The impact of cementation on permeability and strength of porous limestone

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Abstract

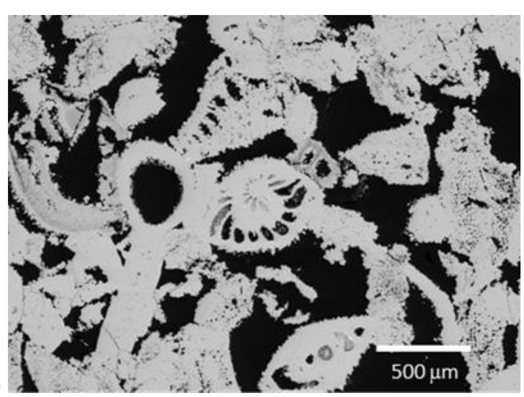
We studied mechanical compaction, strain localization and permeability in Leitha limestone. This carbonate from the area of Vienna (Austria) occurs with a broad range of grain sizes and porosity, due to changes in depositional regime and degree of cementation. Our new mechanical data revealed a simple relation between porosity and mechanical strength. Increasing cementation and decreasing porosity led to a significant increase of the rock strength both in the brittle and ductile regimes. Micromechanical modelling showed that the dominant micromechanisms of inelastic deformation in Leitha limestone are pore-emanated microcracking in the brittle regime, and grain crushing and cataclastic pore collapse in the ductile regime. Microstructural analysis revealed the development of compaction bands in some of the less cemented samples, while more cemented end-members failed by cataclastic flow in the compactant regime. In contrast to mechanical strength, permeability of Leitha limestone was not significantly impacted by increasing cementation and decreasing porosity.

Introduction

A fundamental understanding of the inelastic behavior of porous rocks and its implication on fluid flow at various scales is needed in order to analyze deformation and failure in many sedimentary successions. In porous carbonates, the phenomenology of brittle failure and inelastic compaction as reported by laboratory studies, is similar to that of sandstone over a wide range of porosities (*WONG and BAUD*, 2012). Carbonate rocks are widely recognized to have pore geometry that is significantly more complex than other sedimentary rocks (*CHOQUETTE and PRAY*, 1970). The pore size in a carbonate rock may span over a very broad range, with a distribution that is often bimodal, including a significant subset of microporosity (*BAECHLE et al*., 2008). Field studies on carbonate formations (see for example *TONDI et al*., 2006) suggest that various mechanisms such as grain rotation, pore-collapse, grain crushing, crystal plasticity and pressure solution may lead to inelastic compaction and strain localization in carbonates. Additional complexity arises from the fact that these mechanisms are obviously influenced by microstructural parameters, such as the degree of cementation or the spatial distribution of macro- and micropores. Possibly because of such complex situation, significant variability was observed both in the brittle strength (*BAUD et al*., 2014) and the onset of inelastic compaction of carbonates, even for samples coming from the same sedimentary unit (*DAUTRIAT et al*., 2011). We investigated systematically the mechanical behavior and permeability variations in a porous carbonate from the Vienna Basin in Austria. Our main objective was to study how cementation influences the micromechanics of failure and permeability in a limestone formation.

Material studied and experimental methods

For this study, we chose Leitha limestone, a bioclast carbonate of Middle Miocene age from the Vienna Basin in Austria. The limestone consists predominantly of one allochemical component (bioclasts) and interparticular macropores. These pre-existing macropores have been coated with sparite calcite cement. Although there are micropores embedded in some of the bioclasts, they contribute relatively little to the total porosity, which varies significantly (18-31%) in the formation, primarily due to variable degree of cementation. Microstructural analysis revealed a small proportion of intragranular microporosity in the highest porosity samples (Figure 1a). This microporosity disappeared with increasing cementation and in the low porosity end members, the pore space was almost exclusively composed of macropores (Figure 1b).

(a) 

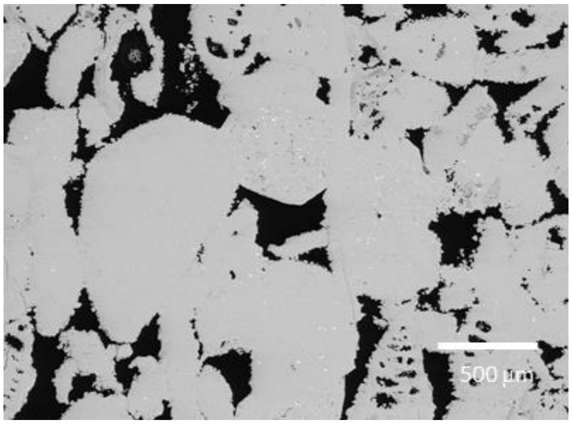
(b) 

