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Douma, Lisanne; Dautriat, J.; Sarout, J.; Dewhurst, D.; Barnhoorn, Auke

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Impact of the Degree of Saturation on the Mechanical Behaviour of the Whitby Mudstone

L. Douma[1]*, J. Dautriat[2], J. Sarout[2], D. Dewhurst[2], A. Barnhoorn[1]

[1]Delft University of Technology; [2]CSIRO Energy

Summary

Mudstones are of great interest in the petroleum industry, since they can act as a source rocks, reservoirs and seals. Understanding the mechanical behaviour of these clay-rich rocks is crucial for successful hydrocarbon exploration and production. This study examines the impact of water saturation on the mechanical behaviour of the Whitby Mudstone. Triaxial compression tests are performed on mudstone samples with different water saturations at effective confining pressures of 5 MPa, 15 MPa, 25 MPa, and 40 MPa. The results show that the degree of saturation significantly affects the rock strength and static elastic properties (Young's modulus and Poisson's ratio). The mechanical properties obtained from partially-saturated mudstones should be treated with care when extrapolating them to in situ conditions.

Introduction

Mudstones are unique since they can act as a source, reservoir, and natural seal. This makes them of highly interest for the petroleum industry. In addition, these clay-rich rocks are recognized as potential host-rocks for nuclear waste disposal (e.g., Bossart et al. 2002) and for CO_2 sequestration projects (e.g., Busch et al. 2008). Understanding the mechanical properties of mudstones is crucial to make predictions on their deformation behaviour, which is, in turn, important for the development of these low permeability reservoirs and to assess the safety in underground repositories (e.g., Cai and Kaiser 2005).

The loss of *in situ* pore water from these clay-rich rocks has a significant effect on their bulk properties. When dehydrations occurs, air can enter the pores resulting in a tensional state of pore water, due to the formation of air-water capillary interfaces on the surface of the mudstone (Ferrari et al. 2014; Ewy 2015). This results in a significant increase in compressive strength and Young's modulus (e.g., Vales et al. 2004; Ramos da Silva et al. 2008; Ghorbani et al. 2009; Minaeian et al. 2017).

Despite the enormous effect of dehydration on the bulk properties of these low permeability rocks, experiments are still performed on poorly-preserved samples without any pore pressure control. The results obtained during those experiments do not represent the *in situ* conditions of mudstones, leading to ambiguities in the interpretation of deformation behaviour and elastic properties of mudstones.

This study shows the impact of water saturation on the mechanical behaviour and static elastic properties of the Whitby Mudstone. Triaxial compression experiments are performed on mudstone samples with varying water saturations at confining pressure conditions of 5 MPa, 15 MPa, 25 MPa, and 40 MPa. The study emphasizes the importance of preserving clay-rich rocks and their testing protocol. The results show the impact of water saturation on the mechanical behaviour and elastic properties of the Whitby Mudstone.

Sample Material and Experimental Protocol

Sample blocks were collected from the same horizon in the coastal outcropping Whitby Mudstone Formation, United Kingdom. The mudstone samples were stored in seawater immediately after recovering to prevent them from drying. Sixteen cylindrical samples with length/diameter ratios of 2:1 were cored normal to the bedding, using seawater as cooling fluid. Four core samples were stored in seawater immediately after coring. The initial saturation of these preserved mudstone samples is 92% ±10%. Three sets of core plugs, each set consisting of four mudstone samples, were equilibrated for two months within desiccators with relative humidity atmospheres of ~85%, ~75%, and ~35%, to create three different sample sets with water saturations of 70% ±10%, 58% ±10%, and 28% ±10%.

The pre-deformation core plugs were visualised using a X-ray Computed Tomography (XRCT) scanner to detect heterogeneities in the rock specimens. In addition, the mudstone plugs with a water saturation of 92%, 70%, and 58% were subjected to a preliminary Nuclear Magnetic Resonance (NMR) spectroscopy to determine (1) the transversal relaxation time T2 (i.e., rate of signal decay) and (2) the water distribution profile along their axis. The specimens were wrapped in cling film to minimize the loss of pore fluids during scanning and NMR spectroscopy.

