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Geotechnical Investigations of Cap Rocks above CO₂-Reservoirs

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Abstract

The experimental investigation of clayey rocks which are typical for cap rock formations above CO₂ storage reservoirs is described and results are given. One series of claystone samples is gathered from the injection well of the Ketzin pilot test site in Germany. Another series comes from the same Keuper formation in a near-surface outcrop in the Southwest of Germany. The near-surface condition allowed drilling of samples with a standard size of 100 mm diameter and 200 mm height as well as large samples with a diameter of 550 mm and a height of 1200 mm.

A special triaxial testing procedure is applied both on standard and large size samples which allows determination of the strength, stiffness and viscosity behavior of the rock in one path. A multi-stage technique (stepwise variation of the confining pressure) gives the strength behavior of each single sample. Stepwise varied deformation rates, over two orders of magnitude, lead to steps in the stress-strain-curve from which the viscosity index can be calculated. The viscosity index can be directly used in the Norton's constitutive relations for a viscoplastic simulation. The comparison of results from standard and large samples shows that for clayey rocks a scale effect is negligible. Strength, stiffness and viscosity are not dependent from the sample size. The observed failure modes of the samples show that the transition from cataclastic to non-cataclastic behaviour occurs in the range of the applied levels of pressure and deformation rates even at room temperature. This transition limit is very important for the judgment of the sealing capacity of a cap rock. If numerical simulations result in deformation rates which, for the given pressure and temperature conditions in a cap rock formation during the CO₂ injection, stay sub-critical for cataclastic behaviour, the formation of new cracks can be excluded.

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1. Introduction

Injection of CO₂ in deep geological formations will cause an increase of formation pressure over a large area. Thus the formations above a CO₂-reservoir and especially the sealing cap rock will deform in a pillow like manner. In the center of the pillow the bottom of the cap rocks is compressed and at the edge it is extended. It must be proven that local deformations will not activate latent discontinuities and that deformation rates will be sub-critical

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with respect to cataclastic behavior of the rock mass. Otherwise the permeability and the potential of hydraulic breakthrough would increase.

Numerical simulations of the problem need input parameters and amongst them, parameters of the rock mass behavior. The level of pressure, relevant deformation rates and temperatures require the use of elastoplastic and viscoplastic constitutive relations in numerical simulations. The transition from non-cataclastic to cataclastic behavior is of prime importance.

The CO₂SINK-Project at Ketzin test site in Germany gave the chance to go through the whole procedure of CO₂-storage from pre-investigation to injection [1]. In a coring campaign, samples from the cap rock formation consisting of Triassic claystones from Keuper were gathered. The work described in this paper was part of the joint research project “COSMOS”, which was in close collaboration with the CO₂SINK-Project.

2. Geomechanical testing of cap rock

2.1. Investigated material

The Keuper rock material from the Ketzin site was sampled in the injection well at a depth of 620 m. It is a highly consolidated pelitic claystone of reddish to brown color (Fig. 2a). Partially it contains homogeneously distributed inclusions of anhydrite lenses with diameters of 1 to 3 mm. The same geological Keuper formation was accessible in a clay pit near Zaisersweiher, Southwest Germany. Due to the near-surface conditions the reddish to brown, slightly silty claystone is significantly less consolidated than the one from Ketzin. The mineral composition is of both materials is given in table 1. All samples show a high content of sheet silicates. Whereas the Ketzin samples contain only illites and chlorites, the Zaisersweiher samples contain also smectite.

Table 1: Mineral composition of samples from Ketzin site (quantitative X-ray analysis)

Mineral	Chemical formula	Ketzin A-4-3	Ketzin A-7-1	Ketzin A-7-3	ZWR 1	ZWR 2
Illite	$KAl_2[(OH)_2 Si_3AlO_{10}]$	43	42	37	38	35
Chlorite	$(Mg,Fe)_3[(OH)_2Si_3AlO_{10}]$	11	7	7	17	19
Quartz	SiO_2	13	11	12	9	9
Plagioclase	$Na_xCa_{1-x}[AlSi_3O_{10}]$	6	9	9	6	3
Dolomite	$CaMg(CO_3)_2$	24	15	18	-	-
Calcite	$Ca(CO_3)$	-	-	-	9	6
Anhydrite	$CaSO_4$	0	13	14	-	-
Hematite	Fe_2O_3	< 1	2	2	3	3
Halite	$NaCl$	2	1	1	3	3
Smectite		-	-	-	18	25

