ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 4 (2011) 5392–5397

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

The effect of CO_2 on the mechanical properties of reservoir and cap rock

Ira O. Ojala[a]

[a]*SINTEF, S P Andersens vei 15B, Trondheim, Norway*

Abstract

We have investigated the effect of CO_2 on the mechanical stability of the reservoir-caprock system. Castlegate and Bentheimer sandstones were used as analogues for reservoir rock. Pierre shale was utilized as an analogue material for a typical cap rock. The effect of CO_2 on carbonate rocks was studied by carrying out Brazilian tests on Lixhe and Austin chalks. The tensile strengths of both salt water and CO_2-salt water exposed samples were observed to decrease with sample porosity. There was a positive correlation with tensile strength and p-wave velocity. The tensile strength of sandstone, shale and chalk is not markedly affected by the presence of CO_2 in our tests. This observation has important implications for modeling fracture growth due to the injection of CO_2 on geological formations because geomechanical models require tensile strength as an input parameter. Future experimental work should quantify the effect of CO_2 on the entire failure envelope by using preserved core material and a triaxial test setup that mimics the in-situ stress and temperature conditions at a storage site.

Kywords: Rock mechanics; tensile strength; shale

1. Introduction

The goal for subsurface CO_2 storage is that the CO_2 remains underground for several thousands of years. It is therefore important that the integrity of the storage site is well characterized and understood prior to the onset of injection. In particular, any possible leakage pathways need to be carefully evaluated. There are several mechanisms that could cause the leakage of CO_2 from subsurface formations. Fluid pressurization during CO_2 injection could lead to fracturing or fault activation in the storage reservoir or the cap rock formation. Similarly, chemical processes such as carbonate cement dissolution or subcritical growth of fractures may act to weaken the rock. It is essential to quantify both the physical and chemical effects of the CO_2-saturated water on the mechanical properties of the host formation. In this study we have investigated the effect of CO_2 environment on the integrity of the reservoir and cap rock system.

doi:10.1016/j.egypro.2011.02.523

2. Background

The Brazilian test is frequently used for evaluating the tensile strength of rocks because the test samples are easy to prepare and the experiments are relatively quick to perform. It can be argued that such loading regime is more representative of in-situ loading than rock fracture experiments that involve direct tension [1]. The resulting fracturing and failure process can be modelled by using weakest link theories that have been developed for tensile failure [2]. In a typical test, uniaxial compression of rock discs leads nearly uniform tensile stress distribution normal to the diametral plane of the sample. The sample fails due to splitting of the rock disc [3]. The tensile stress σ_T sustained by the sample can be estimated from elastic theory [1,2]

$$\sigma_T = \frac{2P}{\pi L D} \tag{1}$$

Where P is load, L and D are length and diameter of the rock sample, respectively. However, some authors have suggested that Brazilian tests should not be used and tensile strength cannot be considered a material property [4]. Yet, the Brazilian test remains a commonly used method for evaluating the tensile strength of crustal rocks. In fact, the tensile strengths of reservoir and cap rocks are often used as input parameters for geomechanical models of storage site behaviour. Good quality laboratory data is an essential requirement for calibrating such numerical models of rock behaviour during CO_2 injection and storage.

3. Test procedure and specimens

Due to the lack of suitable field cores that we used outcrop rocks for the test series. Bentheimer and Castlegate sandstone samples were considered as suitable analogues for reservoir rocks. Castlegate sandstone is an outcrop rock that consists of 70% quartz, 30% feldspar and small amounts of clay [5]. Bentheimer sandstone is composed of 95% quartz, 2% altered feldspars and 3% clay [6]. Pierre shale is composed of 41% clay, 32% quartz & feldspar and 15 % calcite [7]. The effect of CO_2-water on carbonate rocks was investigated by using Austin chalk and Lixhe chalk. Lixhe chalk is composed of 98% $CaCO_3$ and 2% quartz (SiO_2). Previous studies have shown that its mechanical behaviour is close to reservoir chalks [8].With 88% calcite content the Austin chalk is less pure and it has higher silica content than Lixhe chalk [9]. The specimen diameter and length to diameter ratio were within ISRM specifications [10]. The rock porosity was determined from specimen weight and volume. The specimens were aged in CO_2 saturated salt water (3.5% NaCl) for a period of one week prior to testing. The control group was aged in identical P and T conditions for a same time period in 3.5% NaCl salt water. The ageing process was carried out at temperature of 80°C and pore pressure of 25 MPa in order to simulate reservoir conditions. This corresponds to a depth of 2.5 km assuming a geothermal gradient of 32 °C/km and water density of 1 g/cm^3. While such depth condition may be greater than some CO_2 sequestration projects these values were chosen to accelerate the chemical reactions between the CO_2-saturated salt water and the minerals that make up the rock samples. Prior to testing, the p-wave velocities were measured by using the ultrasonic transmission technique with Panametrics 500 kHz transducers, Yokogawa DL 1300A oscilloscope and Wavetek mode 278 12 MHz function generator. The cylindrical surface of the specimen was covered with masking tape as detailed in the ISMR standard [10]. The specimen was tested in a 10 kN MTS loading frame with curved loading jaws as shown in figure 1a. The loading rate was kept a constant 0.2 kN/min. While this rate is somewhat slower than the recommended 0.2 kN/s it still results in specimen failure in a relatively short time of 2-3 minutes. The compressional loads and sample deformation were recorded with a data acquisition system. The sample failed by splitting along the diametral plane as shown in figure 1b. The tensile strength was determined from the peak load sustained by the rock sample by using equation (1). In some tests there were two subsequent peaks in the stress-strain curves. We used the first peak throughout for defining the rock strength. Some of the Lixhe samples failed already during storage in salt water as shown in figure 1c.