Triaxial compression tests were performed on the mudstone core plugs with different water saturations at effective confining pressures of 5 MPa, 15 MPa, 25 MPa, and 40 MPa. A pore pressure of 2 MPa was used for the preserved samples, whereas no pore pressure was applied for the partially-saturated samples. The mudstone samples were deformed at undrained conditions at a constant axial strain rate of 10^{-7} s^{-1}. The axial deformation of the core plugs was monitored with a pair of diametrically opposed Linear Variable Differential Transducers (LVDTs) attached to the top and bottom platens. The radial deformation was measured at the specimen's mid-height using a brass halfring equipped with strain gauges. This data was used to determine the static Young's modulus (*E_3*), Poisson's ratio (*υ_{31}*) and peak strength for loading applied normal to the bedding plane.

Rock Characterization

The XRCT images show that the core plugs are layered, with a horizontal bedding consisting of mainly clay minerals (Figure 1). There are some lighter layers which corresponds to high density minerals, representing calcite layers. The local bright spots indicate the presence of pyrite or fossils in the form of ammonites. The horizontal, darker layers observed in the core plug where Sw = 58% indicate bedding-parallel fractures formed as a result of dehydration.

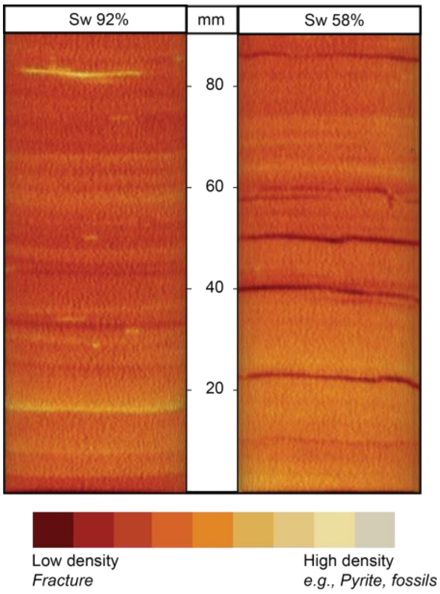

Figure 1 *XRCT-images of the mudstone samples in preserved state (Sw = 92%) and after dehydration (Sw = 58%). Bedding-parallel fractures are formed due to dehydration.*

The transverse spin echo decay (T_2) was obtained from the NMR measurements for the mudstone core plugs with different water saturations. In their initial state, the spin decays are very fast since the pore sizes of these mudstones are very small (Figure 2a). T_2 decreases even further with dehydration. The amplitude of the NMR signal varies between ~0.75 g/cm^3 and ~0.85 g/cm^3 for the preserved mudstone plugs and decreases with decreasing water saturation to a minimum value of ~0.5 g/cm^3.

Figure 2b shows the water content along the core plugs with a water saturation of 58%. The result show that the water content within one core plug is not equally distributed, but is similar between the different mudstone samples originating from the same sample set. The water content is not uniform along the core plugs, possibly due to the presence of layering (i.e., changes in mineralogy) within the samples. In addition, significant drops are observed and can be related to bedding-parallel dehydration fractures.

Geomechanical behaviour

The degree of water saturation has a significant effect on the rock strength and static elastic properties of the Whitby Mudstone (Figure 2). The results show that the peak strength increases with more than a factor of 2, irrespective of the applied confining pressure. The Young's modulus (*E_3*) and Poisson's ratio (*υ_{31}*) were obtained from the most linear part of the curve. In general, the Young's modulus increases with decreasing water saturation. The relation between the Poisson's ratio and water saturation is less obvious, but seems to decrease with dehydration.

The increase in peak strength and Young's modulus with decreasing water content is consistent with the findings of previous studies on clay-rich rocks (Vales et al. 2004; Ramos da Silva et al. 2008; Ghorbani et al. 2009). When a mudstone dehydrates, air can enter the pores, leading to a tensional state of pore water in the mudstone, resulting in an strength increase (Onaisi et al. 1994). In addition, dehydration stiffens the clay aggregates due to thinning of the water film between the contacts of clay particles (Yurikov et al. 2018), hence increasing the Young's modulus.

