THE EFFECT OF TEMPERATURE AND BRINE COMPOSITION ON THE MECHANICAL STRENGTH OF KANSAS CHALK

Madland, M.V.*, Midtgarden, K*, Manafov, R.*, Korsnes, R.I.*, Kristiansen, T.G.[BP Norway], Hiorth, A.[IRIS]

**University of Stavanger, 4036 Stavanger, Norway*
merete.v.madland@uis.no

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE 29 October-2 November, 2008

ABSTRACT

Seawater is injected into the high temperature North Sea chalk reservoirs to improve oil recovery with great success. Increased compaction of the rock, which also is a significant contribution to the oil displacement, is observed when oil is displaced by water, and the phenomenon is referred to as the water weakening effect of chalk. North Sea chalk fields have a reservoir temperature of 90-130°C. At these high temperatures, various ions in the brine form complexes. In this study mechanical tests have been performed on Kansas chalk at elevated temperatures with continuous flooding by different seawater compositions, with -and without SO_4^{2-} and without Mg^{2+}, in order to investigate its effect on the mechanical strength of chalk. A significant increase in compaction was observed for cores flooded with seawater without Mg^{2+} at 70 and 90 °C, respectively. The impact of these specific ions on the mechanism of enhanced water weakening of chalk by seawater is further discussed in terms of: Dissolution of $CaCO_3$ and precipitation of $CaSO_4$(s) which seems to be strongly influenced by the presence of Mg^{2+} ions in particular.

Key words: Chalk, Seawater, Dissolution –and Precipitation processes, Water Weakening

INTRODUCTION

Chalk is a carbonate rock and an important reservoir rock in southern part of the Norwegian sector of the North Sea. The injection of seawater into North Sea chalk reservoirs has proved to have a great potential for improving oil recovery (IOR). There is, however, an additional impact of the seawater injection when water replaces oil in chalks; it leads to enhanced compaction of the reservoir rock, which further has shown to induce seafloor subsidence. The phenomenon is referred to as the water weakening effect of chalks.

So far, experimental studies (Newman, 1983; Andersen et al., 1992; Schroeder et al., 1998; Risnes et al., 2005; Heggheim et al., 2005, and Madland et al., 2006 among others) have documented increasing strain when stressed chalk cores are exposed to water; however, direct evidence of the actual mechanisms is still a debate of discussion. Korsnes et al. (2006) conducted series of mechanical -and pure core flooding tests by use of high porosity outcrop chalk from the quarry of Stevns Klint; focusing on water weakening due to chemical effects. In specific they pointed out that the presence of sulphate ions in the actual injection brine seems to cause a significant weakening of the chalk framework, especially at elevated testing temperatures. The present work is thus a continuation of the work by Korsnes et al. (2006); further studying how flooding of other brine compositions such as seawater without Mg^{2+} at elevated temperatures will affect the mechanical strength of Kansas outcrop chalk, which porosity (38 %) is approx. 10 % lower compared to the previous used (Korsnes et al., 2006).

EXPERIMENTAL PROCEDURE

Core Material and Flooding Fluids

The Upper Cretaceous outcrop chalk from Niobrara Formation is a pure carbonate (>99 % calcite) and is referred to as Kansas chalk. A total number of 8 cores were all drilled from a single chalk block. Synthetic seawater (SSW), seawater without SO_4^{2-} (SSW-U) and seawater without Mg^{2+} (SSW-U3) were used as saturating and flooding brines (Korsnes et al., 2006). Total dissolved solids (TDS) are kept constant to that of SSW by adding NaCl when SO_4^{2-} or Mg^{2+} ions are left out from SSW-U and SSW-U3, respectively.

