

**FINAL TECHNICAL REPORT**  
**Parts 1 & 2**

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Mechanical Behaviour of Partially and Multiphase Saturated CHALKs Fluid-skeleton Interaction : Main Factor of Chalk Oil Reservoirs Compaction and Related Subsidence - Part 2

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## Parts 1 & 2 : Publishable Final Report - Detailed Final Report

As the final report doesn't contain any confidential data, both parts 1 (Publishable Final report) and 2 (Publishable synthesis report) are combined.

### *1.1. Executive publishable summary*

The "Pasachalk" project, started in 1997 with the Pasachalk "1" EC contract and continued with the present "Pasachalk 2" with partners from the universities (Université de Liège - Department GeomaC - geomechanics and Ecole Nationale des Ponts et Chaussées - CERMES) and from Industry (Total Exploration Norway).

These projects were initiated in the framework of the set of problems of the North Sea chalky oil fields, especially in the huge Ekofisk field. In this field, oil is located in a 300 m thick layer of porous chalk ( $n = 40-50\%$ ) at a 3000 m depth. After the depletion phase, which led to about 6 m of compaction of the reservoir and 4 m of subsidence of the sea floor, an enhanced oil recovery procedure has been carried out by injecting sea water (waterflooding). An unexpected consequence of this waterflooding has been the occurrence of an additional seafloor subsidence, corresponding in 2000 to a decrease of the seafloor level of approximately 10 m.

It is now well recognised that the hydro-mechanical coupling involving multiphase fluid interactions (oil and water) is determinant for the interpretation of the phenomenological aspects associated to the chalk compaction and the related subsidence observed in the chalky North Sea oilfields (a.o. Ekofisk) when water flooded. The subsidence due to waterflooding is interpreted as a collapse phenomenon due to "suction" decrease, typical of loose and low plasticity unsaturated soils when wetted under load. On the other hand, time-dependent stress-strain behaviour of geomaterials is one of the major concerns in soil mechanics and, in effect, subsidence includes creep effects.

The basic idea of the Pasachalk project is that the chalk containing oil and submitted to water flooding is a multiphase porous material, similar to unsaturated soil. In chalk, the wetting fluid is water and the non-wetting fluid is oil, in unsaturated soils, the non-wetting fluid is air. In this regard, the volume decrease observed in a chalk submitted to water flooding is considered as a well documented "collapse under wetting" mechanism, which occurs in low plasticity loose fine-grained soils.

The Pasachalk 1 project allowed to define the general constitutive law, including the "suction" aspects, to determine the main parameters for fully "oil" and "water" saturated chinks and to set up the procedure and equipments for working at variable suction levels. In addition a new set of problems has been revealed that constituted the scope of the Pasachalk 2 project :

- viscous behaviour of chalk : the viscous effects has been experimentally investigated within a multiphase coupled framework, i.e. in chalk samples containing various proportion of oil and water. The control of the relative saturations is carried out under conditions of controlled suctions, as in unsaturated soils. Under this experimental conditions, the stress parameter suction is known, and its effect on related viscous mechanical parameters can be adequately investigated. This is an essential and original contribution of the project as no creep tests under a controlled oil-water suction have been performed up to now;

- in addition, several tests at different loading rate have provided the information on the viscous parameters related to the constitutive law;

Besides the time effect, the project lead to quantify the chalk-water and oil-water interactions, especially the critical initial water content, the effect of surface-chemical effects, and all aspects related to chalk wettability. The aim here was to consider the effects of these phenomena within the coupled hydro-mechanical framework. The wettability tests themselves revealed much more difficult to carry that what was expected and only first tests could be carried out.

A new perspective for the physico-chemical explanation of the fluid-chalk interaction has been proposed by the Stavanger College team (Prof. R. Risnes) who joined the partnership on behalf of the industrial partner, Total Exploration Norway. It is based on the major role of a physico-chemical parameter called "water activity". This concept is easily integrated in the "suction" one and this will be the base for the future works.

The experimental and numerical studies, that are detailed in the report, lead to reach following objectives :

- a numerical tool has been set up, taking into account the physical mechanisms of fluid-fluid and fluid-skeleton interactions, for modelling and forecasting the behaviour of the reservoir rock and, hence, of the oilfield. A fully coupled elasto-visco-plastic law, including the fluid-skeleton interaction via the "suction" has been build up;
- the experimental determination of constitutive parameters has been carried out, together with their dependency with respect to geological and physical conditions, using methods derived from the mechanics of unsaturated soils;
- the implementation of the law has been made into a computer finite elements code,
- the model has been calibrated on existing data, aimed at predicting chalk behaviour during oil extraction under several conditions, and at helping for a more efficient oil recovery and safe reservoir management. It has been compared with a commercial code in a "benchmark" exercise and revealed that it was able to predict correctly the hydro-mechanical, coupled, behaviour of an oil reservoir

The model will be now proposed to the oil companies operating in North Sea chalk oil-fields. For this a workshop grouping the major oil companies and the research institutes interested in the chalky oil fields problems will be held in Stavanger (Norway) on 3 - 4 February 2004.

## ***1.2. Technical Report***

## I. INTRODUCTION

The "Pasachalk" project, started in 1997 with the Pasachalk "1" EC contract and continued with the present "Pasachalk 2" has been initiated in the framework of the set of problems of the North Sea chalky oil fields.

In North Sea oil fields, the sea floor subsidence created by the compaction of chalk oil reservoirs during oil extraction is a serious problem. Together with the "casing collapse" and the "chalk production" problems, sea floor subsidence is related to some specific features of the mechanical behaviour of chalk. Chalk mechanical properties are modified during waterflooding (water injection made in order to maintain the pore pressure constant and to enhance the oil recovery), when the initial saturating fluid (oil) is replaced by sea water.

The now ending Pasachalk2 project is based on the application of unsaturated soils mechanics to chalk behaviour during water flooding. Unsaturated soils are three phase porous media containing solid, water as a wetting fluid, and air as the non-wetting fluid. An essential stress parameter in unsaturated soils is the suction, equal to the difference between air pressure and water pressure ( $s = u_a - u_w$ ). When submitted to water infiltration, loose and low plasticity unsaturated soils are known to "collapse", i.e. decrease in volume. A parallel is made in the Pasachalk project with the decrease in volume observed in a chalk containing oil (non-wetting fluid) when injected with water (wetting fluid). The Pasachalk project comprises an experimental approach, a theoretical approach and a numerical approach

During the project, the main assumptions made have been confirmed. However, it has been shown that the coupled hydromechanical multiphase approach adopted should be further enriched to account for other important behaviour features of chalk. Two important phenomena have been emphasized, namely viscosity effects, in relation with the significant creep behaviour of chinks, and the effects of the wettability of the chinks, which are an essential parameter to deal with, in a multiphase approach.

