TITLE

Direct shear tests on Cretaceous Shales from Cap-rock of the Longyearbyen CO2 Storage Pilot, Svalbard, Norway

AUTHORS

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ABSTRACT

This work presents a high stress direct shear box rig along with the results of direct shear tests on shale samples from Longyearbyen CO2 Storage Pilot, Svalbard, Norway. Injection of CO_2 into reservoir increases pore pressure in the reservoir rock and in the interface with cap rock. Reservoir pressure may be increased to a certain level, which can be sustained by the cap rock. Exceeding that pressure may cause slip along pre-existing fractures and reduce the seal integrity. The shear box apparatus is capable of applying high stresses equivalent to the depth of petroleum reservoirs, include confining pressure on samples, and shear to large displacements. Shale samples from Rurikfjellet Formation, depth interval of 367-384 m were tested under various normal stresses of 6.4, 8.2 and 12 MPa. The peak shear strength of the first two samples was almost the same while that tested at 12 MPa had much higher strength. Friction angle and cohesion of shale were 16 degree and 3.2 MPa respectively.

Introduction

This work presents shear strength properties of shale samples from the Longyearbyen CO2 Storage Pilot, Spitsbergen (Svalbard), northern Norway. This shale acts as seal for a potential CO_2 storage site (Fig. 1). Injection of CO_2 into the reservoir increases pore pressure in the reservoir rock and in the interface with cap rock. Reservoir pressure may be increased to a certain level, which can be sustained by the cap rock. Exceeding that pressure may cause slip along pre-existing fractures and reduce the seal integrity. Therefore, properties of fractures and weakness (bedding) planes is an important element to be investigated for cap rock integrity studies.

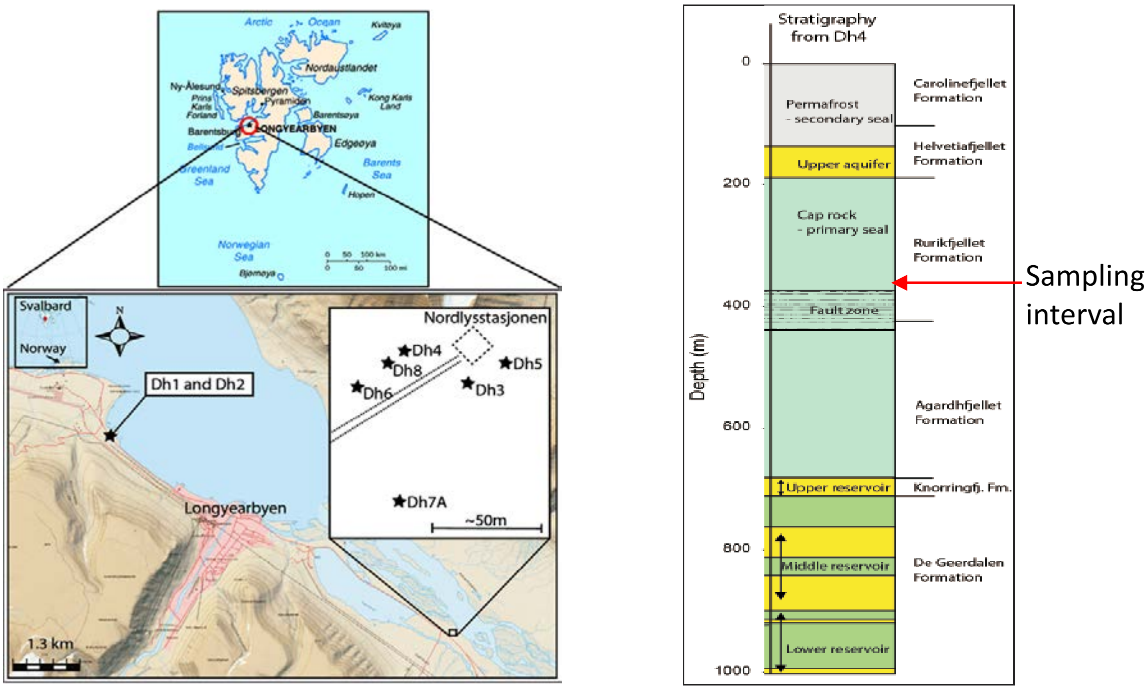

Figure 1 *Location of boreholes drilled at the Longyearbyen CO_2 storage site, Svalbard, northern Norway (left) and stratigraphy column in borehole Dh4 along with the sampling interval for this study.*

There are several publications on characterization of geological, geophysical and mineralogical properties of shale from the Longyearbyen CO2 pilot site (e.g. Ogata et al. 2011, Bælum et al. 2012 and Braathen et al. 2012). There are also a few publications on the mechanical properties of this shale (e.g. NGI 2010, Bohloli et al. 2014, Abbas 2015). Majority of these studies focus on very large (field) scale properties or on small intact samples subjected to simple mechanical tests such as uniaxial compression and indirect tensile tests. However, shear strength properties, especially for fractured samples have not been the subject of those works. This study focuses on the determination of shear strength parameters of fractured shale samples using the direct shear test. The results will then be compared with the shear strength of intact samples tested from the same well.