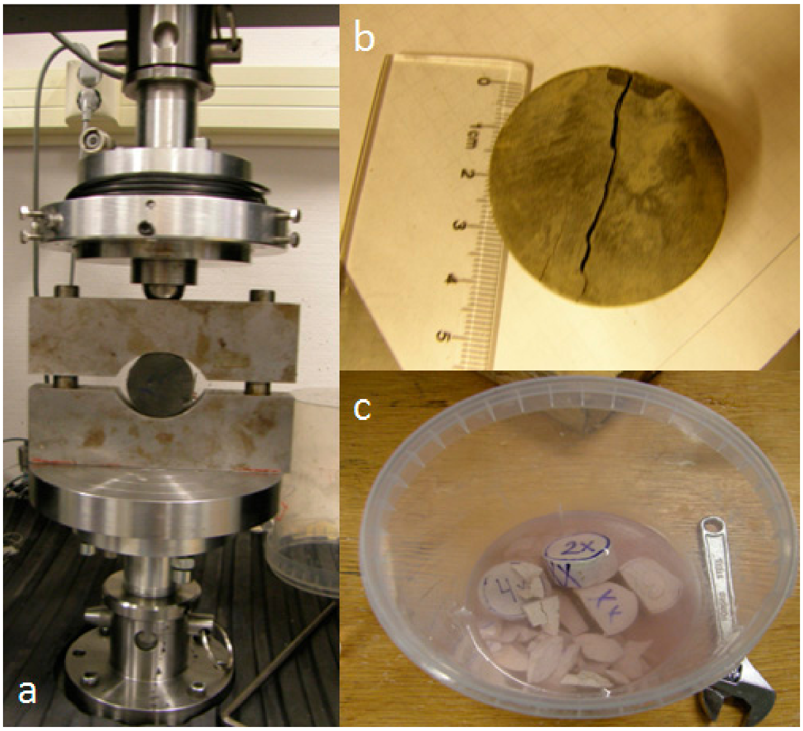

Figure 1a) The test apparatus for Brazilian tests. b) A typical failure mode of the test specimen, here Pierre shale. c) Some of the Lixhe samples failed already during storage in salt water.