The aim of the "Pasachalk2" project. was to enlarge the scope of the multiphase coupled analysis of the behaviour of chalk, by including the additional effects related to the **viscous** behaviour and to the **wettability** effects in chinks. This approach, in which the viscous behaviour and the wettability effects are included in a global multiphase approach, accounting for the effects of the oil-water "suction", is original and is essential for a better understanding of other problems related to chalk behaviour, such as chalk production in boreholes, and casing collapses.

The Pasachalk2 project is composed of an experimental, a theoretical and a numerical approach.

It lead to build an efficient numerical tool for a better management of the reservoir, through a better prediction of its behaviour during exploitation. Benchmark between the Pasachalk code and existing commercial codes , used by oil industry proved the efficiency of the developed code.

The present report accounts for the results of the two main aspects : experimental studies an modelling (establishment of constitutive laws an implementation in finite elements (FE) code). The report ends with the results of the benchmark between the Pasachalk code including the parameters deduced from the lab studies and commercial codes.

## II. EXPERIMENTAL INVESTIGATION

The subsidence due to waterflooding in reservoir chalks is a coupled problem typical of a multiphase geomaterial, i.e. the chalk full of water and of oil. Delage *et al.* (1996) showed how this problem could be considered within a framework taken from the mechanics of unsaturated soils. This approach was confirmed during the Pasachalk EC project (contract no. JOF3CT970033), by running an experimental program (oedometric and triaxial tests) in which the oil-water suction  $s = u_o - u_w$  (where  $u_o$  and  $u_w$  are the oil and water pressures respectively) was controlled. To do so, the independent control of both pressures with  $u_o > u_w$  was achieved, resulting in a positive value of the suction (Pasachalk 2001). In this regard, experimental observations allowed to extend the concept of capillary pressure, in which only oil-water-chalk capillary actions are considered, to that of suction, that also includes the various existing physico-chemical chalk-water interactions.

To better interpret the subsidence that occurred in the chalk deposit since the eighties, it was then planned to account for time-dependent effects (viscous behaviour), that were supposed to be significant in chalks (Andersen *et al.* 1992; Gutierrez & Kolderup 1999). More precisely, it was decided to investigate in the laboratory the time-dependent behaviour of chalk samples containing two fluids (oil and water) under controlled oil-water suction conditions (De Gennaro *et al.* 2003). This approach, that is complementary to standard investigations already carried out with only one fluid (water or oil, among others: Newman 1983, Ruddy *et al.* 1989, Piau & Maury 1994, Andersen 1995, Krogsbøll 1998; Papamichos *et al.* 1997, Schroeder *et al.* 1998, Risnes *et al.* 1999, Homand & Shao 2000), seems indispensable to better account for the real problem in the reservoir.

Experimental results showing some aspects of the time-dependent behaviour of a reservoir chalk are given hereafter and interpreted in the framework of existing knowledge on the time-dependent behaviour of geomaterials. Due to the fact that chalk-fluid interactions depend on wettability, it should be expected that the influence of wettability on the hydro-mechanical behaviour of chalk is significant. Thus, part of the experimentation was also devoted to the definition of the retention properties of the chalk in terms of  $s$ - $S_{rw}$  relationship ( $S_{rw}$  is the partial water saturation degree).

### II.1 Material and methods

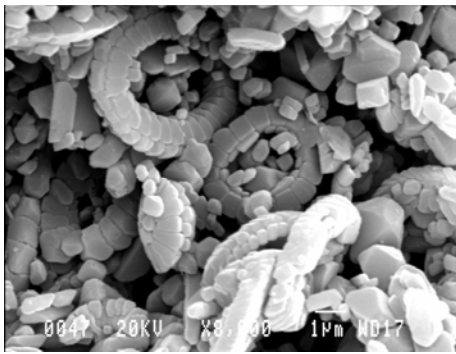
In order to investigate the time-dependent mechanical behaviour of oil reservoir chalks, a series of triaxial compression tests (drained test) and oedometric tests (1D compression tests with lateral deformation prevented), under controlled suction conditions, were performed. Since the basic idea of the Pasachalk project is that the mechanical response of chalk saturated by water (wetting fluid) and oil (non wetting fluid) can be interpreted in the same way as for the mechanical behaviour of unsaturated soils (where water is the wetting fluid and air is the non wetting fluid), emphasis is put on the definition of the retention properties of the chalk and suction control.

#### II.1.1 Chalk tested

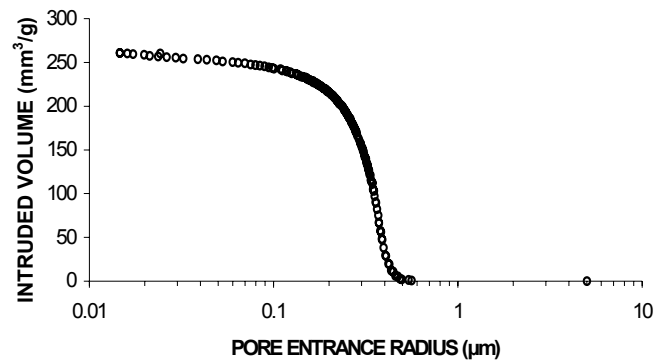
All the tests presented in this report are carried out on outcrop chalk coming from the CBR quarry near the town of Visé (Belgium), also called Lixhe chalk. The microstructure of Lixhe chalk is very close to that of many North Sea Chalks (i.e. skeletal debris of unicellular algae, the coccolithes), this is the major reason that justify the choice of this chalk in this study. The



remains of coccolithes (crystals of calcite) are present in small plates of about 1 to 10 microns dimension (Scanning Electronic Microscopy (SEM) picture, Fig. II-1a). Between the calcite grains, the voids (dimensions 1 to 5 microns) represent about the half of the total volume, with an average porosity of about 40 %. This value of porosity was corroborated by a series of MIP (Mercury Intrusion Porosimetry) tests (Fig. II-1b), the latter allowed to identify a distribution of major pores having an average entrance radius of about  $0.37 \mu\text{m}$ . In the quarry deposit, voids are generally filled with water in chemical equilibrium with the chalk (saturated in  $\text{CaCO}_3$ ), whereas the porous network of the reservoir chalk is generally filled with water and oil. This may have some important implications in the definition of the overall behaviour of the material. Previous investigations on this material allowed to quantify values of the intrinsic permeability of about  $1 \times 10^{-14} \text{ m}^2$  ( $k_{\text{water}} \cong 1 \times 10^{-8} \text{ ms}^{-1}$ ,  $k_{\text{oil}} \cong 7 \times 10^{-9} \text{ ms}^{-1}$ ). The oil used in this study is a non polar organic liquid (Soltrol 170<sup>®</sup>, Phillips Petroleum Company), it does not contain any polycyclic aromatic hydrocarbons so that is not toxic. Besides, Soltrol 170 has been chosen also for its very low solubility in water ( $\ll 1 \text{ mg/l}$  at  $20^\circ\text{C}$ ) and volatility in air ( $\ll 4 \times 10^{-2} \text{ mm}^3/\text{h}$  at  $20^\circ\text{C}$ ), and because is non water miscible. Characteristics numbers for Soltrol 170 are: dynamic viscosity  $\eta_{\text{oil}} = 2.028 \text{ cP}$ , fluid density  $\rho_{\text{oil}} = 0.78 \text{ Mg m}^{-3}$ .



