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 in reducing the effective stress during loading of fully saturated high porosity chalk (>40%) has often been assumed to be represented by an effective stress coefficient close to unity. This assumption entails the differential stress; the difference between the total stress and the pore fluid pressure, to equal the stress the rock matrix is exposed to. Laboratory experiments were conducted by simultaneously increasing the 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 have been discussed, among these consolidation effects, partial saturation effects, micro damage and possible laboratory equipment effects. The strains that were observed during the above mentioned test phase, resulted in a focus on the effective stress coefficient for porous chalk material. The results presented in 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

THEORY

In solid homogeneous material, the applied stresses will theoretically be evenly distributed throughout the substance. Introduction of porosity results in a more complex stress distribution at microscopic levels. External load is transmitted at the intergranular contacts. The pore space is subjected to a hydrostatic fluid pressure and hence balances the external load. Terzagi[5] proposed the relation in equation 1, called 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. This factor obtained theoretical the value of the porosity, however experimentally found equal unity. Biot[1] listed certain limiting assumptions for this theory, among others elasticity. This relation was proposed for soil, yet the common interpretation of the effective stress coefficient α present today is given by the modulus of the bulk and solid, as described by equation 2.[2]

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

$$\alpha = 1 - \frac{K_b}{K_s} \tag{2}$$

K_s and K_b is the hydrostatic strength modulus of solid and bulk respectively. Deformation of materials depends primarily on changes in effective stress. If one assumes no time or chemical effects, one obtains constant bulk volume if the effective stress is kept constant.

EXPERIMENTAL PROCEDURES AND RESULTS

Experimental Set-up and Background

Chalk is a sedimentary rock within the carbonate family. The mineralogy characterization classify chalk as a limestone, as it typically contains >90% calcite. High porosity chalk is usually related to outcrop, yet deeply buried high porosity formations are found as hydrocarbon reservoirs. Under field development and production these formations have during primary production and repressurization by water flooding, experienced shifts in its stress state. 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 as material is commonly interpreted as a linear elastic weak rock. Further more, 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 and standard laboratory procedure is to simultaneously increase the external stresses and the pore pressure. Independent increase of external stress and pore pressure could cause the sample to fail, since the external stresses that are aimed for are well beyond the elastic limit, as chalk is known as a weak material. With a minor difference between the pore pressure and the external stress, this procedure should maintain any bonding between the grains in the rock matrix. Several experiments were conducted according to this procedure, as presented in Figure 1. The stippled curve in this plot is the external stress versus the pore pressure; the total hydrostatic stress is increased to 27 MPa, while the pore pressure increased to 25 MPa, with a constant differential stress at 2 MPa. The external stress has then been increased from 27 to 35 MPa in order to cause the specimen to yield, as the typical hydrostatic yield strength of water saturated Stevns Klint chalk is around 7 MPa[3]. The bulk modulus K_b is calculated to 0.48 GPa in Figure 1. If this value is used in equation 2, knowing that the solid modulus K_s for calcite is 71±5 GPa, one obtain α equal 0.99, i.e., close to 1. This value does not concur with the strains obtained in the build up phase. As seen from the total stress versus axial strain curve in Figure 1, this core sample experienced around 7‰ of axial deformation during the build-up phase. The curve of the actual loading, where the differential stress is increased, shows a shift in the deformation slope, however, the deformation prior to this last phase is significantly. The interpretation of these deformations leads to a further investigation of the effective stress relation.

