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Experimental Investigation of the Effective Stress Coefficient for Various High Porosity Outcrop Chalks

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ABSTRACT: The contribution of the pore fluid pressure to the reduction of the effective stress during loading of fully saturated high porosity chalk (>40% porosity) has often been assumed to be represented by an effective stress coefficient close to unity. This assumption entails that the differential stress, which is the difference between the total stress and the pore fluid pressure, is equal to the stress the rock matrix is exposed to. Laboratory experiments were conducted by simultaneously increasing total stress and pore pressure. These tests resulted in substantial strains that should not occur if the assumption of an effective stress coefficient close to unity was true. Different explanations for these strains are discussed, among these consolidation effects, partial saturation effects, microscale damage, and possible laboratory equipment effects. The strains that were observed during the test phase mentioned above led to the initiation of a subsequent study focusing on the effective stress coefficient for porous chalk material. The results from this study suggest that the effective stress coefficient for high porosity outcrop chalks depends on the applied stress and the pore fluid, and is not a constant, nor close to unity as commonly presumed.

KEYWORDS. Effective stress coefficient, Compressibility, Outcrop chalk

1. THEORY

In solid homogeneous materials, the applied stresses will theoretically be evenly distributed throughout the substance. Introduction of porosity results in a more complex stress distribution at microscopic level. External load is transmitted at the intergranular contacts. The pore space is subjected to a hydrostatic fluid pressure and hence balances the external load. Terzaghi (1923) proposed the relation in equation 1, describing effective stress σ' as the difference between the external load σ_{tot} and the pore fluid pressure P_p; however, with a correction factor for the pore pressure, the effective stress coefficient α.

$$\sigma' = \sigma_{tot} - \alpha \cdot P_p \quad \rightarrow \quad \alpha = \frac{\sigma_{tot} - \sigma'}{P_p} \qquad (1)$$

This coefficient α should according to the theory be equal to the porosity value; however, it was experimentally found to be equal to 1 in soils [Terzaghi, 1923]. Biot (1941) listed certain limiting assumptions for this theory, amongst others, elasticity. The effective stress theory was proposed for soil; in rock mechanics, the common interpretation today is that the effective stress coefficient α is given by the modulus of the bulk and solid, as described by equation 2 [Charlez 1991].

$$\alpha = 1 - \frac{K_b}{K_s} \qquad (2)$$

K_s and K_b are the hydrostatic strength moduli of the solid and bulk, respectively. Deformation of material depends primarily on changes in effective stress. Provided that time dependency and chemical effects can be neglected, a constant bulk volume is obtained if the effective stress is kept constant.

2. EXPERIMENTAL PROCEDURES AND RESULTS

2.1. *Experimental Set-up and Background*

Chalk is a sedimentary rock within the carbonate family. Chalk mineralogically represents a limestone, as it typically contains >90% calcite. High porosity chalk is usually related to outcrops, yet deeply buried high porosity formations can be found forming hydrocarbon reservoirs. Primary production and repressurization by water flooding during field development and production have induced shifts in the stress state in these formations. The governing factors for the stress state of in-situ rock matrix are the principal stresses in horizontal and vertical direction. However, the total stresses need to be corrected for the contribution of any fluid pressure within the pore space, according to the effective stress relation described in the theory section.

Chalk is commonly interpreted as a linear elastic weak rock. Furthermore, high porosity chalk is considered to obtain values of the effective stress coefficient close to unity. Laboratory testing at in-situ stress conditions requires both external load and pore pressures. It is standard laboratory procedure to increase the external stresses and the pore pressure simultaneously. Since the external stress level required often is beyond the elastic limit of the material, independent increase of external stress and pore pressure could cause the sample to fail. This is particularly important for chalk as it is known to be a weak material. With only minor difference between the pore pressure and the external stress, all bonds between the grains in the rock matrix should be maintained. Several experiments were conducted according to this procedure, as presented in Fig. 1.

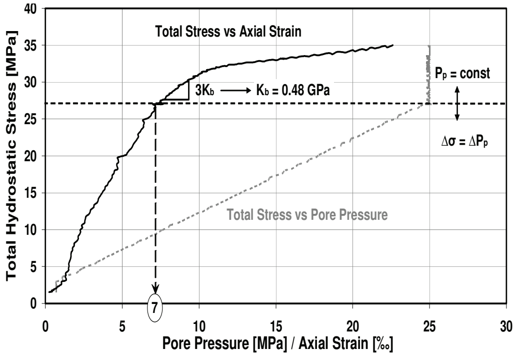

Figure 1. Simultaneous increase of total stress and pore pressure, Stevns Klint core, porosity 0.489.

The stippled curve in Fig. 1 represents the total hydrostatic stress versus the pore pressure. The total hydrostatic stress was increased to 27 MPa, while the pore pressure increased to 25 MPa, keeping a constant differential stress of 2 MPa. The total hydrostatic stress had then been increased from 27 to 35 MPa in order to cause the specimen to yield; the typical hydrostatic yield strength of water saturated Stevns Klint chalk is around 7 MPa [Madland, 2005].

