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

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Abstract

The compactive and dilatant deformation in porous carbonate rocks is an important problem in fault development, geotechnical engineering and reservoir management. Active faults, as well as the criterion of biodegradation and ground-borne models pore pressure, causing an increase in the effective stress possibly leading to faulting mechanisms and induced deformation of a reservoir or aquifer. Ability to understand and predict the occurrence and onset of faulting events in carbonate rocks with a high porosity is a key to resolving the problem. Bounding fault zones are characterized by a high degree of porosity and permeability, which makes them prone to dilatancy. 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 high-porosity carbonate rocks: Majella grainstone and Saint-Maximin limestone. This study is also expected to enhance our understanding of the deformation mechanisms observed and extensively analyzed in the Majella mountain, Italy (Todt et al., 2006). We studied in the laboratory the development of compactive localization in these two very porous carbonate rocks, supporting the mechanical data with an extensive microstructural analysis, using a high-resolution field emission scanning electron microscope (FSESEM).

Microstructural observations

Majella carbonate grainstone

St. Maximin limestone

Porous Cretaceous carbonate grainstone from Majella Mountain, Central Apennines, Italy. Initial porosity is about 15%.

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

25 experiments were performed on the more porous Saint-Maximin limestone. More scattering on the mechanical data was found for Saint-Maximin limestone compared to Majella grainstone. Saint-Maximin is significantly weaker than Majella grainstone in particular in the presence of water. Fig. 5a and 5b present the differential stress as a function of axial strain for experiments performed at wet and dry conditions, respectively. In dry conditions, brittle failure was observed up to 8 MPa of confining pressure. In wet conditions, no evidence of brittle failure was observed beyond 3 MPa of effective pressure. In most experiments, stress-softening was observed at all pressure conditions for dry and wet experiments.

The stresses of permanent deformation $\sigma$ and $\sigma^*$ 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. (2006), we can quantitatively this effect with the parameter $\lambda = \sigma^*/\sigma_*$. We obtained $\lambda_{\text{Majella}} = 0.78$ and $\lambda_{\text{St. Max}} = 0.94$. These values are in the range found by Baud et al. (2000) for a series of sandstones of porosities ranging from 3 to 13%. Following their conclusions, the weakening effect observed on the carbonate rocks 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 carbonate.

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 Grasswein and Rudnicki (2005):

$$\left(\frac{\sigma^*}{\sigma_*}\right) = \left(\frac{\sigma}{\sigma_*}\right)^{\lambda}$$

The exponent $\lambda$ increases with increasing porosity for the set of data presented in Fig. 6c. Unlike for porous sandstones (Baud et al., 2006), the shapes of yield caps for carbonates of porosities ranging from 14 to 37% vary significantly and is in most cases not elliptical.

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 envelope for Majella grainstone and Saint-Maximin limestone can not be described 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 concluding a systematic study to understand the onset and development of strain localization in this rock.

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References