active tectonics, as well as the extraction of hydrocarbon and groundwater modifies pore pressure, causing an increase in the effective stress possibly leading to faulting mechanisms and inelastic deformation of a reservoir or an aquifer. Ability to interpret and predict the occurrence and extent of such deformation depends on fundamental understanding of inelastic behaviour, failure mode and brittle-ductile transition in the carbonate rocks. *Baud et al.* (2000) and *Vajdova et al.* (2004) published a comprehensive set of mechanical data for three limestones of porosities ranging from 3 to 18%. They showed that porosity has a major influence on the compressibility, the brittle strength and the onset of grain crushing and pore collapse under triaxial and hydrostatic conditions in porous carbonates. Moreover, the phenomenology of dilatant and compactant failure was found qualitatively similar in limestones of porosity between 3 and 18%. In most cases, shear-enhanced compaction was associated with homogeneous deformation and no compaction localization was observed (*Vajdova et al.*, 2006)

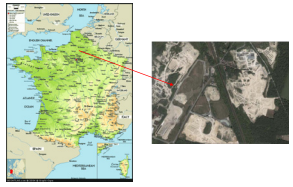
The aim of this study is to extend the work of *Baud et al.* (2000a) and *Vajdova et al.* (2004) by studying systematically the mechanical behavior of two much higher porosity carbonates: Majella grainstone and Saint Maximin limestone. This study is also expected to enhance our understanding of the deformation mechanisms observed and extensively analysed in the Majella mountain, Italy (*Tondi et al.*, 2006). We studied in the laboratory the developement of compaction localization in those two very porous carbonate rocks, supporting the mechanical data with an extensive microstructural analysis, using an high resolution field emission scanning electon microscope (FESEM).

Majella carbonate grainstone



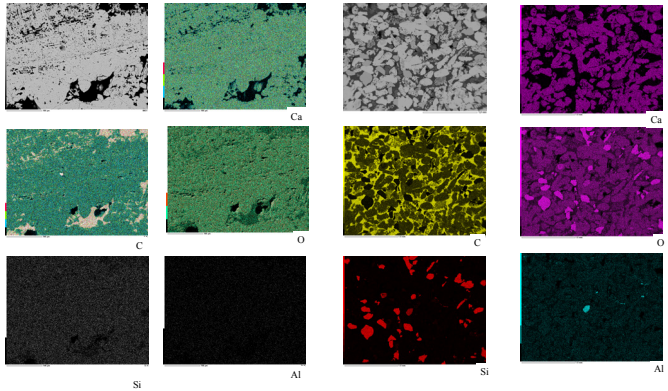
Porous Cretaceous carbonate grainstone from Majella Mountain, (Central Apennines, Italy). Initial porosity is about 31%. Different deformation mechanisms spanning from deformation bands to stylolites have been distinguished from Tondi et al., JSG, 2006.

St. Maximin limestone



Lutetian St. Maximin limestone location and quarry (France). Initial porosity is about 37%.It is commonly used for prestigious buildings.

Semiquantitative chemical analysis

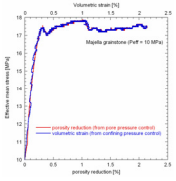


Majella grainstone is compositionally dominated from $CaCO_3$, while the composition of St. Maximin reveals the presence Si and Al.

Experimental procedure

Jacketed samples of cylindrical shape with diameter of 20 mm and length 40 mm cored perpendicular to bedding were compressed in conventional triaxial configuration at room temperature at the Rock Physics laboratory of Institut de Physique du Globe de Strasbourg. The samples were subjected to confining pressures ranging from 3 to 50 MPa. A computer controlled stepping motor connected to a pressure transducer regulated the confining pressure with an accuracy of 0.05 MPa. The axial load was applied by a piston controlled by a second computer-controlled stepping motor which displacement was measured outside the pressure vessel with a capacity transducer with accuracy 0.2 mm. Axial displacement was measured outside the pressure vessel with a LVDT mounted on the moving piston and servo-controlled at a fixed rate (corresponding to a nominal strain rate of 10^{-5}/s).