Figure 1 *– Backscattered SEM images of undeformed Leitha limestone of (a) 31% and (b) 21% initial porosity. No significant microporosity was observed in the sample of 21% porosity.*

Cylindrical samples (20 mm in diameter and 40 mm in length) were cored orthogonal to the sedimentary bedding from several blocks collected in the quarry Hummel St. Margarethen/Burgenland near Vienna (Austria). The samples were dried *in vacuo* at 40°C for a minimum of 48h. Porosity was measured by helium pycnometer. Permeability was measured using gas (Nitrogen) by the steady-state flow technique at a confining pressure of 2 MPa (see *FARQUHARSON et al*., 2016 for details). The samples were then saturated with deionized water. Conventional triaxial compression experiments were performed at room temperature following the protocol of *BAUD et al*. (2015). Jacketed samples were deformed in drained conditions (with a pore pressure of 5 MPa) at a nominal strain rate of 10^{-5}/s and at confining pressures ranging from 5 to 160 MPa.

Results

The difference between the confining pressure and pore pressure will be referred to as the “effective pressure” in the following. Hydrostatic data are presented in Figure 2. The hydrostats could be separated in three successive stages: (1) The first nonlinear part at low effective pressures corresponds to microcrack closure. (2) Then the behavior becomes poroelastic and (3) beyond a critical pressure denoted *P** (*WONG et al*., 1997), we observed an acceleration of the compaction corresponding to the onset of grain crushing and pore collapse. *P** can be therefore seen as the onset of inelastic compaction. *P** increased quickly and regularly with decreasing porosity, from 28 MPa at 31% to 125 MPa at 18%. We noted however that if the compressibility of Leitha limestone decreased significantly when porosity decreased from 31% to 25% (from about a factor 3), it did not change between 25% and 21%, yet again decreased between 21% and 18%. Most of the hydrostatic experiments were stopped when the plastic volumetric reached around 4%.

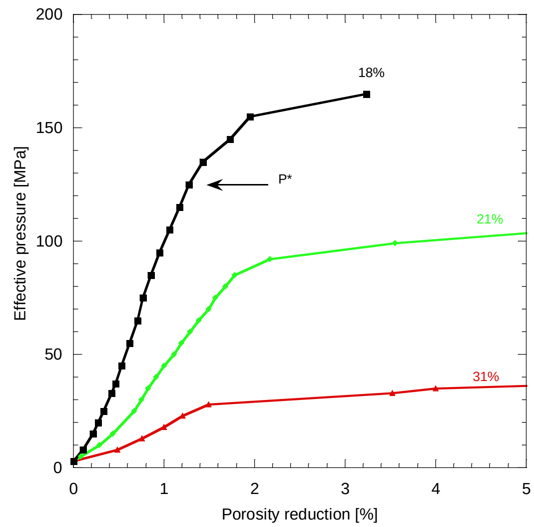


Figure 2 *– Effective pressure as a function of porosity reduction in hydrostatic experiments. Arrow indicates the critical pressure P* for the onset of pore collapse. The initial porosity of the samples is indicated next to the curves.*

Representative triaxial data for samples of porosities 21% and 31% are presented in Figure 3. Brittle behavior was only observed for the low porosity end-members at effective pressures up to 20 MPa. At all tested pressures the curves were punctuated by episodic stress drops, in some cases of high amplitude (up to 5 MPa). Previous studies showed that this is usually an indicator that some compaction localization occurred in the samples (*BAUD et al*., 2004; *CHEUNG et al*., 2012).

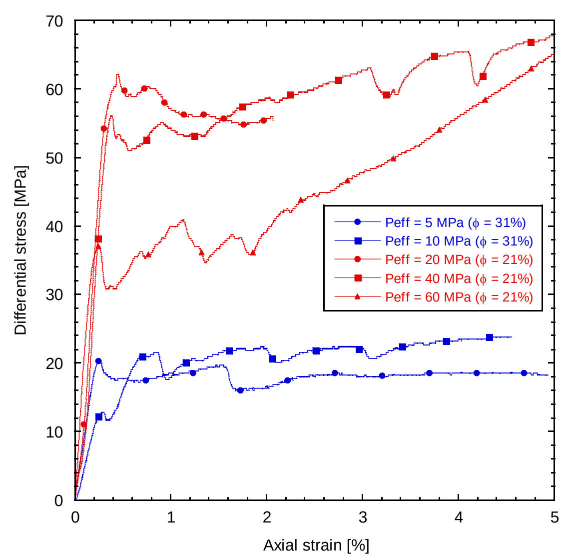


Figure 3 *– Selected mechanical data for triaxial compression experiments on Leitha limestone samples of initial porosities 31% (blue) and 21% (red). Differential stress is plotted as a function of axial strain.*

Significant strain hardening was only observed in the low porosity end-members when deformed at relatively high effective pressures. All the tested samples experienced shear-enhanced compaction (Figure 4).

