HOW WETTING CONDITIONS DICTATE CHALK MECHANICS AT UNI-AXIAL STRAIN CONDITIONS – INSIGHTS FROM EXPERIMENTS PERFORMED AT IN-SITU STRESS, TEMPERATURE AND PORE PRESSURE

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ABSTRACT

This paper document how the mechanical strength of chalk depends on the chemistry of pore fluids. Three experiments with different pore fluid compositions were performed at uni-axial strain conditions maintaining constant overburden stress during pore pressure depletion and subsequent compaction phase. The pore fluids were: i) 100% NaCl-brine, ii) 10%-90% NaCl-brine and oil mixture and iii) 100% oil. Significant differences were observed during the depletion and time-dependent compaction phase. The oil-saturated core was stronger than core saturated by brine-oil mixture, while the brine-saturated core accumulated most strain. During compaction, seawater was injected that led to additional strain; most so in the oil-saturated core, intermediate additional strain in the brine-oil mixed core, and least additional strain was observed in the brine-saturated core. This is in line with earlier results on how the ion composition of seawater significantly impacted chalk mechanics. Other significant observations include the additional side stress required to maintain the zero radial strain requirement, and irrespective of the original fluid composition, it is found that after only 2.5 PVs of seawater injection the creep rate for all three cases attained the same value. This indicates that the seawater induced weakening is abrupt, and it is more prominent when there is less water in the core originally.

INTRODUCTION

During primary phase oil production from a reservoir, the extraction of pressurized fluids reduce the pore fluid pressure leading to an increase in the effective stress, which in turn drives compaction. Reservoirs can be re-pressurized by injecting seawater to reduce the effective stress and mobilize oil. Even though the pressure is maintained, there is still considerable amount of compaction observed in the reservoirs. This compaction has been linked to the interaction of ions in the brines with the rock itself. Considerable research has been carried out concerning this water induced compaction in chalk reservoirs in the past few decades [1-4]. These studies have been carried out on water-wet chalk. This research has primarily shown that the pore fluid composition alters the mechanical

integrity of chalk, as seawater and other simplified brines affect the mechanical strength. Different ions in the water, e.g. sulphates and magnesium ions, change the macroscopic mechanical behaviour of chalk, thus altering the way in which the brines and oils move through the porous rock and hence affecting oil recovery [2-4]. In recent studies of isotropic (hydrostatic) loading tests [5,6], it was shown that values characterizing the mechanical properties of chalk decreased when the wetting state was changed towards more water-wet. However, how do the results in [5,6] apply to high fluid pressures at uni-axial strain condition? In addition, how does the initial water condition dictate the mechanical response after the core has been flooded by seawater? This paper deals with the cases where the cores are initially saturated by different fluids and then the wettability is altered by aging to more mixed-wet state.

MATERIAL, EQUIPMENT, AND EXPERIMENTAL PROGRAM
Test Material and Saturation Fluids
The experiments in this study are performed on an outcrop chalk from a quarry in west-central Kansas in the USA (~39% porosity). The Kansas chalk type is considered to be a pure chalk with a non-carbonate content in the range 1-3% [2,7] and a permeability in the range 1-2 mD. This chalk is from Late Cretaceous geological age. Tang and Firoozabadi [7] argue that it is a good analogue to some clean North Sea reservoir chalks in regards to porosity, capillary pressure, and absolute and relative permeability.

Three different initial fluid saturations were used: Core K01 was saturated and flooded by 1.1M NaCl-brine. NaCl-brine was used as a simplified formation brine to minimize rock-fluid interactions prior to seawater flooding. Core K02 was saturated by approx. 10% NaCl-brine and 90% of Heidrun and Heptane oil that were mixed in 60%-40% (by volume). This oil was filtered through a 6.5µm filter. Core K03 did not contain any brine and was saturated only by the same oil. Both cores K02 and K03 were flooded with two pore volumes of this oil in each direction at 50°C. After the cores, K02 and K03, were saturated, they were submerged into the same oil and aged for 3 weeks at 8 bar and 90°C. The aging was performed to alter the wettability properties of the chalk cores. Wettability was not measured after aging. The aging procedure followed here would yield a wettability along the same lines as the results of Zangiabadi et al. [6] where they aged the cores with the same oil together with 20% brine, which gave a wettability index of 0.65. The wettability index (WI) is a measure of the available sulphate adsorption sites, where a WI equal to 0 means completely oil-wet and 1 means completely water-wet [6]. Strand et al. [8] reported wettability indexes below 0.5 on Stevns Klint chalk that were aged after being completely saturated by 60%-40% Heidrun/heptane mixture without initial water. Zangiabadi et al. [6] also reported acid number 1.92 mg KOH/g oil for the same oil mixture that is used in this study as well. Zangiabadi et al. [6] and Strand et al. [8] conclusively report that by increasing the acid number in the oil, the cores become more oil-wet after aging.