The bulk modulus K_b for the core in Fig. 1 was found to be 0.48 GPa. If this value is inserted in equation 2 and the known solid modulus K_s for calcite is used (71±5 GPa), the α value equals 0.99, i.e. close to 1. As seen from the total hydrostatic stress versus axial strain curve in Fig. 1, the core experienced around 7‰ of axial strain during the simultaneous ramping of the confining and pore pressure. This deformation is unexpected since the effective stress coefficient is calculated to be 0.99. A simultaneously increasing in confining and pore pressure should therefore result in approximately constant effective stress.

The actual loading phase with its increase in differential stress shows a shift in the deformation slope (curve in Fig. 1). The trend shifts when the stress is increased above 27 MPa total hydrostatic stress. However, the deformation prior to this last phase is significant. The interpretation of this deformation led to a more detailed investigation of the effective stress relation.

2.2. Investigation of the Effective Stress Coefficient (α)

The effective stress coefficient was measured for samples of high porosity outcrop chalk. The coefficient was analyzed with respect to compressibility, i.e. no volume change of the bulk represents constant stress. Accordingly, if the pore pressure in a porous material is increased and the mean stress simultaneously regulated such that volumetric strain is eliminated ($\Delta\varepsilon_v = 0$), no changes in the effective stresses occur. The theory for such procedure is described in detail by Charlez (1991).

Internal strain gauges were installed for all cores to be able to control the strain within ±0.1‰. The experiments conducted in this study had all been performed by using tri-axial loading cells, and all samples had been fully saturated with its respective pore fluid under vacuum prior to testing. The majority of the experiments were performed at the rock mechanics facilities at the University in Stavanger, (UiS); however, some studies were performed at the Rock & Fracture Mechanics Laboratory at the ConocoPhillips Research Centre in Bartlesville, (CoP-BTC). An example of the test program is illustrated in Figure 2. A regulating margin of 4.5 MPa differential stress was established to prevent pressure communication between the pore fluid and confining fluid (20-40 minutes). This was done to avoid leakages that occur if the pore pressure exceeds the confining pressure.

The portion in Fig. 2, from 80 to 160 minutes is where the effective stress coefficient has actually been measured. This is the phase where the bulk volume is kept constant. The pore pressure is ramped with constant load rate, and the confining pressure is regulated to prevent the core from deforming. When $\Delta\varepsilon_v = 0$ equation 1 may be used to calculate the effective stress coefficient *α*. If the case in Fig. 2 is used as an example, the effective stress σ' in equation 1 is assumed constant at 4.5 MPa. The total hydrostatic stress σ_{tot} and the pore pressure P_P are taken from their respective curves between 80 and 160 minutes (Fig. 2). The volumetric strain fluctuations are included in Fig. 2 for credibility. High porosity chalk is very soft and it is difficult to keep the volume constant. However, these cores were nonetheless kept within 0.1‰ volumetric strain.

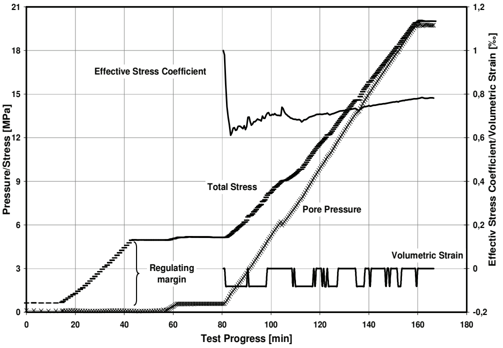

Figure 2. Constant bulk volume test for core 1, tested pre yield with distilled water as pore fluid.

The pore pressure did catch up with the confining pressure after 160 minutes. This naturally terminated the test, since the regulating margin disappeared. The 8 cores presented in Table 1 were all tested similar to the core in Fig. 2. However, different test parameters were varied within the experiments, such as stress state, core material, pore fluid, and loading rate.

When measuring the effective stress coefficient *α*, a transient effect is observed. There will always be some initial consolidation and a small delay before the core starts deforming. Further, equation 1 will always force the initial *α* to equal 1, since the effective stress is initially assumed equal to the differential stress (4.5 MPa in Fig. 2). This transient effect becomes obvious from Fig. 2, where *α* declines from 1 to 0.6. The trend of *α* is then stable, yet converging throughout testing.