(a)



(b)

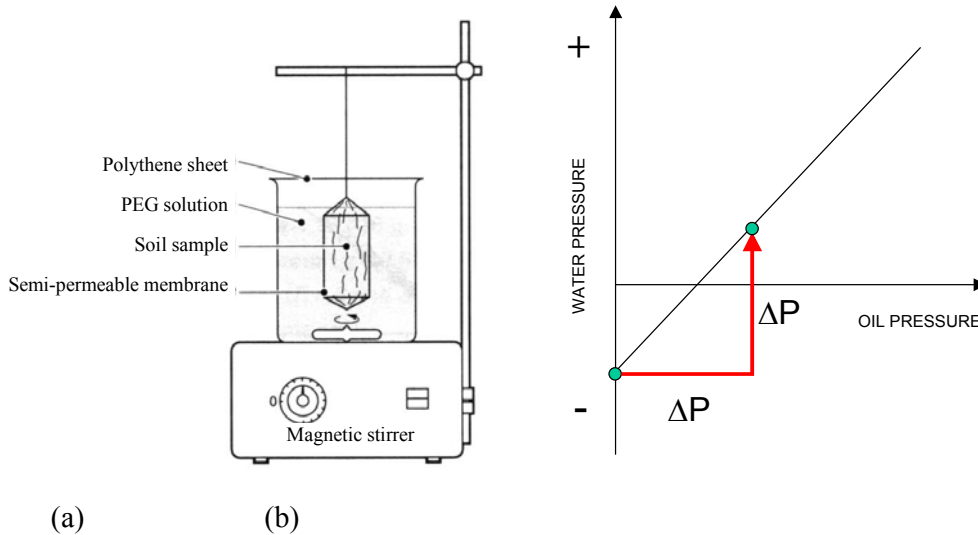
**Figure II-1.** (a) SEM view of Lixhe chalk microstructure (after Risnes *et al.*, 2003), (b) MIP of Lixhe chalk

### II.1.2 Suction control : osmotic and overpressure techniques

In a porous medium (i.e. chalk) the contact between two non miscible fluids (oil and water) induces a discontinuity of the values of pressure ( $u_o - u_w$ ) through the interface separating the two fluids. This discontinuity is also called capillary pressure (Laplace 1806; quoted in Morrow 1970). In the context of thermodynamics, capillary pressure is only a component of a more general potential energy, introduced in geomechanics since the early sixties, called "suction". Due to the key role played by suction on the behaviour of chalk, experimentation required a set of testing procedures allowing to control suction. Two techniques have been used in this study: (i) the osmotic technique and (ii) the overpressure technique.

The osmotic technique (Kassiff & Benshalom 1971, Delage *et al.* 1992, Cui & Delage 1996) is rarely used in unsaturated soils, and apparently never used in petroleum engineering. The technique is based on the osmotic principle. The difference between two solutions having different concentrations and separated by a semi-permeable membrane induces a difference between the pressures of the two solutions, this difference is the osmotic pressure. A partially saturated sample is then inserted and sealed in a tube-shaped cellulosic semi-permeable

membrane characterised by a specific value of MWCO (Molecular Weight Cut Off). The membrane containing the sample is then immersed in an aqueous solution of big sized molecules of polyethylene glycol (PEG) continuously stirred, the whole system is at atmospheric pressure (Fig. II-2a). Since PEG molecules can not cross the semi-permeable membrane, suction is applied to the water through the membrane by osmosis and its value is controlled by the concentration of the solution: higher PEG concentrations provide higher suctions (Williams and Shaykewich 1969; Delage et al. 1998). Being used essentially for the experimentation on water partially saturated soils, a first verification of the resistance of the special semi-permeable membrane (Spectra/Por<sup>®</sup> 12000-14000 Daltons MWCO, Spectrum Laboratories Inc.) to the contact of oil has been necessary. This preliminary investigation provided satisfactory results, enabling the use of this technique for controlling suction during some tests on chalk full of oil and water (De Genaro *et al.* 2003).



**Figure II-2.** (a) Suction control by osmotic technique (after Cui & Delage 1996), (b) Suction control by overpressure technique (principle)

The overpressure technique (also called axis translation method) is probably the most used technique to control suction in unsaturated soils. It allows to impose the values of suction by working in the positive range of pressures. This is obtained by increasing simultaneously the values of pressure of the wetting fluid (water) and non-wetting fluid (oil in this study), translating the pressure of the wetting fluid in the positive range (Fig. II-2b). The use of a small pore sized ceramic porous stone permits to impose on the two fluids saturating the porous sample two different pressures (Richards, 1941). This ceramic porous stone permits a free movement of water through it, while the oil (as a non wetting fluid) can not cross it if its pressure does not exceed the capillary pressure value  $p_c$  of the ceramic porous stone. Independent control of both oil and water pressures is then possible, allowing for a wide range of suction control.

Further details of these techniques are given in section II.2 (Chalk wettability and retention properties).

### *II.1.3 Experimental apparatus : mechanical devices and procedures*

As introduced previously, a series of triaxial compression tests (drained test) and oedometric tests (1D compression tests with lateral deformation prevented), under controlled suction conditions, were performed to study the mechanical viscous behaviour of Lixhe chalk. These apparatuses are briefly described hereafter.

#### Triaxial cell

The fully saturated samples have been tested in a "auto-compensated" triaxial cell Geodisign<sup>®</sup> providing 60 MPa confining pressure and specially designed to allow any kind of stress paths; even stress or strain controlled. In addition, fluid of flow for permeability measurements is possible through the sample at any (below 50MPa) upstream and dowsream pressure (Annexe 1).

The originality of the "auto-compensated" cell is that it doesn't require an heavy frame for the axial loading : it is an internal cylinder that provide the axial force, the reaction being given by the cell body itself. The auto-compensation acts in the axial direction, and is related to the action of the confining pressure on the axial piston. A connection between the confining chamber and the auto-compensation chamber allows to apply the same pressure in opposite direction on equal surfaces (surfaces A and B in Annexe 2a). Consequently, during deviatoric tests, the force applied by the piston in the axial direction gives purely the deviator stress. The cell is servo-controlled by means of four volume-pressure controllers (GDS<sup>®</sup> or home made similar equipment) connected to a data acquisition-piloting system (Annexes 1 and 2b). Two GDS<sup>®</sup> with a maximum capacity of 64 MPa are used to apply the confining pressure and the deviator stress, respectively.