Testing Equipment and Mechanical Test Procedure

The purpose of this present study is not to simulate any water injection of North Sea chalk reservoirs at in-situ stress conditions, however, rather to select a repeatable type of test in order to further study and thus improve the approach towards a more in depth understanding behind the mechanisms causing the water weakening of chalks. All tests are performed by use of the same equipment, following a similar test procedure as described by Korsnes et al. (2006). Hydrostatic- and creep tests with continuous flooding by seawater and modified seawater were performed in a hydraulically operated standard triaxial cell equipped with a heat regulating system. During the experiments at 70, 90 and 130°C, the temperature was kept constant; ±0.2°C. The axial displacement was measured by an outside linear voltage displacement transducer (±0.05 mm) that follows the movement of the piston. All chalk samples were saturated with their respective flooding fluids one day prior to the mechanical testing. To avoid boiling at temperatures beyond 100 ºC a pore pressure of 7 bar was applied in any case. Each core was mounted in a triaxial cell; the confining -and pore pressure was increased simultaneously to an effective stress equal to 0.5 MPa, which was kept constant throughout the heating of the cell. Apprx. 1.5 PV`s of the respective brine was injected and as the predetermined testing temperature was established, the sample was left over night to equilibrate. The following day the sample was isotropically loaded and then left to creep at a stress level of 19 MPa. The creep period lasted 5 days and within this period of time 10 PV`s of the actual brine was flushed through the core.

Results and Discussion

From the hydrostatic tests, not only the yield point, which is the point where the stress-strain curves depart from the linear trend, but also the bulk moduli are determined for each of the samples. The slope of the trend line in the elastic region determines the bulk modulus, which is a measure of the stiffness of the material. From the following creep phase, axial strain or deformation at a constant stress level is observed and the obtained results from the cores tested are compared depending on the testing temperature as well as the 3 brines injected. It should be emphasized that the combination of a limited number of cores tested and the various testing parameters; 3 injection brines, and 3 testing temperatures, makes it more difficult for comparison reasons, however, some trends seem to be obvious.

Yield Strength, Bulk Modulus, and Creep Strains

In Table 1 values of yield strength, bulk modulus (K-modulus) and porosity are given for each of the core tested at either 70, 90 or 130 ^oC and by use of 3 different injection brines. Cores exposed to seawater injection have been tested at either 70 ^oC (C1, C17) or 130 ^oC (C6). Only two cores have been flooded with seawater without sulphate (SSW-U), both at 130 ^oC (C5, C7) and the remaining three cores were flooded with seawater without magnesium (SSW-U3) at 70 ^oC (C4) and 90 ^oC (C14, C2).

Table 1. Summary of the observations from hydrostatic –and creep phase

Core number	Porosity [%]	Flooding fluid	Temperature [C]	Yield [MPa]	K-modulus [GPa]	Tot. creep after 6500 min. [%]
C1	38.81	SSW	70	14.2	0.89	1.23
C17	38.41	SSW	70	13.0	0.99	0.81
C6	38.81	SSW	130	14.1	0.79	0.95
C5	39.33	SSW-U	130	15.3	0.92	0.81
C7	37.88	SSW-U	130	15.6	0.88	0.52
C4	39.68	SSW-U3	70	10.6	0.70	1.68
C14	39.76	SSW-U3	90	10.5	0.60	1.56
C2	39.49	SSW-U3	90	11.1	0.50	Failed

Studying only the impact of various brine compositions without taking into account any temperature effects due to any differences in testing temperatures; from the values of yield strength one can observe a trend indicating that cores flooded with seawater without sulphate (SSW-U) are the strongest ones, Figure 1b. Yield strength equals 15.3 and 15.6 MPa for C5 and C7 accordingly, Table 1 Cores flooded with seawater without magnesium (SSW-U3) are definitely the weakest ones (C2, C4, C14); average yield strength of 10.7 MPa which is 30% lower compared to the cores flooded with SSW-U. The three cores exposed to seawater (SSW) injection show intermediate yield strength; values varying in the range of 13 to 14 MPa (C1, C17, C6).

Evaluating the results concerning the bulk modulus, the trend is not as clear as observed for the yield strength. Still, also for the K-modulus the lowest values (0.5-0.7 GPa; Table 1) are determined for the three samples flooded with SSW-U3. However, the differences in K-moduli are not significant considering the cores flooded with SSW and SSW-U; once again if only fluid effects are concerned.