Methodology and material

A recently developed direct shear box test was employed to measure shear strength and frictional properties of pre-fractured shale samples from Svalbard. The shear box rig can apply very large displacements, up to 50 mm, and very high normal stresses, up to 450 kN. It has the capacity of running shear tests in dry or wet conditions, with or without pore pressure during shearing (Fig. 2). Direct shear box measures the shear stress required to displace material subjected to a certain normal load and thus provides friction angle and cohesion of the sheared plane. The shear tests were run based on the ASTM D5607-08 standard (ASTM, 2013).

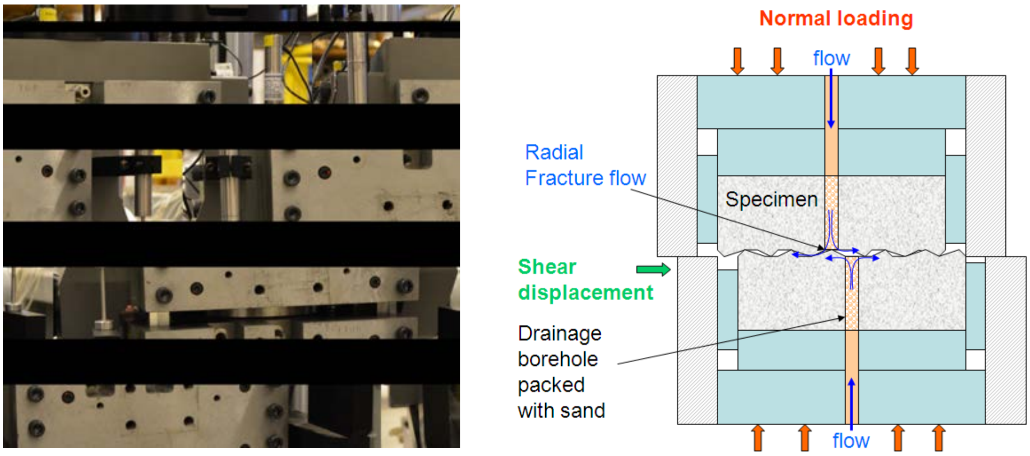

Figure 2 *The direct shear apparatus used in this study; (left) direct shear box and (right) schematic cross section of the box and sample showing application of normal load, shear force and introduction of fluid flow to slip surface.*

Core samples from bore hole Dh6, depth interval of 367-384 m from Rurikfjellet formation were used for this study. The cores were drilled in 2012 and sealed off with aluminium foil and paraffin immediately after drilling and were transported to NGI laboratory in Oslo, where they were preserved in a climate room. Three test specimens with the dimensions of 40 mm in diameter and 70 mm in length were prepared from the original cores. The prepared core samples had the tendency of discing along the bedding plane and it was therefore easy to separate them along the bedding to get a pre-fracture specimen to test (Fig. 3). Thus, each test specimen consisted of two cylindrical parts, separated with a natural bedding parallel fracture and held together with a masking tape. We used a very thin film of epoxy (about 0.1 mm thick) to encapsulate test specimen in the shear box. The middle section of specimen is unconfined in radial direction with a gap of about 10 mm, allowing fracture to develop and slide, free in horizontal plane when subjected to shearing.