2.2. Testing technique

For the investigation of the mechanical properties of the pelitic rocks different triaxial testing devices were used:

- a spindle drive uniaxial testing apparatus (no further description)
- a newly developed triaxial apparatus with a high-precision volume measurement
- a large triaxial testing apparatus for rock mass samples

2.2.1. Triaxial test with high precision volume measurement

For the triaxial tests on standard size samples an innovative triaxial testing apparatus with a high-precision measurement (Fig. 1a) was used. The testing machine has a load capacity of 100 kN axial force and 12 MPa confining pressure and 1.6 MPa back pressure. Displacement control is possible in the range of 0.001 to 10 mm/min. Force control ranges from 0.001 to 50 kN/min. The cylindrical samples can have a size of 100 mm diameter and 100 mm height. The volume change of the sample can be measured with an accuracy of 50 mm³. This means, a volume change of less than 0.01 % can be measured on a 100 x 100 mm sample.

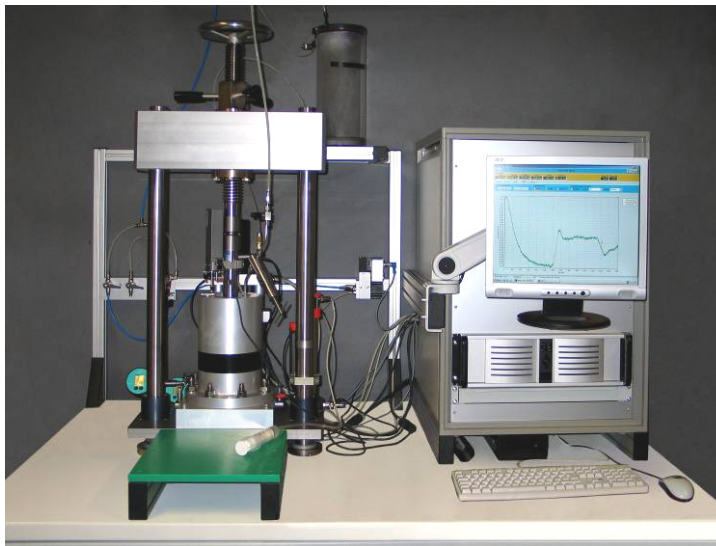


Fig. 1a: Triaxial testing apparatus with high-precision volume measurement

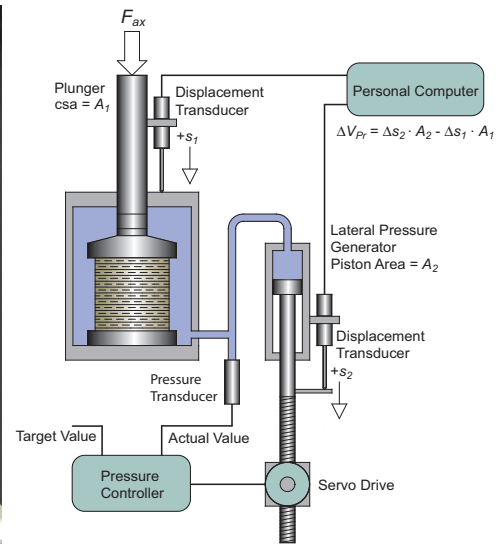


Fig. 1b: High-precision volume measurement of volume

2.2.2. Large scale triaxial testing

Large scale triaxial testing enables investigation of representative elementary volumes (REV) of rock masses. The sampling and testing technique was developed at the Universität Karlsruhe. Fig. 2a shows the sampling site in Zaisersweiher. The samples are drilled using a single core barrel. They are molded with plaster of Paris in a steel casing for retrieval.

The triaxial cell has a capacity of 6.4 MN axial force and 2 MPa confining pressure. Rock samples have a diameter of 550 mm und a height of 1200 mm. Fig. 2b shows the installation of the displacement measuring devices. Axial displacement is measured between load platens with ultra-sonic transducers. The change of diameter is measured with three measuring tapes placed around the specimen ever quarter height. The axial force is measured by an internal load cell.



Fig. 2a: Sampling of 550 mm cores in Zaisersweiher



Fig. 2b: Installation of 550 mm specimen in the large triaxial cell

2.3. Testing Results

2.3.1. Ketzin samples

Uniaxial compression tests show that without confining pressure the material behaves nearly linear elastic up to brittle failure at an axial strain of about 0.5% and axial stress of 46 MPa (Fig. 3b). By measuring axial and lateral strain with strain gauges, the axial stiffness was determined to be $E \approx 10$ GPa and the Poissons ratio to be $\nu \approx 0.13$.



