TITLE

Brazilian tensile strength test: post-failure behavior of Jurassic and Cretaceous shales from Svalbard

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ABSTRACT

This study presents results of indirect tensile tests on cap rock shale samples from Svalbard CO2 storage pilot. It elaborates on tensile strength and the relationship between loading direction and post-failure behaviour of cap rock shale samples. Several test plugs were sampled from Jurassic and Createaceous Age cores of borehole Dh2, Dh4 and Dh6 from depth range of about 400 to 700 m. Samples were tested both parallel and perpendicular to bedding plane. Result of the tests showed that cap rock shale samples subjected to the Brazilian test in different directions relative to bedding planes differs not only in terms of the peak strength but also in the shape of the post-failure curve. The cap rock shale loaded perpendicular to bedding have higher strength and those loaded parallel with bedding show lower strengths. Samples loaded perpendicular to bedding bear load up to a maximum peak followed by a large drop and never reaches the maximum peak load again. For samples loaded parallel with bedding a maximum load is reached at failure followed by sudden drop, but load can increase to the same or higher level than the initial failure stress.

Introduction

Mechanical anisotropy, deformation behaviour and post-failure behaviour of cap rock shales are of paramount importance in various engineering problems such as subsurface excavations, petroleum production and CO2 storage (Hudson and Harrison 1997, Tutlouglu et al. 2015). Strength anisotropy, pre-failure and post-failure behaviours of rock can be determined using laboratory tests such as the Brazilian tensile strength test. A disc-shaped specimen is subjected to compression across the diameter, which results in a tensile stress field inside the specimen, and leads to failure of specimen in tension. Deformation of test specimen can be studied in detail and be related to loading direction and failure processes.

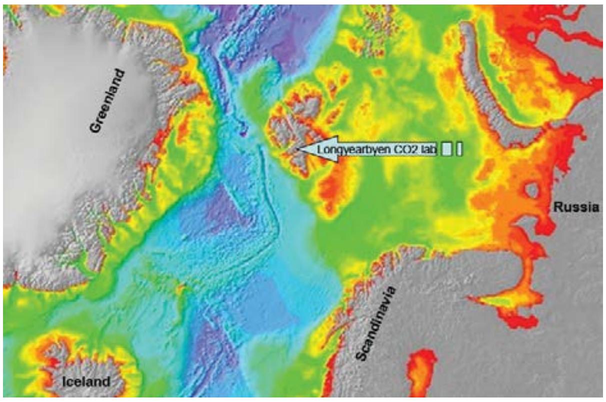

Figure 1 *Location of the study area, Longyearbyen CO2 Lab, 78 degrees North.*

Mechanical characterisation of cap rock shales from three bore holes (Dh2, Dh4 and Dh6) from the Longyearbyen CO_2 Lab (Braathen et al. 2012) (Fig. 1) has been presented in Bohloli et al. (2015), where the main focus was the strength values rather than failure behaviour of the shale samples. The current research extends beyond tensile strength anisotropy and focuses on the relationship between loading direction and post-failure behaviour of cap rock shale samples loaded in different directions relative to bedding plane. Several test plugs were sampled from cores of borehole Dh2, Dh4 and Dh6 from depth range of about 400 to 700 m (see Table 1 for details). They cover three geological formations; Rurikfjellet, Agardfjellet and Knorringfjellet of Jurassic and Createaceous Age.

Methodology

We use the Brazilian tensile strength test, also known as indirect tensile strength test, to determine tensile strength of cap rock shales and measure their deformation properties (e.g. pre- and post failure). Brazilian test is one of the widely used methods in engineering practice to determine the tensile strength of rocks indirectly. A disc-shaped specimen is loaded diametrically by two steel jaws that cover an arc of contact of approximately 10º at failure (ISRM, 2007) as shown in Fig. 2. Height of specimens is in most samples close to radius of specimen according to ISRM recommendation. Details on specimen dimensions are given in Table 1. One layer of masking tape was wrapped around the specimens. Load is applied continuously at a constant rate such that failure is reached typically within 30 seconds. Axial load versus time is recorded and plotted for tested specimens.