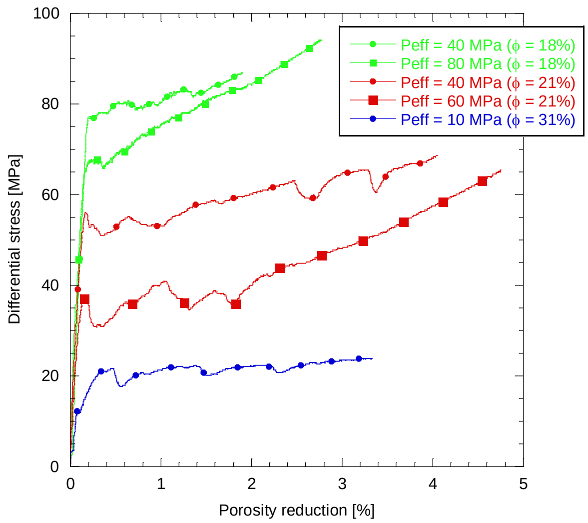


***Figure 4** – Selected mechanical data for triaxial compression experiments on Leitha limestone samples of initial porosities 18% (green), 21% (red) and 31% (blue). Differential stress is plotted as a function of porosity reduction.*

Our triaxial and hydrostatic data on samples of initial porosity 18%, 21%, and 31% are summarized in Figure 5 where the critical pressures *P** and onset of shear-enhanced compaction are presented in the stress space. The triaxial datasets map out a single compactant yield envelope as it has been previously shown for other porous carbonates (*BAUD et al*., 2009; *JI et al*., 2015). Our triaxial data confirmed the large increase in strength induced by the cementation of Leitha limestone. We also note that the yield caps are almost linear for the samples of 21 and 31% initial porosity.

Deformed samples were then saturated with epoxy and polished petrographical thin sections were prepared in the vertical direction on the whole sample length for SEM analysis at the Department of Lithospheric Research, University of Vienna. Failure modes identified by visual inspection and microstructural analysis are shown next to the failure envelopes in Figure 5. Compactive shear bands were observed in samples of 18 and 21% porosity deformed at low effective pressures. At higher effective pressures, homogeneous cataclastic flow developed in all tested samples with these initial porosities. A somehow different behavior was observed in the high porosity end-members (31% initial porosity). Diffuse bands were visible in samples deformed at low effective pressures. Intense grain crushing and pore collapse were evident inside the diffuse bands (Figure 6). A similar failure mode was recently revealed in Saint-Maximin limestone of 37% porosity by *BAUD et al*., 2017a) by Acoustic emission monitoring. We inferred a porosity reduction of about 10% in the compaction bands. This was confirmed by complementary imaging by X-ray Computed microtomography (*BAUD et al*., 2017b).

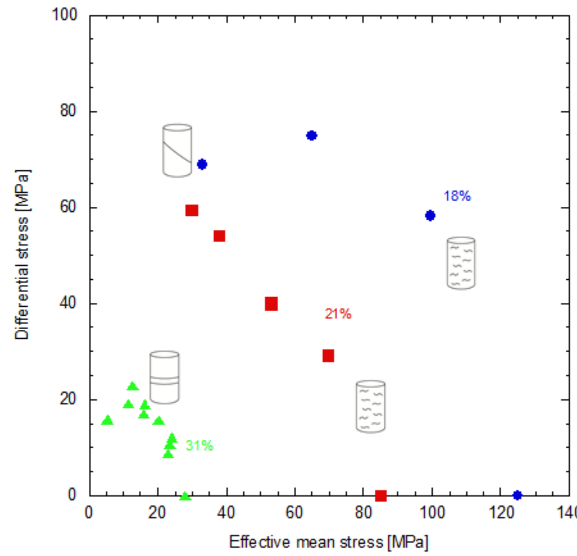


Figure 5 – Compactive yield caps for the onset of shear-enhanced compaction in the effective mean stress and differential stress space for Leitha limestone of initial porosity, 18% (blue circles), 21% (red squares) and 31% (green triangles). Cartoons next to the caps give the failure modes based on visual inspection of the samples and microstructural analysis.