#### Suction controlled triaxial cell

Triaxial tests under suction control were carried out in a high pressure, auto-compensated triaxial cell Geodesign<sup>®</sup> modified in order to allow suction control (Annexe 2). The auto-compensation acts in the axial direction, and is related to the action of the confining pressure on the axial piston. A connection between the confining chamber and the auto-compensation chamber allows to apply the same pressure in opposite direction on equal surfaces (surfaces A and B in Annexe 2a). Consequently, during deviatoric tests, the force applied by the piston in the axial direction gives purely the deviator stress. The cell is servo-controlled by means of four volume-pressure controllers (GDS<sup>®</sup>) connected to a data acquisition-piloting system (Annexe 2b). Two GDS<sup>®</sup> with a maximum capacity of 64 MPa are used to apply the confining pressure and the deviator stress, respectively.

The overpressure technique allows to control suction during the test. Oil and water pressures are applied via two GDS<sup>®</sup>, with a maximum capacity of 3 MPa. The first GDS applies the oil pressure ( $u_o$ ) through two bronze porous stones. The first porous stone is placed at the top of the sample, the second one is part of the composite base pedestal at the bottom of the sample (Annexe 2b). The central part of the composite base pedestal incorporates a high air entry value ceramic porous stone connected to the second GDS used for the application of water pressure ( $u_w$ ). Strain measurements are obtained locally, by means of a special frame mounted around the chalk sample (Annexe 2b) and equipped with 5 LVDTs (Linear Variable Differential Transformers).

All the chalk samples tested have initial dimensions of about 38 mm in diameter and 76 mm in height. They were extracted from a block of outcrop chalk, taking care that all the samples had same orientation, machined on lathe, then oven dried during 24 hours at 105°C and finally oil saturated under vacuum (-94 kPa during 24 hours). In order to impose the selected

suction level and to reduce time for equalisation in the triaxial cell, samples were pre-equilibrated out of the cell using the osmotic technique. When the equilibrium was reached, samples were transferred inside the cell and the suction level was re-established by means of the two GDS controllers. The specimens were mounted with filter papers at both ends and over the cylindrical surface in order to have maximum drainage surface and a more homogeneous suction distribution. Finally, samples were submitted to the selected testing programme.

### Osmotic oedometer

The osmotic oedometer is presented in Annexe 3. In this device, the bottom of the sample is in contact with a semi-permeable membrane below which a solution of polyethylene glycol (PEG) is circulated (Kassiff & Benshalom, 1971; Delage *et al.*, 1992). Water exchanges through the membrane are monitored via visual observation of the water level in a graduated tube placed in the bottle that contains the PEG solution. After imposing the desired suction (i.e. at a given PEG concentration) a period of time of about 15 days was necessary to reach equilibrium. Afterwards compression loading began.

In order to have a more reliable correlation between oedometric tests and triaxial compression tests results under controlled suction levels, the osmotic oedometric cell (cylindrical) has been equipped with two lateral gauges glued on the external side of the thin wall cell (Annexe 3a). The deformation of these gauges, previously calibrated with respect to a given (increasing and/or decreasing) internal radial pressure, allowed for the measurement of the radial stress developing during the tests.

The preparation of the chalk samples tested in the oedometer was identical to that of the triaxial samples. The selected suction level was controlled using the osmotic technique.

## **II.2 Chalk wettability and retention properties**

Studies on wettability have been carried out in order to have an insight into the oil-water interaction mechanisms at the origin of the hydro-mechanical coupled behaviour of chalk.

To this scope, retention properties and wettability characteristics of the chalk have been assessed by means of retention curves obtained using:

- the osmotic technique;
- the overpressure technique;
- the mercury intrusion porosimetry (MIP).

The use of one among the three techniques above mentioned depended on the type of retention test performed, namely : retention following a wetting path (imbibition) or a drying path (drainage).

### *II.2.1 Experimental techniques*

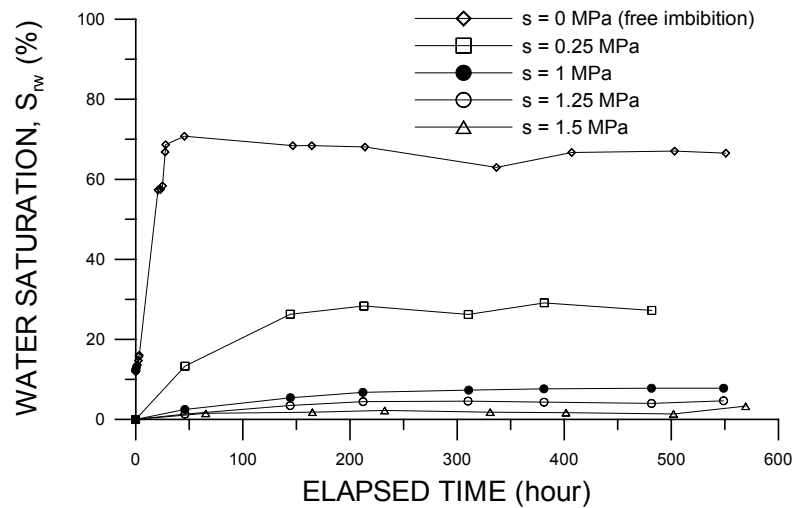
The definition of the  $s$ - $S_{rw}$  relationship in an oil-water saturated chalk depends on the driving fluid used to modify the relative saturation of the sample. Indeed, if the displacing fluid is the wetting fluid, the resulting imbibition path will be different from the path obtained when the non-wetting fluid drives (drying path). In other words, an hysteretic hydraulic behaviour characterises the porous rock. This hysteresis reflects the effect of the microstructure (in terms of accessible pores) and the different degree of wettability of the chalk to each fluid (oil or water), which is in strong correlation with the inter-granular links (capillary and physico-chemical) existing in the sample. In this work the osmotic technique was used to carry out

retention tests following a wetting path (water drives), whereas the drainage path was determined using both overpressure technique and MIP.

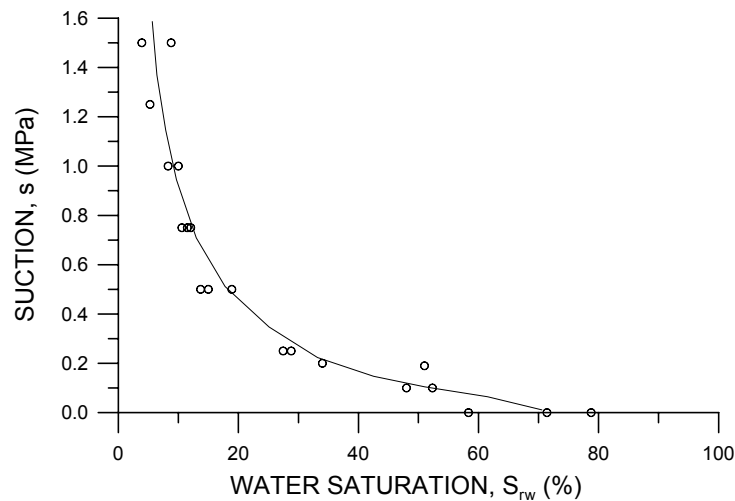
### Wetting path : osmotic technique

The osmotic technique allows to apply a desired value of suction to a sample by osmosis (see section II.1.2). The chalk samples (29 mm diameter, 37 mm high) were initially prepared following the usual procedure, namely: oven dried at 105°C and oil saturated under vacuum (-94 kPa during 24 hours). They were then inserted and sealed in a tube-shaped cellulosic semi-permeable membrane, finally immersed in an aqueous solution of big sized molecules of polyethylene glycol (PEG). Since PEG cannot cross the semi-permeable membrane, a suction is applied to the water through the membrane by osmosis.