Fig. 3

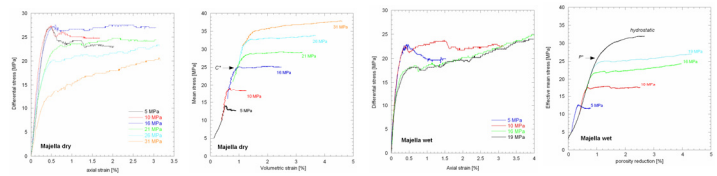


Experiments on the saturated samples were conducted at a fixed pore pressure of 10 MPa under fully drained conditions. A third computer controlled stepping motor connected to a pressure transducer regulated the pore pressure with an accuracy of 0.05 MPa. The pore volume change was recorded by monitoring the piston displacement of the pressure generator with an angular encoder. The porosity change was calculated from the ratio of the pore volume change to the initial bulk volume of the sample. Due to the very porous nature of the rocks investigated in this study, it was impossible to use strain gauges to measure axial and radial strain for nominally dry experiments. In all tests, stress-induced pore collapse resulted in breakage of the gauges even when the surfaced pores were filled with a thin layer of fast cured epoxy (*Baud et al.*, 2000b). Volumetric strain was therefore inferred from the confining pressure monitoring in the same way than for the pore volume change (angular encoder). The example presented in Fig. 3 for a sample of Majella grainstone deformed at an effective pressure of 10 MPa shows that the independent regulation of the pore and confining pressures leaded to comparable estimations of the volumetric strain and porosity reduction: $DV/V = Df$.

Mechanical data for dry and wet Majella grainstone

A total of 20 experiments were performed on Majella limestone. Fig. 4 (a-d) show representative results. In nominally dry conditions (Fig 4 a-b), the samples failed in the brittle regime at confining pressures between 5 and 16 MPa. In this range the stress-strain curves reach a peak beyond which relatively moderate strain-softening was observed. Beyond 16 MPa of confining pressure, the samples did not show any evidence of shear failure. Significant strain hardening was observed at 31 MPa of confining pressure (Fig 4a). Shear-enhanced compaction was observed at all pressure conditions (Fig 4b) from the stress level C^*. It suggests that at low confining pressures, the samples failed by compactive shear bands. Significant weakening effect of water was observed for Majella grainstone. The brittle-ductile transition occured at about 10 MPa of effective pressure in the presence of water (Fig. 4c). As for dry samples, no dilatancy was observed but only compactive deformation from 5 MPa to the onset of grain crushing and pore collapse P^* = 25.5 MPa (Fig. 4d).

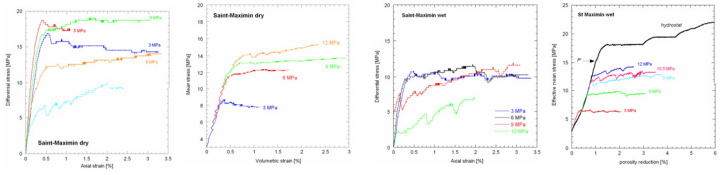
Fig. 4 (a) (b) (c) (d)



Mechanical data for dry and wet Saint-Maximin limestone

25 experiments were performed on the more porous Saint-Maximin limestone. More scattering on the mechanical data was found for this rock. Representative experiments are presented in Fig. 5 (a-d). Saint-Maximin is significantly weaker than Majella grainstone in particular in the presence of water. Fig. 5a and 5b present the differential stress as the function of axial strain for experiments performed in dry and wet conditions, respectively. In dry conditions, brittle failure was observed up to 6 MPa of confining pressure. In wet conditions, no evidence of brittle failure was observed beyond 3 MPa of effective pressure. In most experiments the stress-strain curves were punctuated by stress drops . These stress drops appeared of larger amplitude in the presence of water. Shear-enhanced compaction was observed at all pressure conditions for dry and wet experiments.

Fig. 5 (a) (b) (c) (d)



The onsets of permanent deformation C^* and P^* are summarized in the stress space in **Fig. 6 (a-b)**. No dilatancy was observed in all our experiments on Majella grainstone and Saint-Maximin limestone and we therefore obtained a single compactive yield envelope for both rocks. The weakening effect of water appears to be more pronounced in Majella than in Saint-Maximin. Following *Baud et al.* (2000b), we can quantify this effect with the parameter: $\lambda = \left(P^*_{wet} / P^*_{dry}\right)^{2/3}$

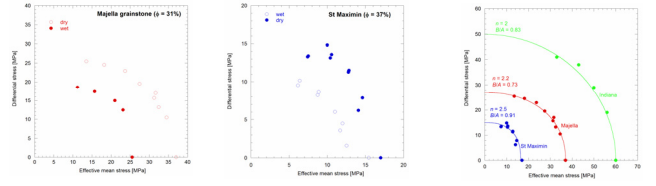
We obtained : $\lambda_{Majella}$ = 0.78 and λ_{SMax} = 0.94. These values are in the range found by *Baud et al.* (2000b) for a series of sandstones of porosity ranging from 13 to 35%. Following their conclusions, the weakening effect observed on the carbonates might be related to a reduction of the specific surface energy in presence of water. This in turn would imply that microcracking played an important role in the macroscopic yield of the carbonates.