Further comparing the values of K-modulus and yield strength obtained for the cores exposed to either SSW or SSW-U, however, now at a specific temperature; 130 ^{o}C, it seems like the cores flooded with SSW are weakened by approx. 10%. As expected this reduction in strength obtained for lower porosity Kansas outcrop chalk is somewhat lower compared to results reported by Korsnes et al. (2006); yield strength was reduced by 25 %, however, in this case chalk cores from Stevns Klint with average porosity of 48 % were flooded with SSW and SSW-U at 130 ^{o}C.

Chalk-fluid interactions have shown to be strongly influenced by variations in testing temperature (Heggheim et al., 2005; Korsnes, 2007). As seen from Table 1 it is only the cores exposed to either injection of SSW or SSW-U3 that were tested at various temperatures; 70 (C1, C17) or 130 ^{o}C (C6) and 70 (C4) or 90 ^{o}C (C14, C2), respectively. Comparing the results obtained for one and the same brine at various temperatures, the effects of temperature is not as unambiguous as the fluid effect. Considering the yield strength unexpected results are obtained; values of yield strength obtained for the cores exposed to SSW at 70 ^{o}C (C1, C17) and 130 ^{o}C (C6) show a slight strengthening with increasing temperature and these results are definitely in contradiction to previously temperature effects observed (Korsnes, 2007). However, the values of K-modulus seem to indicate a weakening of the chalk material as temperature is increased. A similar trend is also observed from the cores which were flooded with SSW-U3. It should be mentioned that the mechanical strength of chalk generally decreases with increasing porosity (DaSilva et al., 1985) and minor variations in porosities may cause unexpected results, even though the difference in core porosity is less than 2%, Table 1.

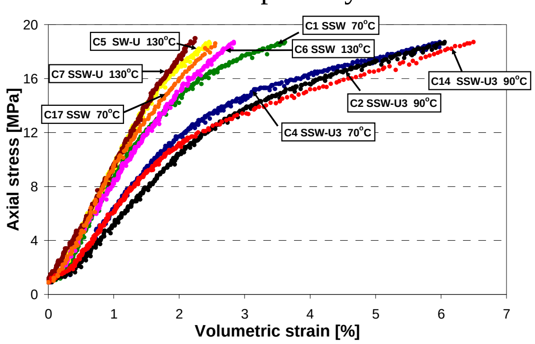

Figure 1a. Axial stress vs. volumetric strain from hydrostatic tests

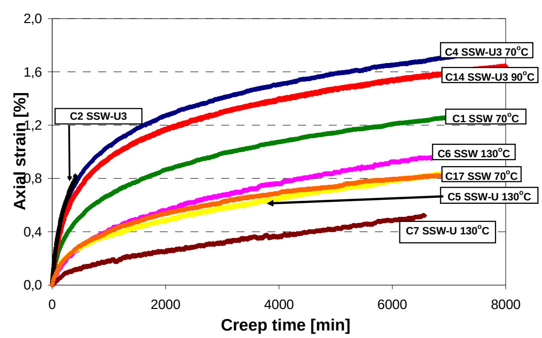

Figure1b. Axial strain vs. time during creep phase

Figure 1b show axial strain during the creep phase (strain at constant stress). It can be seen that the samples flooded with SSW-U3 obtained an enhanced axial creep compared to the cores flooded with SSW and SSW-U. It is concluded that chalk cores flooded with seawater without sulphate obtain the least strain during the creep period. This observation also agrees with previous results for high porosity chalk (Korsnes et al., 2006)

Independent of the testing temperature, both from the hydrostatic tests as well as the following creep phase, it is obvious that cores exposed to SSW-U3 injection do show a pronounced deformation compared to those flooded with SSW or SSW-U.

An illustrative fluid effect is observed from the axial creep (%) vs time (min) curve in Figure 2. For one of the cores, C17, the injection brine was switched from seawater (SSW) to seawater without magnesium (SSW-U3) during the creep phase. This fluid substitution resulted in apprx. 30% additional strain after 12 PV`s flooding with SSW-U3.