Results of retention tests are presented in Fig. II-3. Chalk sample are progressively wetted in order to attain the desired value of suction. Note that during oil production, the same process is involved: oil is pushed out of the porous network by water injection (waterflooding), and the chalk deposit is submitted to a water imbibition process.



(a)



(b)

**Figure II-3.** (a) Water imbibition curves at various suction levels, (b) retention curve of Lixhe chalk following a wetting path (after De Gennaro et al. 2003)

As it can be inferred from the results in Fig. II-3a, the exchange kinetic is function of the imposed suction level. The higher the suction, the slower is the change in water saturation. From the plateau of the imbibition curves in Fig. II-3a a final value of  $S_{rw}$  is obtained, corresponding to the given level of imposed suction. The relationship between  $s$  and  $S_{rw}$  can be established plotting the couple of points  $s-S_{rw}$ , as shown in Fig. II-3b. These points corroborate previous observations (PASACHALK 2001), allowing to define the retention curve for Lixhe chalk under a wetting path. As it can be noted, at low suction levels chalk is quite prone to water saturation (average  $S_{rw} \cong 80\%$  when  $s = 0$ ), this reflects a general tendency of this material to be water-wet rather than oil-wet.

It is worth to observe that at high suction levels residual oil saturation is of about 10%. A slight increase in  $S_{rw}$  values (from 10% to 20%) induces an important decrease of suction values (from 1 MPa to 0.4 MPa, i.e. about 60% reduction), reflecting the high sensitivity of the rock to wetting.

#### Drying path : overpressure technique and mercury intrusion porosimetry

As already mentioned (section II.1.2), the overpressure technique allows to control suction increasing simultaneously the values of pressure of the wetting fluid (water) and non-wetting fluid (oil in this study), so that the pressure of the wetting fluid is translated in the positive range (Fig. II-2b). The application of this technique for the retention tests has been accomplished using a special cell (Annexe 4, multiphase cell), similar to that developed by Longeron et al. (1995). The use of a small pore sized ceramic porous stone permits to impose on the two fluids saturating the porous sample two different pressures (Annexe 4b). This device allowed to complete the results obtained using the osmotic technique, by assessing the drainage path of the retention curves (i.e. oil driving from an initial water saturated state).

The retention curve of the chalk following a drainage path can be also estimated using MIP results. In this case, it is assumed that during intrusion the mercury (non-wetting fluid for the chalk) displaces its vapour phase (wetting fluid for the chalk), in the same way that oil displaces water. This analogy is completed admitting that the interaction between fluids is purely capillary. Based on the Laplace's capillary law, the following relations hold true :

$$p_{c(Hg)} = \frac{2\sigma \cos\theta}{r} \quad (II-1)$$

$$s = p_{c(ow)} = p_o - p_w = p_{c(Hg)} \frac{\sigma_{ow} \cos\theta_{ow}}{\sigma \cos\theta} \quad (II-2)$$

where,  $p_{c(Hg)}$  is the mercury capillary pressure,  $\sigma$  is the interfacial tension, and  $\theta$  is the contact angle between the mercury, its vapour phase and the solid (we assume  $\sigma = 0.482$  N/m and  $\theta = 147^\circ$ ; e.g. Léon y Léon 1998). Equation (II-2) is obtained admitting same pore radius  $r$  when using equation (II-1) for the couples oil-water and mercury-vapour. Considering  $\sigma_{ow} = 0.044$  N/m, the only parameter unknown in Equation (II-2) is  $\theta_{ow}$ , that can be written as follows:

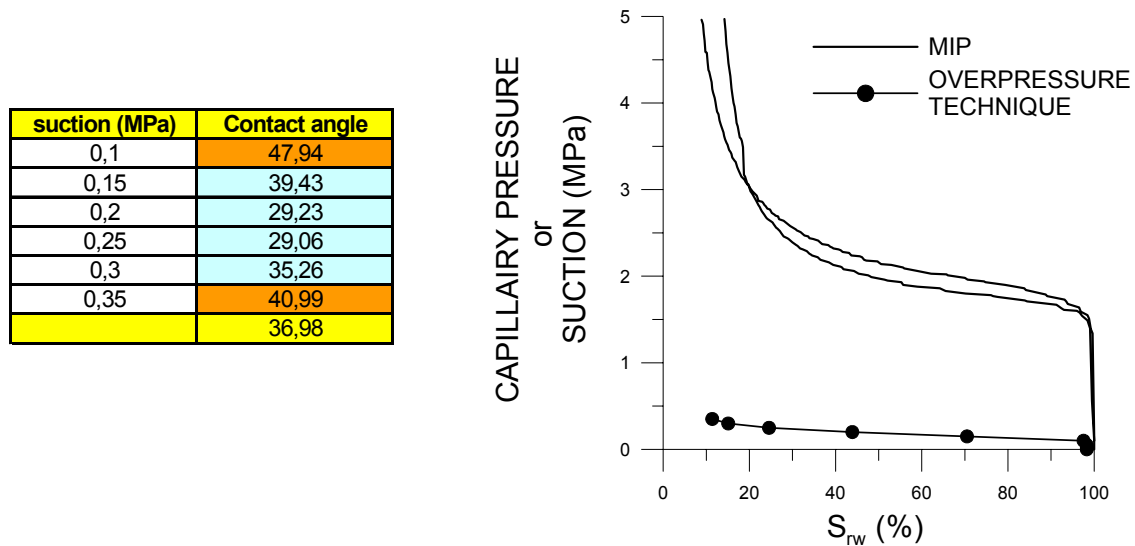
$$\cos\theta_{ow} = \frac{s}{p_{c(Hg)}} \frac{\sigma \cos\theta}{\sigma_{ow}} \quad (II-3)$$

Thus, if  $s$  is the oil-water suction applied using the overpressure method and  $p_{c(Hg)}$  the capillary pressure during the MIP test, using Eq. (II-3) is possible to estimate the value of  $\theta_{ow}$ . Obviously, this holds true admitting exclusively capillary interaction mechanisms between fluids and skeleton.