In Fig. 6c, we compare the shape of the dry failure envelopes with published data of *Vajdova et al.* (2004) on Indiana limestones of 16% porosity. To fit the failure envelopes we used the following expression proposed by *Grueshow and Rudnicki* (2005) :

$$\left(\frac{P}{a}\right)^n + \left(\frac{Q}{b}\right)^n = 1$$

The exponent *n* increases with increasing porosity for the set of data presented in Fig 6c. Unlike for porous sandstones (*Baud et al.*, 2006), the shape of yield caps for carbonates of porosity ranging from 16 to 37% varies significantly and is in most cases not elliptical.

Fig. 6 (a) (b) (c)



Microstructural observations

Majella carbonate grainstone

Preliminary microstructural observations revealed extensive grain crushing and pore collapse in deformed samples of Majella grainstone. At 5 MPa of confining pressure, we observed a low angle shear band (**Fig. 7**) at one end of the sample (below).

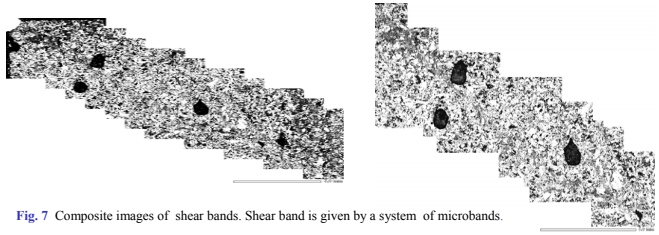


Fig. 7 Composite images of shear bands. Shear band is given by a system of microbands.

Outside of the band, damage developed in thin sub-horizontal segments with length between 100 to 300 mm. **Fig. 8** presents several examples of such structures, with intense grain crushing in some cases or/and concentration of smaller particles between larger grains. At higher confining pressures (>10 MPa), we did not observed shear localization and stress-induced microcracking and pore collapse were visible in all the sample volume (**Fig. 8**) without any clear pattern of localization.

Fig. 8 Grain crushing in Majella (Pc = 5 MPa; dry)

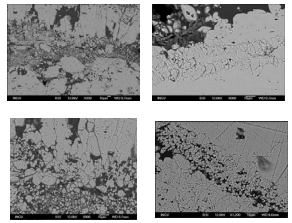
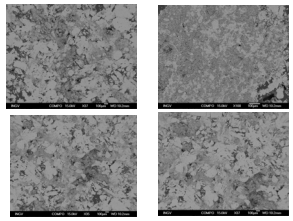


Fig. 9 Ductile deformation in Majella (Peff = 20 MPa; wet)



St. Maximin limestone

In St Maximin limestone, compaction involved more extensive microcracking than in Majella grainstone (**Fig. 10**). Over a wide range of confining pressures, we observed compaction localization in bands of various orientations. **Fig. 11** gives an example for a sample deformed at a confining pressure of 9 MPa.

Fig. 10 grain crushing (Pc = 9 MPa)

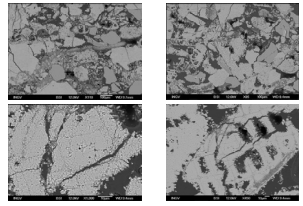
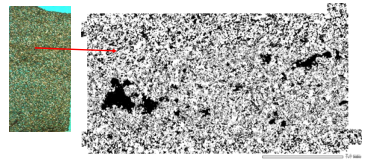


Fig. 11 Compaction localization (Pc = 9 MPa)



Summary

- No dilatancy was observed in Majella grainstone and Saint-Maximin limestone deformed over a wide range of confining pressures in dry and wet conditions.
- The mechanical strength of both rocks can be described by a single failure envelope for the onset of shear-enhanced compaction.
- The failure envelopes for Majella grainstone and Saint-Maximin limestone can not be decribed adequately with an elliptical cap.
- Preliminary microstructural observations revealed that at low confining pressures compactive shear bands developed in both rocks.
- At higher confining pressures, grain crushing and pore collapse were observed in both rocks. However we found more extensive microcracking in Saint-Maximin limestone.
- The weakening effect of water is more pronounced in Majella grainstone which contains a higher percentage of calcite.
- Compaction localization was observed in deformed samples of Saint-Maximin limestone. We are currently conducting a systematic study to understand the onset and development of strain localization in this rock.

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