4. Results

The tensile strength of Castlegate sandstone ranged from 0.37 to 0.86 MPa and 0.55 to 0.78 MPa for the CO_2-water and water saturated rocks, respectively. There were 20 tests in total for the Castlegate samples with 10 tests for each fluid type. The average tensile strengths were 0.61 and 0.65 MPa for CO_2-water and water saturated samples, respectively. The tensile strength of Bentheimer sandstone varied from 1.9-3.1 MPa and 1.9-3.2 MPa for CO_2-water and water saturated samples. The average tensile strength was 2.4 and 2.6 MPa for CO_2-water and water saturated samples, respectively. While these values suggest that the CO2-saturated samples are slightly weaker it is important to notice that some of the samples also had lower porosity. The average porosity of the water saturated Bentheimer was 1% greater than the 26% that was measured for the CO_2 exposed group. Hence, the lower tensile strength may have been caused by the lower initial porosity of the sandstone samples. The dependence of tensile strength on sample porosity is illustrated in figure 2a for Castlegate sandstone. Austin chalk exhibited a similar variation of tensile strength with porosity. The strength of the salt water specimens varied from 1.2 to 2.4 MPa. With tensile strength varying from 0.8 to 2.1 MPa the CO_2-water samples were slightly weaker. The observed variation in chalk tensile strength may also have been influenced by porosity differences. Figure 2b illustrates how the tensile strength of Austin chalk decreases in a linear fashion with increasing porosity. Austin chalk also exhibited a positive correlation between tensile strength and p-wave velocity. In contrast, the tests on Lixhe chalk exhibited no clear dependence of tensile strength on sample porosity. In fact, some of the water saturated samples failed purely as the result of the ageing process as illustrated in figure 1c. The tensile strength of CO_2-water saturated Lixhe samples ranged from 0.56 to 0.76 MPa. The water saturated sample strength varied from 0.36 to 0.74 MPa. At 0.64 MPa the average tensile strength of CO_2-water exposed rock samples was greater than the 0.49 MPa strength of water exposed specimens. These results could be an indication that CO_2 has a strengthening effect on relatively high porosity (38-43%) chalk with low quartz content. The differences in initial porosity and calcite content may explain the different deformation behaviour exhibited by the two chalks. The tensile test data for Pierre shale is illustrated in figure 2c. The mechanical properties of shale were not markedly affected by the CO_2 environment. The CO_2-water exposed samples had an average tensile strength of 0.65 MPa. The shale samples that had been aged in water environment had strength of 0.70 MPa. The relatively small variation in tensile strength is likely to reflect the natural variability of rock strength in shale.

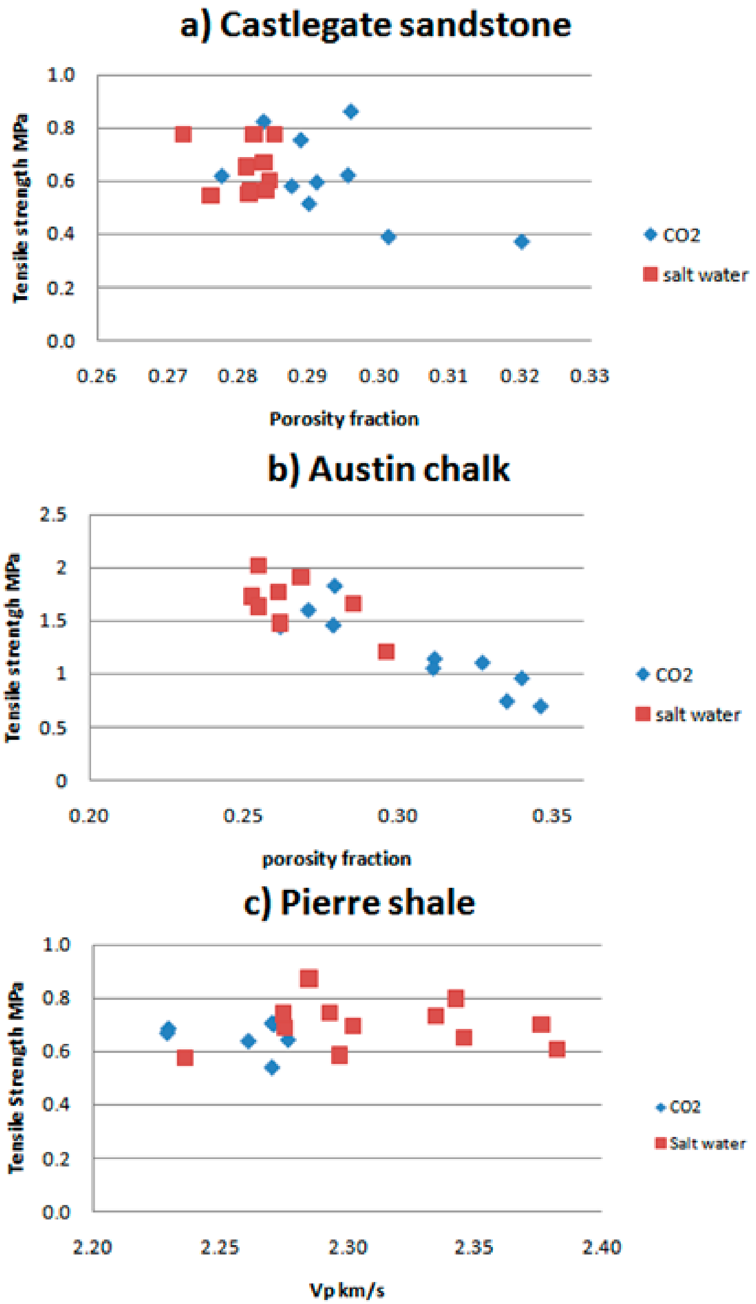

Figure 2 The tensile strength of a) Castlegate sandstone and b) Austin chalk as a function of porosity. C) The tensile strength of Pierre shale as a function of p-wave velocity.