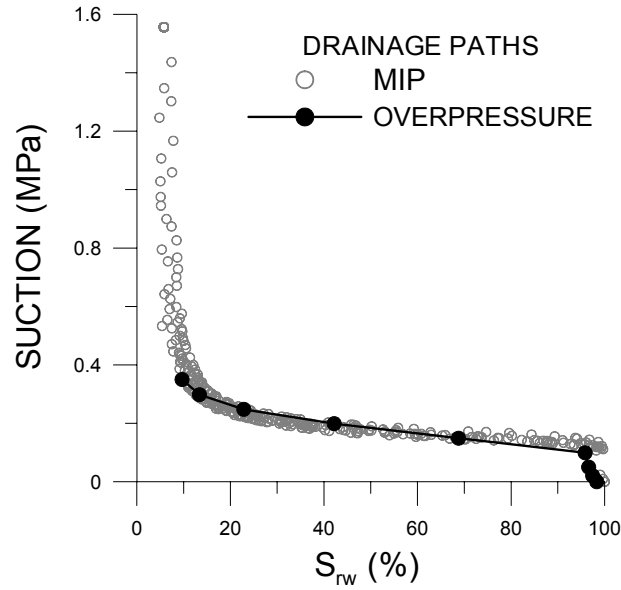
The contact angle value between oil and water depends on the wettability characteristics of the solid surface where the fluids spread. Ringheim (1992) obtained  $\theta_{ow} = 73^\circ$  for Ekofisk chalk with crude oil and formation water. This value classifies Ekofisk chalk as weakly water-wet (being  $\theta_{ow}$  between  $0^\circ$  and  $80^\circ$ ; Anderson 1986).

Figure II-4a shows the results obtained with MIP and overpressure technique. Since the second term in the right-hand side of Eq. (II-3) is constant,  $\theta_{ow}$  will vary following the ratio  $s/p_{c(Hg)}$ . This ratio is almost constant only in the middle part of the retention curves (i.e.  $S_{rw}$  between 20% and 70%), but it decreases near the asymptote at  $S_{rw} = 10\%$  and at the beginning of the test. The average value of  $\theta_{ow}$ , derived using Eq. (II-3) and the experimental data plotted in Fig. II-4a, is of about  $37^\circ$  (see table onset in Fig. II-4a). This value characterises Lixhe chalk as almost water-wet.

Figure II-4b shows the comparison between the retention curve obtained with the overpressure technique and the retention curves derived by MIP data using Equation (II-2) with  $\theta_{ow} = 37^\circ$ . For MIP curves all the available test data have been considered. Overpressure technique and MIP bear similar results. The air entry value obtained is of about 120 kPa, MIP data define an asymptotic value of residual water saturation of about 10%, this asymptote is less well accurate using overpressure technique. Indeed, as expected, owing to the variability of  $s/p_{c(Hg)}$  ratio, a scattering between the two methods exists at high degrees of water saturation ( $S_{rw} \cong 97\%$ ) and near the asymptote at  $S_{rw} \cong 10\%$ . It is likely that within the population of major pores (entrance radius  $0.37 \mu\text{m}$ , Fig. II-1b), a sufficient quantity of bulk water interacting with oil can give rise to capillary forces. Hence, capillary effects are predominant within the saturation range from 20% to 70% (i.e. where MIP and overpressure technique are coinciding). However, different types of interactions, other than capillary, between fluids and chalk seem to exist within the sample at the extreme saturation (i.e. where MIP and overpressure technique are not coinciding). These interactions, at the intra-granular level, result from physico-chemical effects and are well described by a much reliable variable, the oil-water suction.



**Figure II-4.** (a) Derived contact angles from MIP and overpressure method,



**Figure II-4.** (b) retention curves of Lixhe chalk following a drying path (MIP assuming  $\theta_{ow} = 37^\circ$ )

### II.2.2 Wettability of Lixhe chalk

The results obtained with the three previous techniques (osmotic, overpressure and MIP) served to characterise Lixhe chalk wettability using the Amott-Harvey index (Andersen 1995) given by the following relation :

$$WI = WWI - OWI \quad (II-4)$$

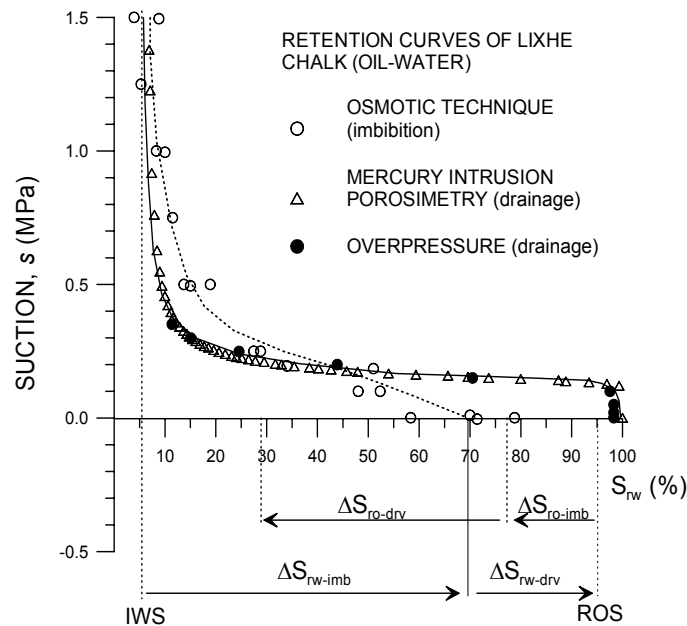
where :

$$WWI = \frac{\Delta S_{rw-imb}}{\Delta S_{rw-imb} + \Delta S_{rw-drv}} ; OWI = \frac{\Delta S_{ro-imb}}{\Delta S_{ro-imb} + \Delta S_{ro-drv}} \quad (II-5)$$

In Eq. (II-5) "imb" means *imbibition*, "drv" means *driving*. WWI index varies between -1 and 1, which in turn means strongly oil wettable and strongly water wettable, respectively.

The meaning of terms  $\Delta S_{( )}$  is given in Fig. II-5, where all the retention curves of Lixhe chalk (on drying and wetting paths) have been plotted). Following Anderson (1986), the extreme states of saturation are indicated as : IWS (Irreducible Water Saturation) and ROS (Residual Oil Saturation). Being ROS not defined, we will admit that it will vary in such a way that  $\Delta S_{rw-drv}$  will be comprise between 0% and 30% (i.e. between the minimum and maximum attainable forced water imbibition). The same variation is considered for  $\Delta S_{ro-imb}$ , with the additional condition that  $\Delta S_{ro-imb} \leq \Delta S_{rw-drv}$ . Finally,  $\Delta S_{ro-drv}$  it will always attain the IWS state (Anderson 1986). With these hypotheses, the resulting WWI index varies between 0.4 and 1, defining Lixhe chalk from water wettable to strongly water wettable.