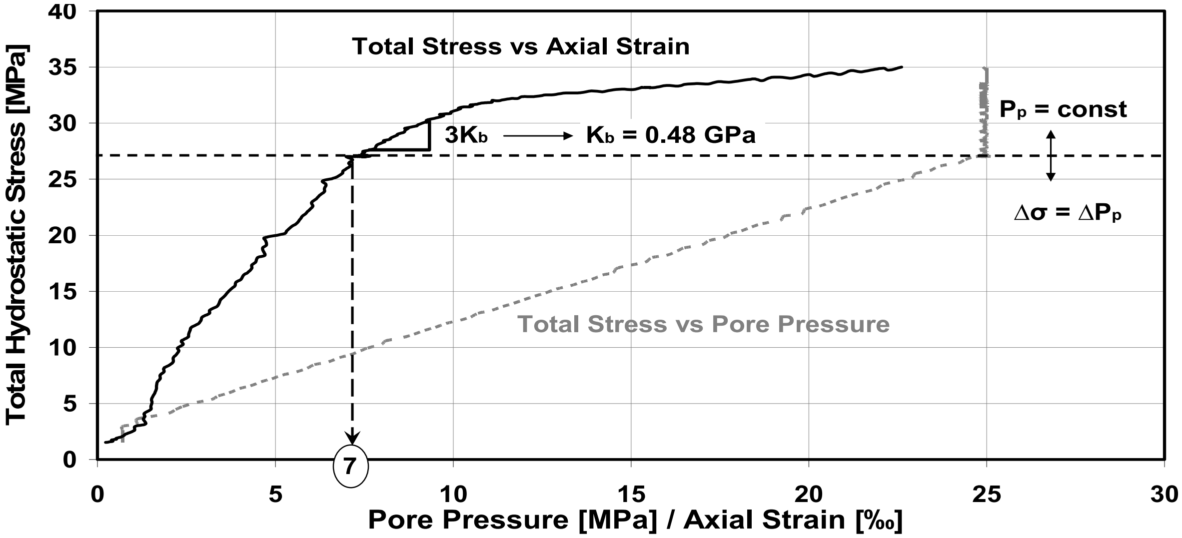

Figure 1. Simultaneously increase of total stress and pore pressure, Stevns Klint core, porosity - 0.489

Investigation of the Effective Stress Coefficient (α)

The effective stress coefficient has been measured for samples of high porosity outcrop chalk. If one increases the fluid pressure in the pores of a specimen, and simultaneously regulates the hydrostatic total stresses and hence keeping the volumetric strain constant, $(\Delta\varepsilon_v = 0)$, there is no actual loading taking place, i.e.; the effective stresses are constant[2]. Internal strain gauges have been installed on all cores to be able to control the strain within ±0.1‰. The experiments conducted in this study have all been performed by the use of tri-axial loading cells, and all samples has been fully saturated under vacuum with its respective pore fluid prior to testing. The majority are performed at the rock mechanics facilities at the University in Stavanger, (UiS), however some studies are performed at the Rock & Fracture Mechanics Laboratory at the ConocoPhillips Research Centre in Bartlesville, (CoP-BTC). As seen in Figure 2, an initial regulating margin (differential stress) is established to prevent pressure communication between pore and confining space, i.e. if the pore pressure exceeds the confining pressure, leakage takes place. The constant bulk volume portion of the test then starts at 80 min. The pore pressure is increased at constant load rate, and the total stress is regulated to prevent the core from deforming. The effective stress coefficient is then calculated according to equation 1. At 160 minutes the pore pressure catches up with the confining pressure, and the test is finished due to no more regulating margin left. Different test parameters are varied in the experiments, such as stress state, core material, pore fluid and loading rate.