The Triaxial Cell Setup

The chalk cores were mounted into the triaxial cell that allows for continuous measurements of the axial and radial strains during flooding fluids at elevated stresses, pressures, and temperatures. The cell was equipped with a heating element and a regulating system with precise temperature control. Four pumps were connected to the triaxial cell to control the axial stress (σ_{ax}), confining pressure (σ_{rad}), flooding rate (Gilson pump) and pore pressure on the downstream side (P_p). An external linear voltage differential transducer (LVDT) monitored the length of the plug (L). The circumferential diameter on the middle of the core was measured with an extensometer. All the tests were performed at uni-axial strain conditions, with varying radial stress to ensure zero lateral (radial) strain and constant overburden stress such that the stress-path is similar to those that are occurring in the real field scenarios. In these tests, the deformation only took place in the axial direction and a constant axial stress was maintained. The extensometer attached around the core plug measured the radial deformation in the core as a function of time. The signal from extensometer was sent to the computer (LabView software) and was used to change confining pressure for the purpose of avoiding any radial deformation and maintaining zero radial strain. Changes in the confining pressure also affected the axial stress, so the piston pressure was automatically regulated to ensure constant axial stress.

Test Procedure

The experiments were performed at uni-axial strain conditions according to the following procedure: i) Mount the core in the triaxial cell; ii) Increase confining pressure (σ_{rad}) to 1.2 MPa and pore pressure (P_p) to 0.7 MPa simultaneously; iii) Increase temperature to 130°C; iv) Increase σ_{rad} to 40 MPa and P_p to 38 MPa simultaneously; v) Increase axial stress (σ_{ax}) to 42.5 MPa; vi) Start uni-axial strain test. Pore pressure depletion from 38 MPa to 15 MPa; vii) Observe creep at constant overburden; viii) Inject seawater according to the recipe shown in Zangiabadi et al. [6] and observe the creep strain.

During pore pressure depletion in uni-axial strain experiments, Hooke's law is modified such that Young's Modulus is calculated using,

$$E\delta\varepsilon_{ax} = \frac{3\alpha\delta P_p\delta\sigma_{rad} - 2(\delta\sigma_{rad})^2}{\delta\sigma_{rad} - 2\alpha\delta P_p} \qquad (1)$$

where E defines the Young's or elastic modulus, δP_p defines the change in the pore pressure from 38 MPa to the point where the core starts to yield, $\delta\sigma_{rad}$ defines the change in the radial stress and $\delta\varepsilon_{ax}$ defines the change in the axial strain corresponding to the same pore pressure values, and α is the Biot coefficient taken equal to 1 for calculations.

RESULTS
Pore Pressure Depletion Phase
Pore pressure depletion is carried out from 38 MPa to 15 MPa at uni-axial strain conditions. The yield, total axial strain and Young's Modulus values for the three cores during the pore pressure depletion phase are given in

Table 1. For the K03 core (100% oil), the yield strength and elastic modulus is found to be 2 and 1.4 times larger, respectively, than the results for the K01 core (100% brine). The total axial strain after loading is 4 times larger for the K01 core compared to the K03 core. The axial stress vs axial strain curves for all cores are given in Figure 1(a).

Uni-Axial Strain Compaction and Seawater Injection
The uni-axial compaction at constant overburden and pore pressures observed for the three cores is shown in Figure 1(b). The uni-axial compaction observed for K01 and K02 is 5.6% and 2.3%, before seawater injection, which goes up to 8.6% and 5.3%, respectively, after injecting seawater for 40 days. No compaction is observed for K03 prior to seawater injection, but shoots up to 7.5% after injecting the seawater for only 15 days. The strain rates before and after seawater injection for all tests are given in Figure 1(c). The strain rates for K01 and K02 prior to seawater injection are 0.05%/day and 0.07%/day, which increase to 0.17%/day and 0.19%/day, respectively, immediately after the start of injection. The strain rate shoots up to 0.77%/day from zero for K03 immediately after the start of seawater injection. After 2.5 PVs (5 days) of injection, all three cores attain the same value of around 0.17%/day strain rate. Please note that the starting time of seawater injection is taken as zero time (reference time) to make it easy to analyse the results.

DISCUSSIONS
The uni-axial compaction experiments, similar to Omdal et al. [9], have been performed, where the radial stress is automatically adjusted to ensure zero radial strain. The experiments have been carried out by depleting pore pressure whilst keeping the overburden stress constant, before the pore pressure was kept constant at 15 MPa over time. This experimental setup opens up for a range of studies in addition to the mechanical consequences reported here. For example, we can simulate the actual reservoir history with respect to stress, temperature and pore fluid composition, how the pore pressure affects the mobility of oil and water at actual PVT-values, and, to which extent adsorption, dissolution and precipitation depend on pore pressure and stress.