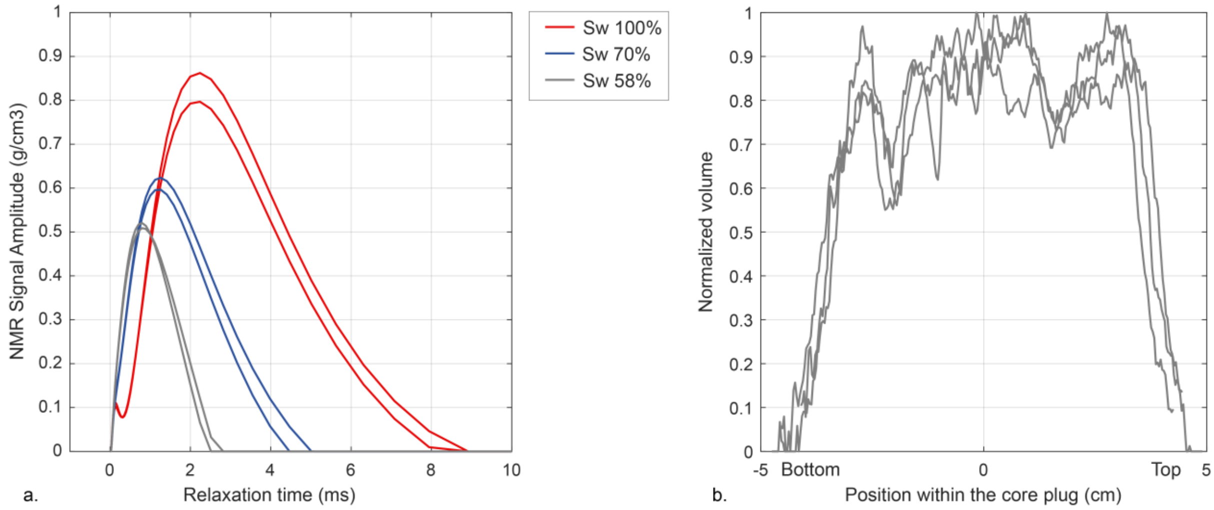

Figure 2 *NMR data from the Whitby Mudstone core plugs with different water saturations (Sw). a. The signal amplitude of the* T_2 *distribution curves decreases with decreasing water saturation. b. Example of the normalized water distribution of the mudstone core plugs with a water saturation of 58%. The water distribution between the different core plugs is similar indicating minimal heterogeneity between them.*

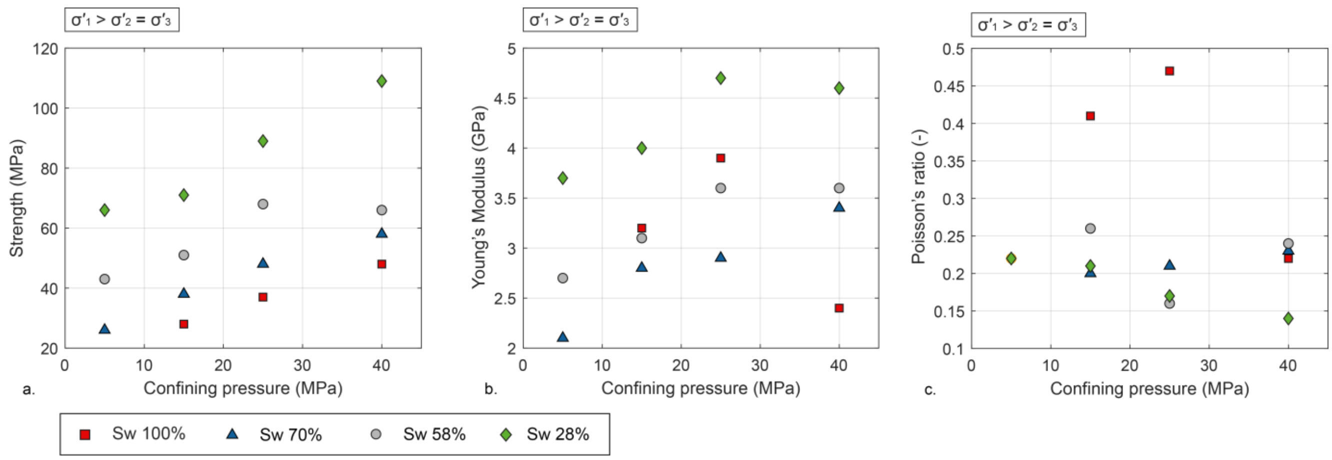

Figure 3 *Impact of water saturation and confining pressure on a. peak strength, b. Young's modulus, and c. Poisson's ratio. Loss of pore fluids leads to a significant increase in peak strength and Young's modulus, irrespective of the applied confining pressure. The Poisson's ratio generally decreases with dehydration.*

Conclusions

Sixteen triaxial deformation experiments were performed on Whitby Mudstone samples with different water saturations. Dehydration of clay-rich rocks leads to significant changes in the peak strength and the static elastic properties, including Young's modulus and Poisson's ratio. The mechanical results obtained from partially-saturated clay-rich rocks should be treated care when extrapolating them to *in situ* conditions.

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