Fig. 3a: Cylindrical sample of siltstone from Ketzin site before testing

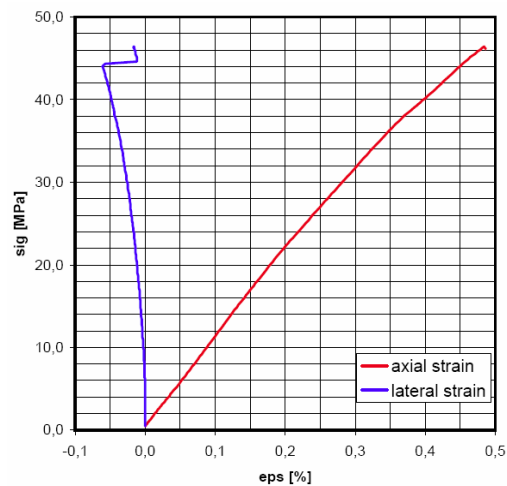


Fig. 3b: Stress-strain behaviour in a uniaxial compression test up to brittle failure

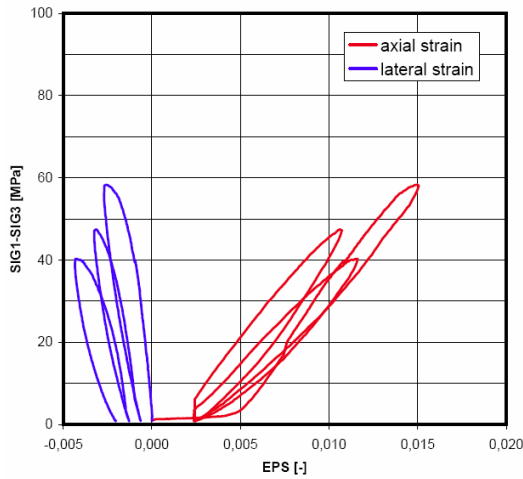


Fig. 4a: Stress-strain behaviour in a multi stage triaxial test with different confining pressures

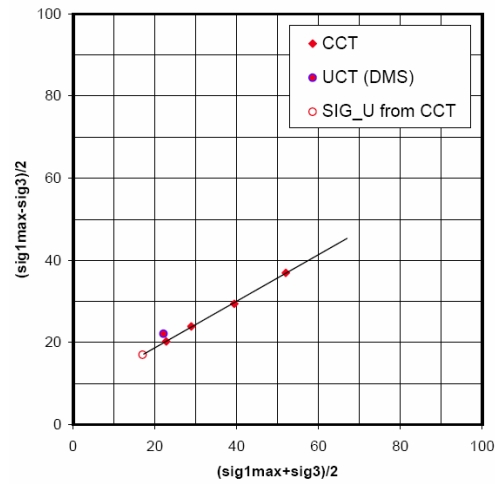


Fig. 4b: Results from triaxial(CCT) and uniaxial (UCT) tests on cap rock samples

Multi-stage triaxial tests on Ketzin samples (Fig. 4a) show that the transition from brittle (cataclastic) behaviour to ductile (non cataclastic) behaviour even at room temperature is reached when a confining pressure $\sigma_3 > 5$ MPa is applied. The claystone shows a friction angle of $\phi = 35^\circ$ and a cohesion of $c = 9.0$ MPa (Fig. 4b).

2.3.2. Zaisersweiher samples

In order to investigate scale effects in the behaviour of cap rock like materials, the Zaisersweiher samples were tested in standard and large size. The tests were carried out as multi-stage tests with stepwise variation of the deformation rate. Fig. 5 shows a sample with a diameter of 55 cm and a height of 125 cm before (a) and after (b) testing. A total shorting of 11 % did not produce open cracks. The material behaves non cataclastic.