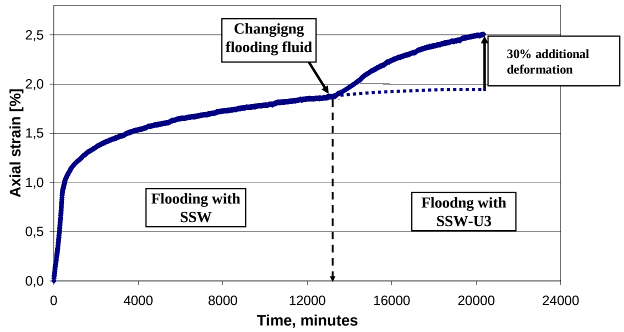

Figure 2. Axial strain vs. time during hydrostatic loading and creep phase with flooding of SSW followed by SSW-U3

The enhanced weakening of chalk cores due to injection of SSW-U3 seem to be caused by precipitation- dissolution processes taking place. More specifically, at high temperatures, ions in the brines form complexes. In particular magnesium will form a complex with sulphate, thus the presence of magnesium in seawater at elevated temperatures will prevent enhanced precipitation of anhydrite. It is therefore expected that varying the magnesium concentration in the injection brine will have an effect on the mechanical compaction of chalks. Most probably from the experiments at elevated temperatures when removing Mg^{2+} from seawater composition; formation of anhydrite, $CaSO_4$(s) is facilitated. The removal of Ca^{2+} ions during precipitation of anhydrite will further lead to increased dissolution of calcite and altogether these processes most likely seem to explain the enhanced deformation as observed when flooding with SSW-U3, Figure 1a,b, and Figure 2b.

CONCLUSIONS

Although no systematic temperature effects were observed when flooding chalk cores with either SSW or SSW-U3, a pronounced fluid effect at elevated temperatures was detected also for Kansas outcrop chalk which average porosity is 10 % lower compared to the Stevns Klint as used by Korsnes et al., 2006. Anhydrite formation, and dissolution of chalk may be possible mechanisms for water weakening of chalk, but these mechanisms will be further investigated also by use of scanning electron microscope (SEM).

ACKNOWLEDGEMENT

The authors acknowledge ConocoPhillips and the Ekofisk co-venturers, including TOTAL, ENI, StatoilHydro and Petoro, and the Valhall licence, including BP and Shell, for financial support and for permission to publish this work.

REFERENCES

Andersen, M.A., Foged, N., 1992. The Link Between Waterflood-Induced Compaction and Rate-Sensitive Behaviour in a Weak North Sea Chalk. Fourth North Sea Chalk Symposium, Deauville, France

DaSilva F., Sarda J. P., Schroeder C., “Mechanical behaviour of chalks”, Second North Sea chalk Symposium, 1985, Stavanger, Norway, Book II.

Heggheim, T., Madland, M.V., Risnes, R., Austad, T., 2005. A chemical induced enhanced weakening of chalk by seawater, J. Pet. Sci. Eng., 46, 171-184.

Korsnes, R.I., Madland, M.V., Austad, T., 2006. Impact of Brine Composition on the Mechanical Strength of Chalk at High Temperature. Eurock 2006, Multiphysics Coupling and Long Term Behaviour in Rock Mechanics, Eds. Cottheim, A.V., Charlier, R., Thimus, J.F. and Tshibangu, J.P., Taylor & Francis, London, pp. 133-140.

Korsnes, R.I., 2007. Chemical induced water weakening of chalk by fluid-rock interaction. A mechanistic study. PhD thesis. ISBN 978-82-7644-316-5. ISSN 1890-1387

Madland, M.V., Finsnes, A., Alkafadgi, A., Risnes, R. Austad, T., 2006. The influence of CO2 gas and carbonate water on the mechanical stability of chalk. J. Pet. Sci. Eng., 51, 149-168

Newman, G.H., 1983. The effect of water chemistry on the laboratory compression and permeability characteristics of some North Sea Chalks. J. Pet. Techn. 35, 976-980.

Risnes, R., Madland, M.V., Hole, M., Kwabiah N.K., 2005. Water weakening of chalk – Mechanical effects of water-glycol mixtures. J. Pet. Sci. Eng., 48, 21-36.

Schroeder, C., Bois, A.-P., Maury, V. And Halle, G., 1998. Water/Chalk (or collapsible soil) interaction: Part II. Results of tests performed in laboratory on Lixhe chalk to calibrate water/chalk models, Eurock`98, Trondheim, Norway.