**Figure II-5.** Retention curves of Lixhe chalk (drying and wetting paths): estimation of Amott-Harvey index

### II.3 Mechanical behaviour

During PASACHALK 1 project the subsidence of North Sea chalk deposits has been presented and interpreted exclusively in the light of the multiphase hydro-mechanical coupling (PASACHALK 2001). Preliminary results from of PASACHALK 1 project showed time-dependent mechanical response of chalk samples subjected to one-dimensional compression tests in oedometric suction controlled conditions (PASACHALK 2001), corroborating previous observations on similar materials (e.g. Ruddy et al. 1986, Andersen et al. 1992, Krogsbøll 1998). The main scope of the experimental study on the mechanical behaviour of chalk carried out during PASACHALK 2 project was to highlight the effect of time dependency in a multiphase geomaterial, such as chalk full of oil and water. Experimental and theoretical approaches on time-dependent stress-strain behaviour of geomaterials is one of the major concerns in soil and rock mechanics (e.g.: Richardson and Whitman, 1963; Bjerrum, 1967; Singh and Mitchell, 1968; Adachi and Oka, 1982; Janbu, 1985; Tatsuoka et al., 2000). To do so, two complementary phenomenological effects were analysed : creep (ongoing deformation under constant effective stress) and rate dependency (loading rate effects). Both aspects are tackled in the experimental study, which is completed by an accurate investigation of the effect of suction on creep.

To investigate time-dependent stress-strain behaviour of chalk, a series of oedometric and triaxial tests with one saturating fluid (oil and/or water) and under suction controlled condition were performed. Results of this investigation are summarised in the following sections.

### II.3.1 Fully saturated samples

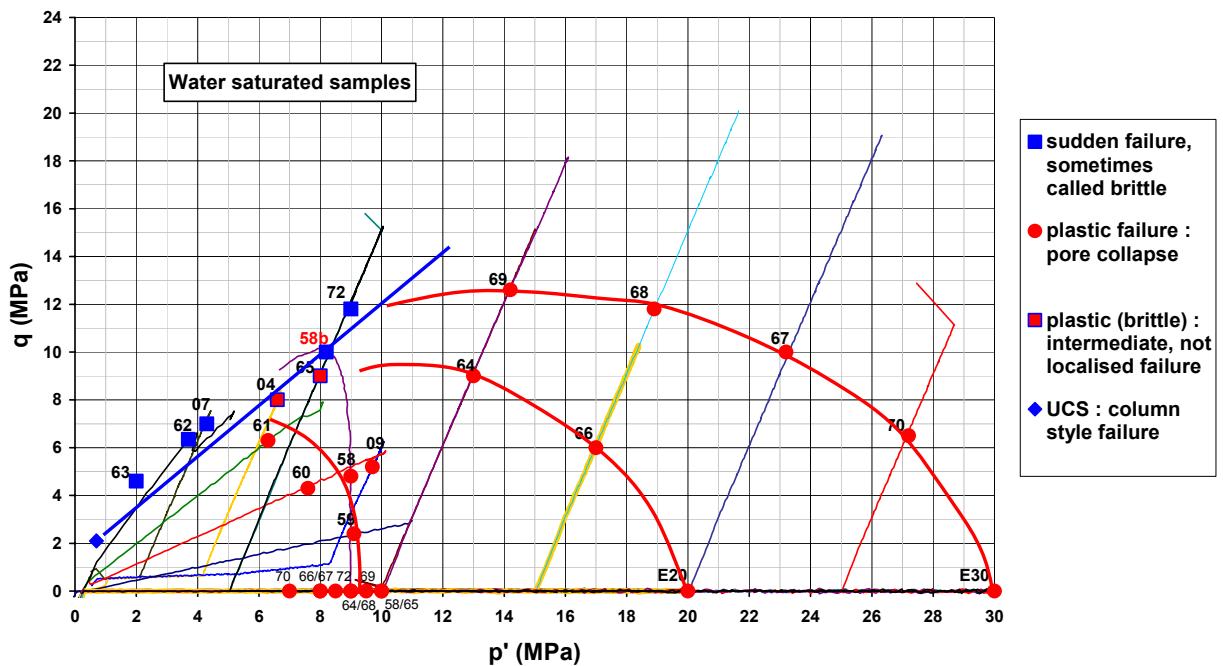
The fully saturated samples (oil and water at the two ends) were tested in order to obtain the extreme states between which the unsaturated chalk will vary. The mechanical behaviour has been studied by numerous (more than 100) tests, using a wide range of stress paths : isotropic, triaxial (deviatoric increase with confining pressure constant), proportional (ratio  $p/q$  constant), purely deviatoric (increase of  $q$  with  $p$  constant).

This set of test also included injection tests at different stress levels and creep tests (compression tests at different loading rates).

#### Tests at constant loading rate

The first aim of these tests, using a loading rate of  $10^3$  MPa/s, is to draw the failure envelopes of the chalk and to assess the hardening behaviour. For this, the multi-stress path tests include loading ways with hardening.

The figures II-6 and II-7 give respectively the results for the water and oil saturated samples on form of a  $p'$ - $q$  diagram (mean effective stress - deviatoric stress) on which are located all the failure points of the testes samples. The number is the internal number of the sample. The lines represent the stress path followed by each test. The shape and color of the mark indicates whether the type of failure is a "volumic - pore collapse" or a "shear - brittle - sudden" one. Some samples, after hardening can show a "volumic" failure followed by a "brittle" one



**Figure II-6.** Tests on Lixhe chalk with several stress paths including hardening : water saturated samples

Despite some scattering, the failure envelopes are clear : the "collapse" mechanism (in red) shows an important hardening with few change of the shape of the failure envelope (more change for the water saturated samples than for the oil saturated ones). On the other hand the "shear" failure mechanisms seems not to be affected by the hardening.

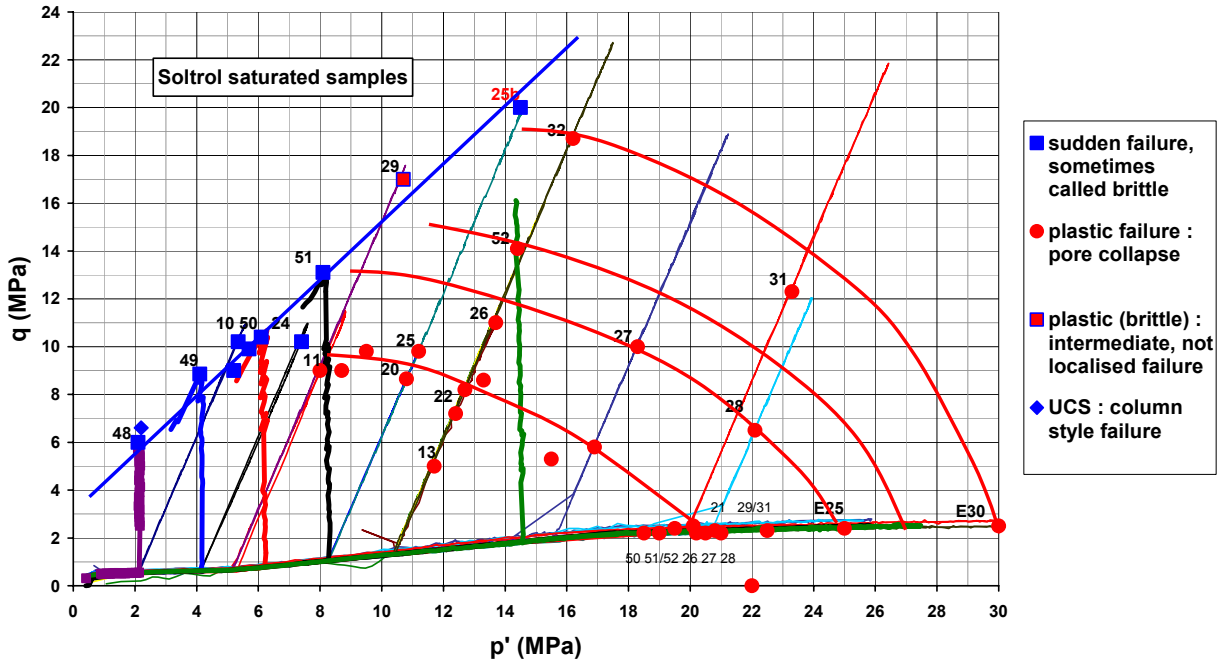


Figure II-7. Tests on Lixhe chalk with several stress paths including hardening : oil (Soltrol) saturated samples

Tests at different loading rates - creep effect

A serie of tests has been performed on fully oil saturated samples and on water saturated samples.