5. Discussion and conclusions

We have measured the tensile strength of various reservoir and cap rock analogues by using the Brazilian test methodology. The effect of CO_2 on tensile strength was investigated by exposing rock discs to CO_2 saturated salt water. The CO_2 exposed samples were tested in an identical fashion to rock samples that had been aged in salt water. However, the tensile strength did not appear to be affected by the CO_2 environment. Our experiments suggest that the tensile strength is a function of rock porosity and p-wave velocity. Such correlation has also been observed in previous studies of tensile rock strength [1]. They observed an exponential decrease in tensile strength with increasing sample porosity. The uniaxial compressive strength (UCS) of sedimentary rocks has also been related to both porosity and p-wave velocity in experimental studies [11]. Such correlations can be used for deriving strength parameters from log or seismic data. In fact one may expect that both UCS and tensile strength display similar dependence on other rock properties such as porosity as in our tests. This is because the plane Griffith criterion predicts a correlation between uniaxial compressive strength and tensile strength [2]. Both UCS and tensile strength are important geomechanical parameters that are used for calibrating numerical models of the reservoir and cap rock system during CO_2 storage [12]. The tensile strength is used for predicting fracture pressure and hence the possibility of leakage during injection or long-term storage. Such models require experimentally determined strength parameters on CO_2 saturated rocks as input data. This is why it is essential to carry out rock mechanical laboratory tests on preserved core material from a storage site. It is therefore anticipated that the effect of CO_2 on rock strength will be investigated more thoroughly in future experimental work. This work could also involve triaxial test set-ups so that the entire failure envelope of CO_2 exposed rocks can be explored in a systematic fashion.

Acknowledgements

I would like to thank Hans Lund for carrying out the laboratory tests. This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research program *Centres for Environment-friendly Energy Research (FME)*. The authors acknowledge the following partners for their contributions: Aker Solutions, ConocoPhilips, Det Norske Veritas AS, Gassco AS, Hydro Aluminium AS, Shell Technology AS, Statkraft Development AS, Statoil Petroleum AS, TOTAL E&P Norge AS, and the Research Council of Norway (193816/S60).

References

[1] Aydin A, Basu, A. The use of Brazilian Test as a Quantitative Measure of Rock Weathering. Rock Mech Rock Engng 2006;39:77-85.
[2] Jaeger JC, Cook NGW. Fundamentals of rock mechanics.2nd ed. London: Chapman & Hall, 1971.
[3] Rocco C, Guinea GV, Planas J, Elices M. Mechanisms of rupture in splitting tests. ACI Mater J 1999;96:52-60.
[4] Hudson JA, Brown ET, Rummel F. The controlled failure of rock discs and rings loaded in diametral compression. Int J Rock Mech Min Sci 1972:9;241-248.
[5] Fjær E, Larsen I, Scheldt T. What is the Poisson's ratio of a soft rock? In: Alaska Rocks 2005, Proceedings of the 40th U.S. Symposium on rock mechanics, Anchorage, ARMA-USRMS 05-826.
[6] Dautriat J, Gland N, Guelard J, Dimanov A, Raphael JL. Axial and radial evolutions of compressed sandstones: end effects and shear-band induced permeability anisotropy. Pure Appl Geophys 2009;166:1037-1061.
[7] Bailey L, Denis JH, Goldsmith G, Hall PL, Sherwood JD. A wellbore simulator for mud-shale interaction studies. J Pet Sci Engng 1994;11:195-211.
[8] Homand S, Shao J F. Mechanical behaviour of a porous chalk and water/chalk interaction. Oil & Gas science and technology –Rev. IFP 2000:55;591-598.
[9] Lee Y-J, Wiltschko DV. Fault controlled sequential vein dilation: competition between slip and precipitation rates in the Austin chalk, Texas. J Struct Geology 2000;22:1247-1260.
[10] Bieniawski ZT, Hawkes I. Suggested methods for determining tensile strength of rock materials. Int J Rock Mech Min Sci Geomech Abs 1978;15:99-103.

[11] Chang C, Zoback MD, Khaksar A. Empirical relations between rock strength and physical properties in sedimentary rocks. J Pet Sci Engng 2006;51:223-237.
[12] Vidal-Gilbert S, Tenthorey E, Dewhurst D, Ennis-King J, Van Ruth P, Hillis R. Geomechanical analysis of the Naylor field, Otway Basin, Australia: Implications for CO2 injection and storage. Int J Greenhouse Gas Control 2010;4:827-839.