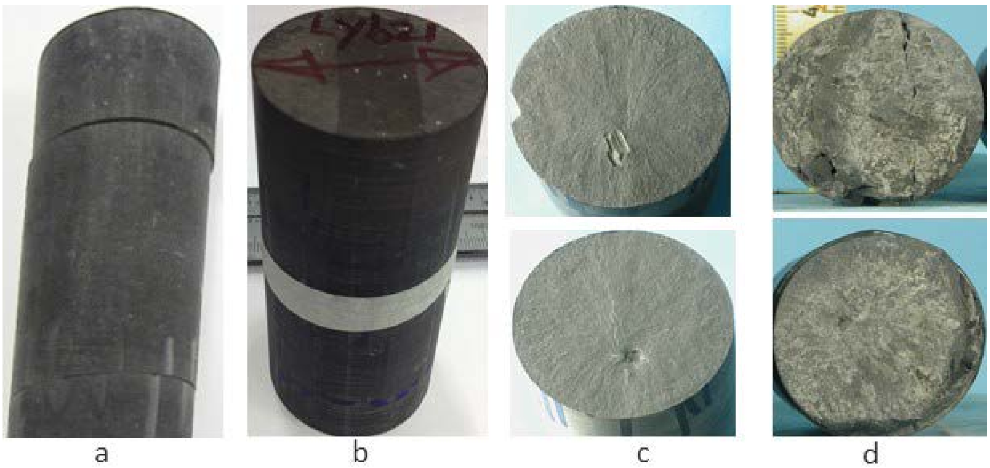

Figure 3 *Shale cores from Svalbard used in this study. (a) discing of shale core along the bedding plane, (b) a test specimen separated along bedding plane and attached and taped together, (c) surface of the fracture before shearing and (d) after shearing in the direct shear box.*

Three shale specimens were subjected to the direct shear test. The specimens had their natural water content since they were sealed immediately after coring and opened short time prior to testing. No fluid was introduced to the fracture surface. All samples were sheared for 10 mm displacement and were run under constant normal load. Loading area reduces proportional to horizontal displacement. Therefore, a linear function was used for correction of the load to stress giving the following constant normal stresses during shearing:

- LYB17-1: Normal stress = 6.4 MPa
- LYB20: Normal stress = 8.2 MPa
- LYB21: Normal stress = 12 MPa

Results

Results of the shear tests shows a relatively large elastic deformation before reaching plastic region and finally peak shear strength. After peak shear, samples bear a lower stress level, the residual shear strength (Fig. 4). Peak and residual shear strengths are typically proportional to normal load and increase with increasing normal load. However, the difference between the peak shear strength of samples LYB17-1 (grey curve in Fig. 4) and LYB 20 (orange curve in Fig. 4) is not significant, although they differ about 2 MPa in normal stress. Nevertheless, the peak and residual strengths of sample LYB21 (green curve) are considerably higher than the other two.

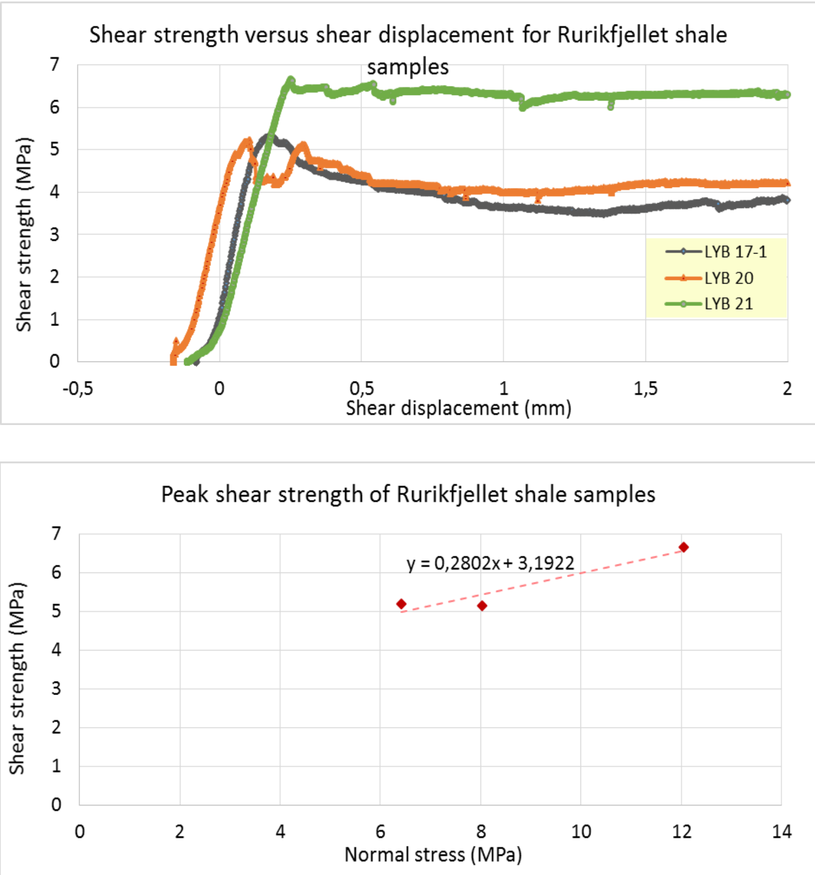

Figure 4 *Results of direct shear tests on three shale samples from Rurikfjellet Formation, Svalbard. (a) Shear strength versus displacement and (b) shear strength versus normal strength with an interpreted failure line.*