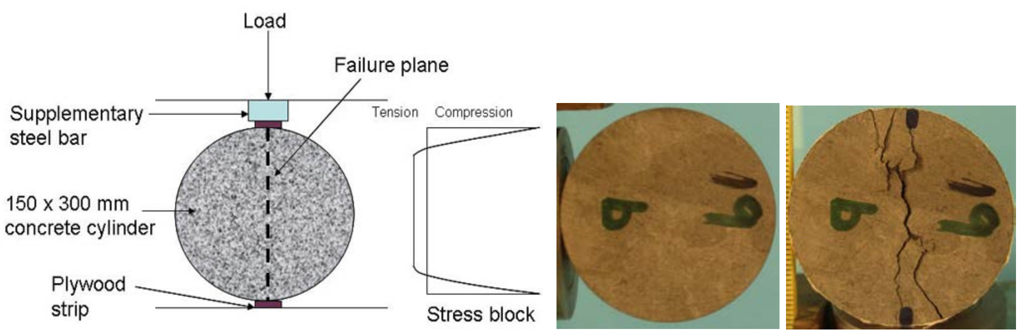

Figure 2 *Left: schematic illustration of Brazilian test (Courtesy of the Concrete Portal, 2015) and right: photograph of a shale sample 19b before and after testing.*

The tensile strength σ_t (MPa) is calculated using the following equation:

$$\sigma_t = \frac{0.636 \cdot P}{D \cdot t}$$

where *P* is the axial load at failure (N), *D* is the diameter of the specimen (mm) and *t* is the thickness of the specimen (mm).

Results and Discussion

Tensile strength of cap rock shale samples

Tensile strength of Rurikfjellet samples of Cretaceous Age from the depth of 308 through 425 m varies between 4.05 and 10.71 MPa perpendicular to bedding. Samples 32A and 32B from depth of 425 m show significantly higher tensile strength than the others. These samples have a high density of 2.85 g/cm^3 and might be related to a fault zone, well known in the well logs. Strong cementation associated with the fault rocks are suggested as the explanation for the higher strengths (see Bohloli et al. 2015). No sample parallel to bedding is available from Rurikfjellet formation. From Knorringfjellet and Agardfjellet formations specimens of Jurassic Age were tested both parallel and perpendicular to the bedding planes. Comparison of test results shows that tensile strength parallel to bedding is lower than that of perpendicular to bedding.

Table 1 *Specifications and tensile strength of cap rock shale samples from Rurikfjellet, Agardhfjellet and Knorringfjellet formations of bore holes Dh2, Dh4 and Dh6.*

Depth (m)	*Sample ID*	*Diameter D (mm)*	*Thickness t (mm)*	*Density g/cm3*	*Tensile strength σ_t (MPa)*	*Load direction*
308	8A	40.4	21	2.58	5.76	Perpendicular to bedding
308	8C	40.4	21	2.58	5.60	
369	18	40.4	21	2.60	4.94	
369	19A	40.3	19	2.54	4.57	
386	25B	40.0	20	2.60	4.05	
425	32A	28.5	15	2.85	10.71	
425	32B	28.5	15	2.85	8.33	
685	C1	25.25	12.49	2.64	4.35	
685	C2	25.19	12.59	2.64	2.38	
699	E1	25.26	12.14	2.39	3.02	
699	E2	25.26	09.13	2.56	2.24	
685	A1	25.10	12.35	2.65	2.80	Parallel with bedding
685	A2	25.14	12.30	2.58	2.44	
685	B1	25.12	12.29	2.58	6.65	
685	B2	25.16	12.33	2.63	3.08	
699	D1	25.26	12.59	2.57	2.94	
699	D2	25.21	12.56	2.28	5.06	