The term elastic and plastic phase in Table 1 is used based on knowledge of material strength; tests labelled elastic were tested with an initial effective stress equal 4.5 MPa as seen in Fig. 2, yet tests labelled plastic were tested with an initial effective stress equal 15 MPa. The converging trends of the coefficient show a very concurrent pattern. While all values of *α* in the elastic phase show an increasing trend, the trend is decreasing in the plastic phase, according to Table 1. The increasing trend in the elastic phase is interpreted as breaking of bonds between the grains which leads to increased influence of the pore pressure; the bulk is converging towards failure. In the plastic phase, the core is moving towards a more hardened state due to a more compact packing of the grains. Accordingly, it seems evident that cohesion influences the effective stress relation.

Pore fluid is known to influence the mechanical parameters for chalk [Madland 2005], as is also seen for core 5 and 6 in Table 1, which show different values of *α*, yet very similar in porosity and loading rate. The more viscous and inert ethylene glycol results in a lower coefficient for core 6.

Table 1. Summary of the observations from the constant bulk volume tests

Core No.	Porosity [%]	Outcrop	Lab	Load rate [MPa/min]	Pore fluid	Stress regime	Coefficient value α	Coefficient trend
1	44.29	Stevns Klint Denmark	UiS	0.16	Distilled water	Elastic	0.60-0.80	Increasing
						Plastic	0.75-0.65	Decreasing
2	43.23			0.13		Elastic	0.60-0.75	Increasing
						Plastic	0.80-0.40	Decreasing
3	44.29			0.15		Elastic	0.55-0.75	Increasing
						Plastic	0.70-0.60	Decreasing
4	44.40			0.16		Elastic	0.70-0.80	Increasing
						Plastic	0.80-0.68	Decreasing
5	44.57			0.15		Elastic	0.65-0.80	Increasing
6	44.50			0.15	Ethylene glycol		0.55-0.67	Increasing
7	47.56		CoP-BTC	0.03	Kerosene		0.70-0.89	Increasing
8	36.80	Kansas US		0.03			0.89-0.93	Increasing

3. DISCUSSION

3.1. Laboratory Effects

Tests performed at different laboratories need in-depth interpretation of laboratory effects that might be sources of error. For a constant bulk volume test, however, (Fig. 2), only a limited number of sources of error exist. Equation 1 identifies two parameters, total stress and pore pressure, given that the bulk volume is constant. The critical source is, however, the measured deformation, hence the bulk volume. The UiS-laboratory used a thicker rubber sleeve surrounding the sample than the stiffer teflon shrinking sleeve used at CoP-BTC. Any sleeve will compact during exposure to stresses. Such sleeve deformation will be registered as strain since the deformation is measured outside the sleeve. Therefore, when forcing the sleeved core diameter constant, the diameter of the core is exposed to a considerable error. To illustrate the effect of this, a worst case scenario would be if core 8 in reality has a coefficient equal 1. Then the experimentally measured value is exclusively laboratory effects, causing an error of around 0.11-0.07. Since core 7 was tested identically to core 8, the corrected value for the worst case scenario for core 7 is found to vary from 0.81-0.96. The values in Table 1 are therefore considered as realistic values with maximum experimental uncertainty of around ±0.1.

3.2. Impact of Inelasticity

The material used in this study is limited to very high porosity outcrop chalk, (36-48% porosity). Conventional assumptions state that the lower a material's porosity and the higher its strength, the lower will the value for α be. A previous study on chalk [Teufel and Warpinski, 1990] concluded that α was influenced mainly by porosity, and decreased with decreasing porosity. They investigated reservoir chalk with 15-36% porosity. However, the obtained values for α in Table 1 contradict these results. The α obtained for the lower porosity Kansas core 8 show the highest value. However, the high porosity Stevns Klint material, which shows a lower α than expected, might be severely influenced by inelasticity.

Teufel and Warpinski (1990) furthermore concluded that nonlinearity invalidates most theoretical and mechanistic models, which also becomes obvious from the present study. The effective stress theory is based upon the assumption of elasticity and linearity of stress-strain relations. Years of research on chalk reveals that these relations do only to some extent apply for this material [Risnes and Nygaard, 1999].

The procedure of increasing the confining and pore pressure simultaneously is on infinitesimal time scales a series of loading -and unloading cycles, which may cause irreversible strains to chalk material. Finally, also creep is considered as responsible, therefore, the loading rate has been varied. Yet no significant effects were found in for example core 4 and 7 in Table 1, where the rate is varied. In addition, most of the cores have also been tested within 2 hours, which minimize any creep behaviour. However, more studies should be performed on the subject.

4. CONCLUSION

The significance of this work is important for the understanding of the effective stress relations of high porosity soft chalk, in particular for core analysis. Chalk testing at in-situ conditions requires implementation of high pore pressure. The experimental observations of the effective stress relations obtained in this work deviates form the theoretical explanation, yet the understanding of the relation is vital. Hence, future work is needed to further discuss the relation for high porosity chalk as a very soft non-linear material. This study clearly shows a stress and fluid dependence of the effective stress coefficient within the same batch of outcrop, as well as a difference between two different outcrops of chalks.

5. ACKNOWLEDGEMENT

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