Peak shear strength versus normal stress is shown in the lower panel of Fig. 4. The interpreted failure line gives a cohesion of 3.19 MPa and friction angle of about 16 degrees. Value for friction angle is relatively low compared to tests on intact shale samples from the same well and slightly deeper (428 m) in triaxial set-up which gave friction angle of 31.5 degrees and cohesion of 3.2 MPa. This discrepancy may be explained by method of testing or lithological variations; first, triaxial tests were done on intact plugs oriented with plug axis and loading direction normal to bedding while specimens for direct shear test consisted of pre-fractured plugs sheared parallel with bedding. Second, there could be inherent differences between the samples tested since the triaxial samples were cored from the deeper interval of 426 m, while direct shear samples are from the depth of 367-384 m.

Mechanical strength of intact samples is typically higher than that of pre-fractured specimens. Therefore, we may expect the strength and frictional properties of shale along bedding (weakness) plane will be lower than that of the intact samples. Injection and storage of CO_2 increases pore pressure and shear stresses may raise closer to the failure line (presented in Fig. 4). Bedding plane acts as a weakness plane upon pressure build-up and thus may slip prior to failure of intact rock.

Conclusion

Pre-fractured shale samples from Rurikfjellet Formation, Svalbard were tested in the direct shear box giving the friction angle of 16 degrees and cohesion of 3.2 MPa. These values are for samples that were detached along their bedding plane, then attached together, encapsulated in a metal cylinder, loaded normally and sheared along the bedding parallel fracture plane. Both the peak shear strength and friction are found to be lower for the tests on bedding parallel pre-fractured samples performed in the direct shear box than the strength values obtained previously from triaxial tests on intact samples, however, lithology and loading orientation relative to bedding plane is not directly comparable. A systematic testing of the anisotropic strength variations in the shale and comparison of the two test methods with same material and same loading orientation relative to fracture plane is recommended for further investigation.

Acknowledgement

The authors would like to acknowledge Axel Walta, Gudmund Havstad, Heidi Debreczeny Wilkinson and Andreas Haugland for the extensive work to mobilize and run the direct shear rig, and Sven Vangbæk for the great effort to prepare test specimens. This work has been supported by Norwegian Research Council through projects PROTECT, SUCCESS FME centre and SAFT as well as by Norwegian Geotechnical Institute GBV.

References

Abbas, M. [2015] Geomechanical characterization of shale caprock of the Longyearbyen CO_2 storage pilot. *Master Thesis*, Department of Geosciences, University of Oslo, 100.

ASTM [2013] Standard test method for performing laboratory direct shear strength tests of rock specimens under constant normal force, *ASTM D5607-08*.

Braathen, A., Balum, K., Christiansen, H., Dahl, T., Eiken, O., Elvebakk, H., Hansen, F., Hanssen, T., Jochmann, M. and Johansen, T. [2012] The Longyearbyen CO_2 Lab of Svalbard, Norway− initial assessment of the geological conditions for CO_2 sequestration. *Norwegian Journal of Geology,* **92**, 353-376.

Bohloli, B., Skurtveit, E., Grande, L., Titlestad, G.O., Børresen, M.H., Johnsen, Ø. and Braathen A. [2014] Evaluation of reservoir and cap-rock integrity for the Longyearbyen CO_2 storage pilot based on laboratory experiments and injection tests. *Norwegian Journal of Geology*, **94**, 171–187.

Bælum, K., Johansen, T., Johnsen, H., Roed, K., Ruud, B., Mikkelsen, E. and Braathen, A. [2012] Subsurface geometries of the Longyearbyen CO_2 lab in central Spitsbergen, as mapped by reflection seismic data. *Norwegian Journal of Geology,* **92**, 377-389.

NGI, 2010: Laboratory Testing – Janusfjellet cap rock material. *NGI report 20061337–00–10–R*, 22.

Ogata, K., Senger, K., Braathen, A., Tveranger, J. and Olaussen, S. [2011] Natural Fractures in a Tight Reservoir for Potential CO_2 Storage (Spitsbergen, Svalbard)-Preliminary Results from Cores. *1st Sustainable Earth Sciences Conference & Exhibition (SES 2011)*.