Post-failure behavior of cap rock shale samples

A typical failure curve shows a stress increase up to a peak load where specimen cracks and load sharply drops to a relatively low level (Tutluoglu et al., 2015). We observed that post-failure behavior of the samples loaded parallel to bedding is different from those loaded perpendicular to bedding. For the first group, it shows a first peak load (failure load) followed by a small load drop and several subsequent peak loads. These secondary and tertiary peaks can reach or even exceed the first peak load (Fig. 3). This indicates that after the first cracking, failure develops and the sample can bear loads that are significantly larger than the first failure load. This behavior is observed for all samples loaded parallel to bedding irrespective of their strength (Fig. 3).

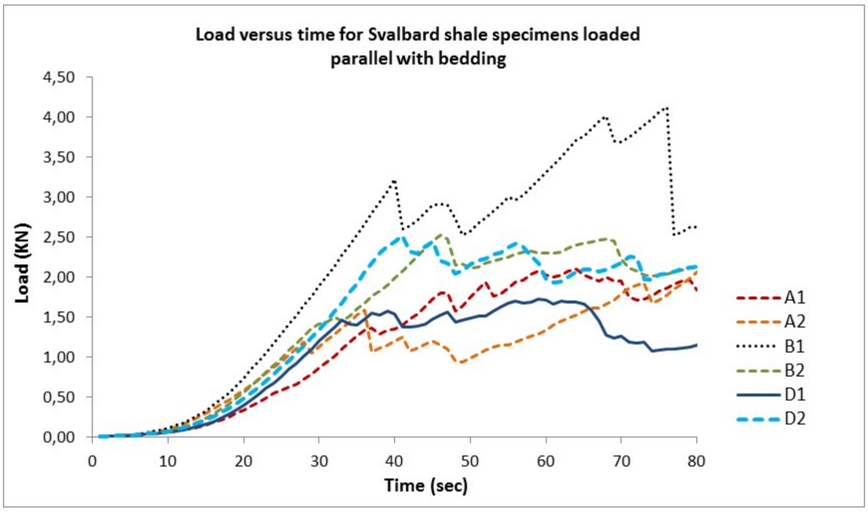

Figure 3 *Load versus time for shale samples loaded parallel with bedding plane. Sample B1 (black-dashed line) reaches the first peak load and fails at around 40 seconds. Further failure development results in peak loads that are higher than the failure peak. A similar trend is also observed for other samples where post-failure peaks are almost as big as the failure peak.*

Specimens loaded perpendicular to bedding plane show almost a typical failure curve throughout the loading time. First, a peak load is reached which indicates cracking of the specimen. Then a sharp load drop is observed (Fig. 4). For some specimens, e.g. 8A and 8C, two peak loads are registered but after these peaks of almost the same magnitude, load decreases significantly and no recovery of load versus time is registered. This shows that first failure/crack in such specimens requires a large load but development of subsequent fractures requires much less stress. Thus, cap rock shale samples tested in the laboratory by the Brazilian tests method that fail perpendicular to bedding plane can't bear large loads in the post-failure region.