Fig. 5a: Large sample from Keuper clay before triaxial test



Fig. 5b: Large sample from Keuper clay after triaxial test

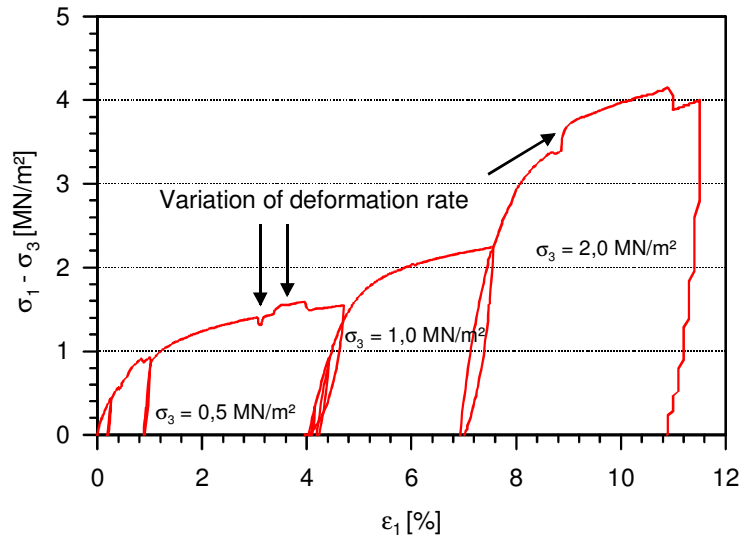
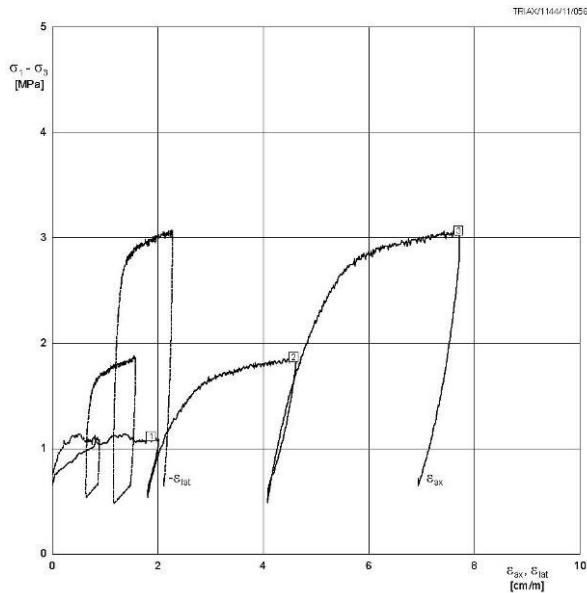
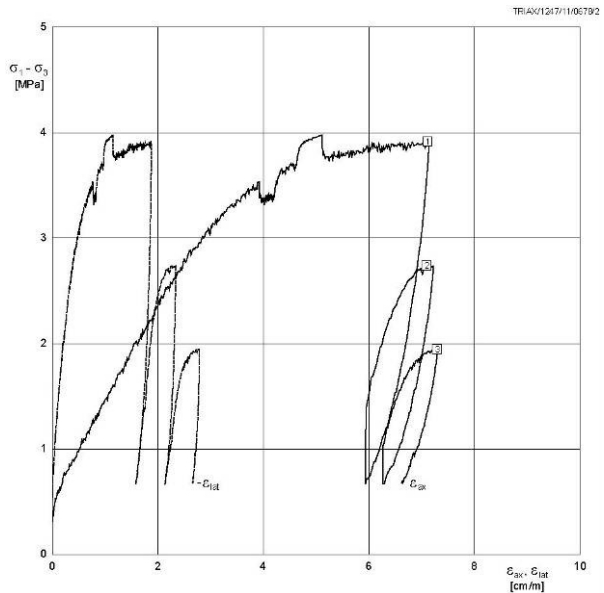


Fig. 6: Triaxial test of a large sample, deviatoric stress vs. axial deformation, multistage technique with variation of deformation rate



SPECIMEN: Probe Nr. ZWR 3/1
 Diameter: 99.7 mm Mass: 3503 g
 Cross-sectional area: 7807 mm² Density: 2.22 g/cm³
 Length: 202.4 mm
 Length-to-diameter ratio: 2.03
 PARAMETER: Loading rate: 0.1 mm/min
 EVAL. POINTS: $\sigma_1 - \sigma_3 = 1.1 \text{ MPa}$ at $\sigma_3 = 0.5 \text{ MPa}$ □
 $\sigma_1 - \sigma_3 = 1.9 \text{ MPa}$ at $\sigma_3 = 1.0 \text{ MPa}$ □
 $\sigma_1 - \sigma_3 = 3.1 \text{ MPa}$ at $\sigma_3 = 2.0 \text{ MPa}$ □



SPECIMEN: Probe Nr. ZWR 3/2
 Diameter: 99.0 mm Mass: 3427 g
 Cross-sectional area: 7698 mm² Density: 2.21 g/cm³
 Length: 201.3 mm
 Length-to-diameter ratio: 2.03
 PARAMETER: Loading rate: 0.1 mm/min
 EVAL. POINTS: $\sigma_1 - \sigma_3 = 3.9 \text{ MPa}$ at $\sigma_3 = 2.0 \text{ MPa}$ □
 $\sigma_1 - \sigma_3 = 2.7 \text{ MPa}$ at $\sigma_3 = 1.0 \text{ MPa}$ □
 $\sigma_1 - \sigma_3 = 1.9 \text{ MPa}$ at $\sigma_3 = 0.5 \text{ MPa}$ □