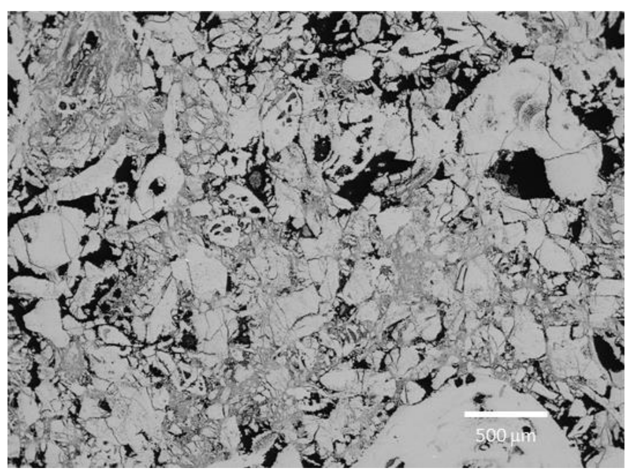


***Figure 6** – SEM micrograph showing intense grain crushing and pore collapse in a sample of Leitha limestone of initial porosity 31%, deformed at an effective pressure of 10 MPa.*

There is an overall trend for permeability of Leitha limestone to increase with increasing porosity (Figure 7). A moderate decrease from 8 to 2 x10^{-12} m^2 was observed with porosity decreasing from 31% to 21%, followed by a dramatic decrease by at least one order of magnitude when porosity decreased further to 18%.

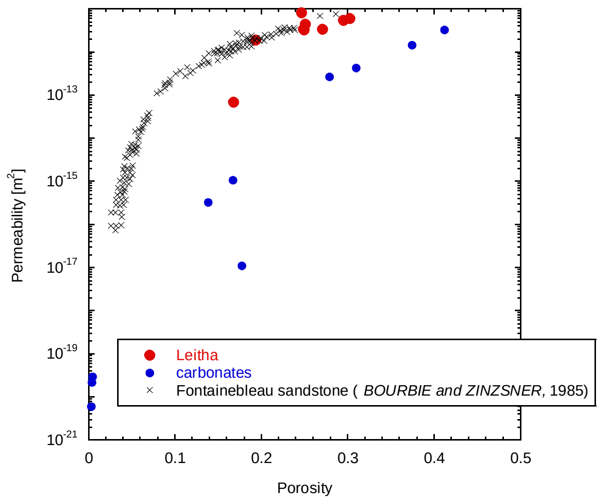


Figure 7 *– Permeability as a function of porosity for Leitha limestone (red circles) published data on Fontainebleau sandstone from BOURBIE and ZINZSNER (1993) (black crosses) and a compilation of data on limestone (blue circles) from HEAP et al. (2014), RUSTICHELLI et al. (2015) and JI et al. (2015).*

The permeability of Leitha is about one order above the trend suggested by published data obtained using the same experimental set-up and conditions by *HEAP et al*. (2014), *RUSTICHELLI et al.* (2015) and *JI et al.* (2015). Our microstructural observations suggested that this is due to large pore sizes in this rock (Figure 1). We applied the equivalent channel model (*WALSH and BRACE*, 1984) to our permeability data on Leitha. According to this model, on the average the hydraulic radius in Leitha limestone did not undergo much change, even when cementation had reduced the porosity from 31% to 21%. This would imply that cement in these samples mainly accumulated in the vicinity of grain contacts or nodal pores, without significantly impacting the throats that control transport.

Comparison with data of *BOURBIE and ZINZSNER* (1985) on Fontainebleau sandstone suggested that if the Leitha limestone had undergone more extensive cementation, then the behavior in this sandstone would provide a proxy for corresponding changes in the permeability.

Conclusions

In this study, sampling carbonates from the same formation over a large interval of porosity, we showed that it is possible to obtain a clear relation between porosity and mechanical strength both in the brittle and ductile regimes. Larger porosity in Leitha limestone resulted in a spectacular decrease of its strength in both regimes. Simple quadratic relations porosity-strength based on our new data could potentially be used as guidance in field scale problems. The main micromechanism of inelastic compaction in Leitha limestone is grain crushing, in contrast with other limestones with a dual porosity (*ZHU et al*., 2010). Compaction bands were observed in the less cemented samples of Leitha limestone (31% porosity) but not in more cemented ones. Our data suggest that increasing cementation created a more heterogeneous structure, in which compaction localization could not develop extensively. Based on our microstructural observations, it is possible that subtle changes in cementation could explain why compaction bands were or were not reported in previous field and laboratory studies, sometimes performed on comparable rocks. Future research involving in situ CT imaging will be performed to better understand the nucleation and growth of compaction bands in limestone.

Finally, we found that porosity differences did not have significant influence on the permeability of Leitha limestone, in contrast to mechanical strength. This is essentially due to the existence of a backbone of connected large macropores in all our samples, which also explains the high permeability (in the range of 2-5 Darcy) of Leitha in comparison to other limestones with similar porosities. In fact, the permeability of Leitha is very similar to published data on Fontainebleau sandstone of comparable porosity. An outstanding question for future work would be to which extend mechanical and/or chemical compaction could significantly impact such high permeability.

Acknowledgments

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