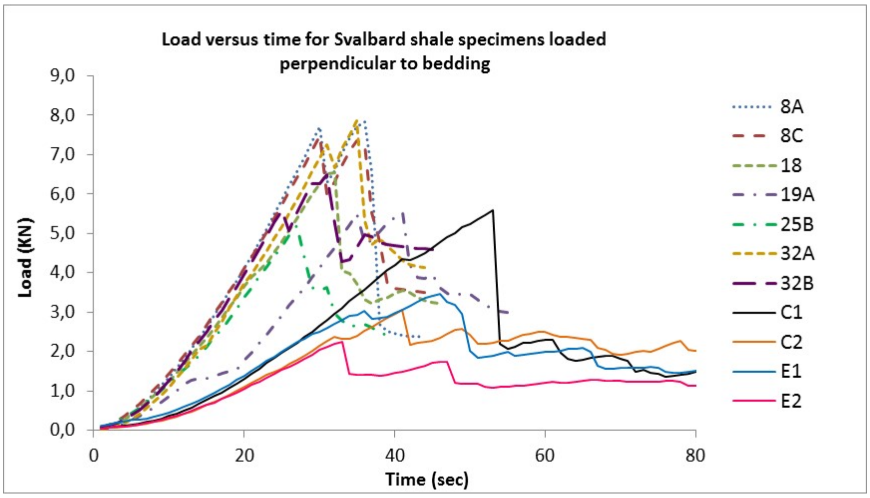

Figure 4 *Load versus time for shale samples loaded perpendicular to bedding plane. Failure of samples is indicated by the first peak load followed by a sudden drop. After the drop, sample bear some loads but never reaches the same level as the failure peak.*

From our experiments it can be stated that the post-failure behavior of cap rock shale specimens tested is dependent on loading direction. This observation implies that samples that fails parallel to bedding plane can bear relatively large load/stress in the post-failure region. On the other hand, samples that fail perpendicular to bedding plane have higher strength but bear quite small loads in the post-failure region.

Post-failure behavior of rocks may be monitored by acoustic/microseismic measurements. Each failure, indicated by a peak load followed by sudden stress drop, makes an acoustic event. This happens in the post-failure region too. Assuming a shale loaded parallel to bedding plane and similar to the Brazilian testing conditions, it may create a first acoustic emission then followed by several events. The magnitude of post-failure events may exceed that of the first acoustic event. In contrary, if a shale fails perpendicular to bedding, it may produce a major acoustic emission (or two) followed by much smaller events. This can be a potential application of post-failure data for microseismic monitoring. However, it has not been validated in the laboratory yet and requires further investigation.

Conclusions

Shale samples subjected to the indirect tensile test in different directions relative to bedding differs not only in terms of the peak strength but also in the shape of the post-failure curve. This study shows that cap rock shale specimens from Svalbard CO2 storage site loaded perpendicular to bedding have higher strength and those loaded parallel with bedding show lower strengths, as is well known from previous studies due to general anisotropic behaviour of shales. However, for samples loaded perpendicular to bedding, they bear load up to a maximum peak followed by large drop, which never reaches the maximum peak again in time domain. For samples loaded parallel with bedding, on the other hand, a maximum load is reached at failure followed by sudden drop which can increase to the same or higher level than the initial failure stress. This information from laboratory can be of importance also for seismic monitoring in field, although, in-situ boundary conditions might affect the post peak behavior compared to tests performed in the laboratory.

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References

Bohloli B., Skutveit E., Grande L., Titlestad, G.O., Børresen M.H., Johnsen Ø., Braathen A., 2015. Evaluation of reservoir and cap-rock integrity for the Longyearbyen CO2 storage pilot based on laboratory experiments and injection tests. Norwegian Journal of Geology 94, p. 171-187.

Braathen A., Balum K., Christiansen H., Dahl T., Eiken O., Elvebakk H., Hansen F., Hanssen T., Jochmann M. & Johansen T. 2012. The Longyearbyen CO2 Lab of Svalbard, Norway− initial assessment of the geological conditions for CO2 sequestration. Norwegian Journal of Geology 92, 353–376.

Concrete Portal, 2015. Available through: http://www.theconcreteportal.com/hard_strength.html

Hudson J.A. and Harrison J.P., 1997. Engineering rock mechanics: an introduction to the principles, 1st edn. Pergamon, an imprint of Elsevier Science, Oxford, UK.

ISRM, International Society for Rock Mechanics, 2007. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. Ulusay P. and Hudson J.A. (edits.), 627 p.

Tutluoglu L., Öge I.F., Karpuz C., 2015. Relationship Between Pre-failure and Post-failure Mechanical Properties of Rock Material of Different Origin. Rock Mech Rock Eng 48, p. 121-141.