+

Fig.7a: Multi-stage triaxial test with increasing confining pressure steps

Fig.7b: Multi-stage triaxial test with decreasing confining pressure steps and variation of deformation rate

Fig 6 and 7 show the stress-stain diagrams of multi-stage tests of large and standard size specimen from Zaisersweiher. Strength and stiffness behavior as well as the viscosity are comparable. Standard samples give an average friction angle of $\phi = 24^\circ$ and a cohesion of $c = 0.28$ MPa. The large samples give a friction angle of $\phi = 30^\circ$ and a cohesion of $c = 0.20$ MPa. The Young's modulus is $E \approx 800$ MPa.

The evaluation of the steps in the stress-strain-curve, caused by the stepwise variations of the deformation rate, gives the viscosity index $I_{v\alpha}$. It can be determined using eq. (1) and (2):

$$q \approx q_\alpha \cdot [1 + I_{v\alpha} \ln(\dot{\epsilon} / \dot{\epsilon}_\alpha)] \tag{1}$$

$$I_{v\alpha} \approx \frac{q - q_\alpha}{q_\alpha \cdot \ln(\dot{\epsilon} / \dot{\epsilon}_\alpha)} \tag{2}$$

where $q = \sigma_1 - \sigma_3$ and q_α stand for the deviatoric stress and the reference deviatoric stress, $\dot{\epsilon}$ and $\dot{\epsilon}_\alpha$ stand for the axial strain rate and the reference axial strain rate. The viscosity index for both standard and large size samples is $I_{v\alpha} = 0.03$.

The viscous behaviour of cap rocks can be described using Norton's creep law [3] to determine the secondary (steady state) creep rate $\dot{\epsilon}_s$ according to eq. (3)

$$\dot{\epsilon}_s = A \cdot e^{\frac{-Q}{RT}} \cdot q^n \tag{3}$$

Norton's creep law is based on the assumption that creep is a thermally activated process. The exponent n can be determined directly from the viscosity index $I_{v\alpha}$ using eq. (4). Further parameters are a structural parameter A , the activation energy Q , the absolute temperature T , and the universal gas constant R .

$$I_{v\alpha} \approx \frac{1}{n} \tag{4}$$

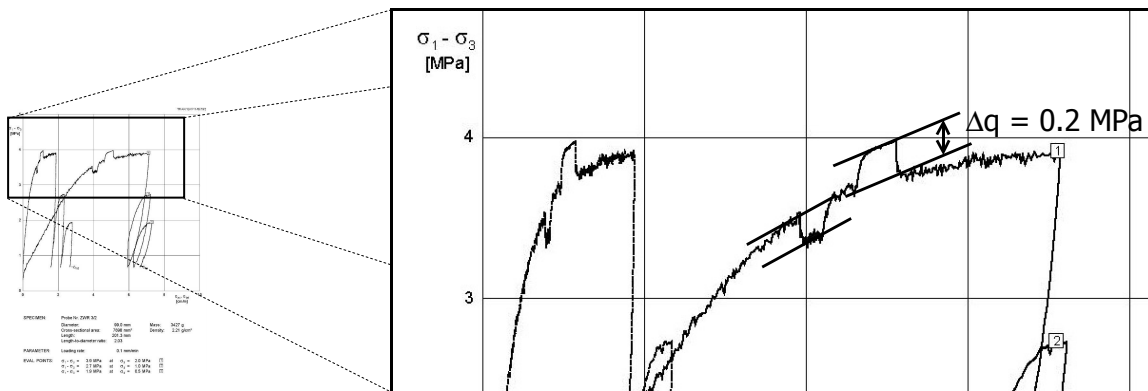


Fig. 8: Determination of the viscosity index $I_{v\alpha}$

3. Conclusion

The following conclusions can be drawn:

- The rate dependent behavior of cap rocks can be determined by innovative triaxial testing technique.
- Rate dependent material behaviour has to be considered with a constitutive law including nonlinear viscosity.
- The investigated cap rock materials behave non-cataclastic even at room temperature if at a given stress level the deformation rate is below a critical value.
- Scale effects are negligible.

4. Acknowledgements

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