As expected from simpler hydrostatic tests reported by e.g. Zangiabadi et al. [6], we observe that K03 (100% oil) obtains the highest elastic modulus and highest yield during pressure depletion and that these values decrease with increasing brine content.

Prior to seawater injection, the side stresses are automatically reduced as the core compacts (Figure 1(d)). This is interpreted as a signature of work hardening during time,

since less stress is required to keep the core at zero radial strain. However, when seawater is injected, the core weakens. Because of that, both the axial strain is increased, and similarly, the side stress required to maintain zero radial strain is increased. The side stress for the oil-saturated core increased by 6.3 MPa whilst the 10% and 100 % brine-saturated cores obtained approx. 3% additional axial strain, and correspondingly, the extra side stress required to sustain zero radial strain was 2.3 MPa and 1.7 MPa, respectively. We expect that a similar phenomenon could occur in reservoir systems when seawater is injected. In these cases, it is expected that the horizontal stresses would increase, since the uni-axial strain condition applies to reservoirs with large width to height ratios.

In Figure 1(c) before seawater injection, the compaction (strain) rate is different for all tests. However, irrespective of the original fluid composition, it is found that after only 2.5 PVs of seawater injection the creep rate for all three cases attained the same value. This shows that the wetting conditions have minor impact on the compaction rate after flooding 2.5 PVs of seawater through the core. In addition, it shows that the seawater induced weakening is abrupt and more prominent when there is almost zero initial water in the core. Thus in mixed wet cores, oil is not blocking seawater access to the intergranular contacts.

CONCLUSIONS

1. Completely oil-saturated core is found to be stronger compared to partially or completely brine-saturated cores.
2. Uni-axial compaction rate accelerates when seawater is injected.
3. The initial accelerated compaction by seawater injection is affected by the initial fluid chemistry.
4. After injecting 2.5 PVs of seawater, initial saturation and wetting state have minor effects on compaction rate.

ACKNOWLEDGEMENTS

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FIGURES AND TABLES

Table 1: Mechanical properties of the chalk cores

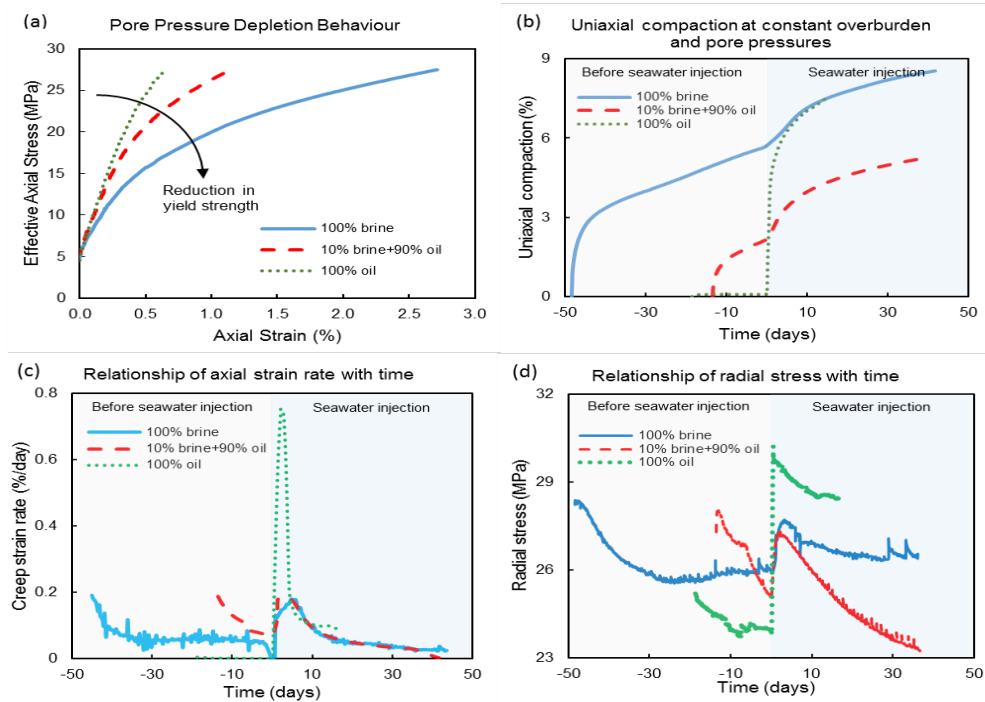| Core		K01	K02	K03
Yield Stress	MPa	8.85	14.92	18.45
Total depletion strain	%	2.72	1.16	0.64
Young's Modulus	GPa	2.81	3.47	4.05

Figure 1: (a) Axial stress vs axial strain for all cores. (b) Compaction curves for all tests. (c) Compaction strain rate for all tests. (d) Radial stress curves for all tests. Please note that the starting time of seawater injection is taken as t=0 days in (b), (c) and (d).