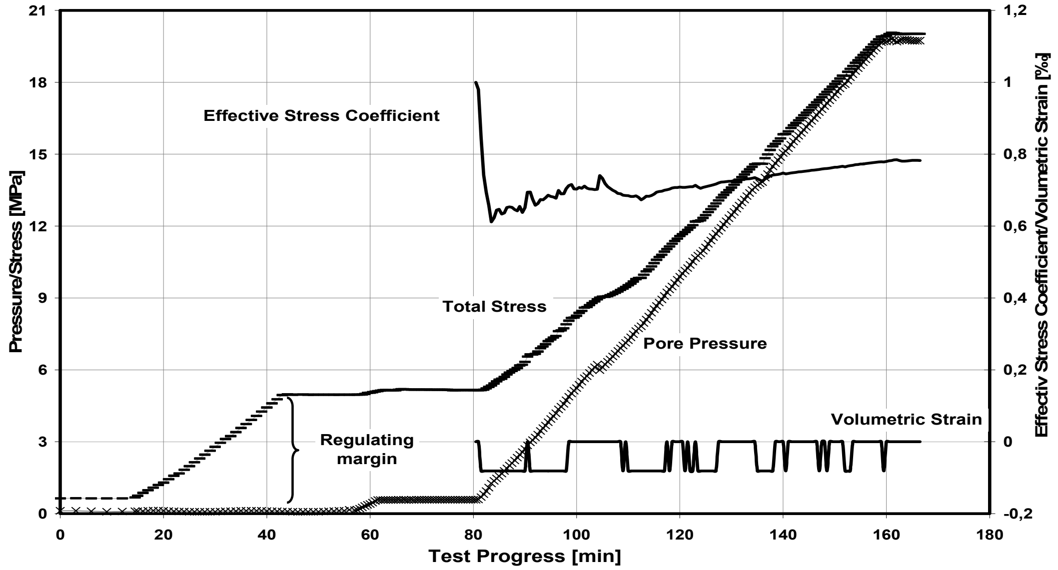

Figure 2. Constant bulk volume test, core 1, pre yield, distilled water as pore fluid

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

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 and the mathematical calculation make α start at unity, as the effective stress is assumed equal the differential stress. This transient effect is observed as α decline from 1 to 0.6 in Figure 2.

The trend of α is then stabile, yet converging throughout testing. The term elastic and plastic phase in Table 1 is used based on knowledge of material strength; test labelled elastic was tested with an initial effective stress equal 5 MPa as seen in Figure 2, yet test labelled plastic was tested with an initial effective stress equal 15 MPa. The converging trend of the coefficient observed show a very concurrent pattern, whereas all values of α in the elastic phase show an increasing trend, while the trend is decreasing in the plastic phase, according to Table 1. From this it is evident that cohesion influences the effective stress relation. 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 more compact packing of the grains. Pore fluid is known to influence the mechanical parameters for chalk[3], 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.

DISCUSSION

Laboratory Effects

Tests performed at different laboratories needs in-depth interpretation of laboratory effects. For a constant bulk volume test, only a limited number of sources for error exist. Equation 1 identifies two parameters, total stress and pore pressure, given that the bulk volume is constant. The critical source is the measured deformation, hence the bulk volume. 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 exposing to stresses and the strain is measured outside the sleeve. When forcing the sleeved core diameter constant, the diameter of the core is exposed to a considerable error. However, core 7 and 8 of different material show a significant difference according to Table 1. If the measured α for core 8 is exclusively laboratory effects it is a measure of the error in a worst case scenario, i.e., assumed true α is 1. If this worst case error is then added to the value of α measured for core 7, the corrected value for core 7 is then found to vary from 0.81-0.96.

Impact of Inelasticity

The material used in this study is limited to very high porosity outcrop chalk, (36-48%). Conventional assumptions state that the lower porosity and higher strength, the lower α the material obtain. A previous study on chalk[6] concluded that α was influenced mainly by porosity, and decreasing with decreasing porosity. This study investigated reservoir chalk from 15-36% porosity. However, the obtained values of α in table 1 contradict these results. The α obtained for the lower porosity Kansas core 8 show the highest value. The high porosity Stevns Klint material which shows a lower α than expected might be too influenced by in-elasticity. Further, the study[6] also concluded that nonlinearity invalidates most theoretical and mechanistic models, which is also observed in this study. The effective stress theory is based upon the assumption of elasticity and linearity of stress-strain relations.

Years of experience on chalk reveals that these relations do only to some extent apply for chalk[4]. The procedure when simultaneously increasing the pore pressure and the external stress is on infinitesimal time scale really many loading and unloading cycles, which may cause irreversible strains to chalk material. These strains have also been discussed as simply the cores responding to creep, hence the loading rate has been varied, but no significant effects where seen between for example core 4 and 7 in table 1. The majority of the cores have also been tested within 2 hours, which minimize any creep behaviour. However, more studies should be performed on the subject.

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.

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