First tests consist in drained isotropic compression at different loading rates.

Some test were performed with the "de Waal" procedure<sup>1</sup> but this lead to problems of determination of the model parametres due to the complexity of the obtained results. One example of the results is given on figure 1 that shows the axial effective stress as a function of the axial strain.

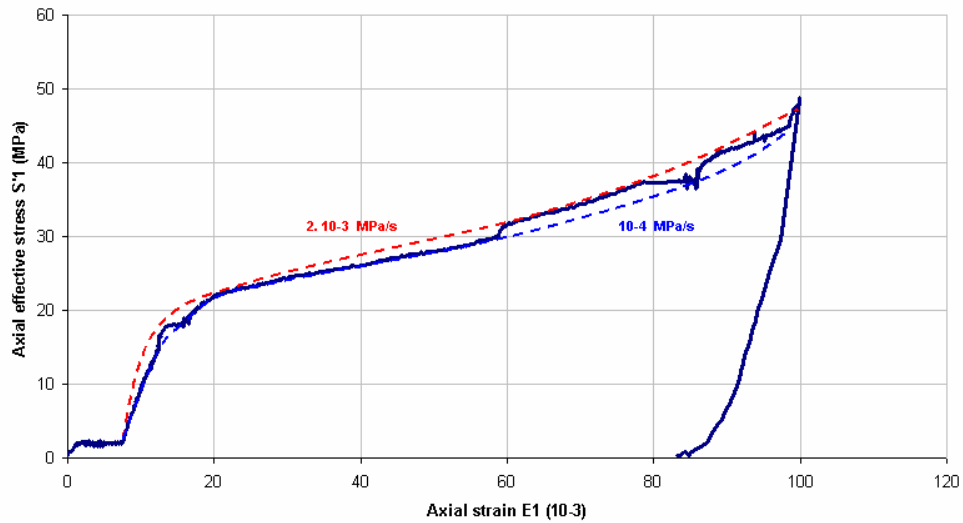
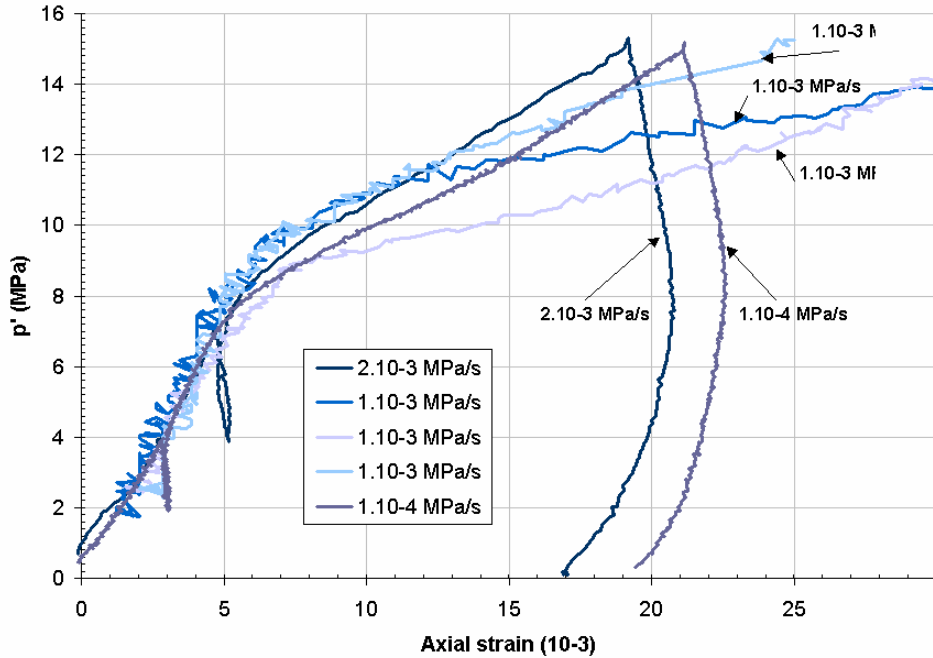


Figure II-8 : Ko test using the "de Waal" procedure - stress -strain curve #142

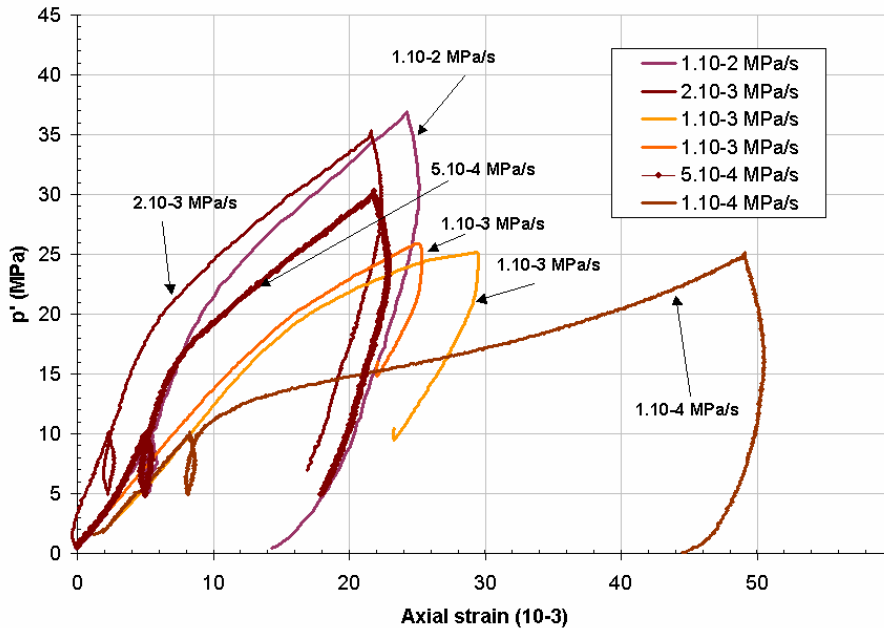
<sup>1</sup>This procedure consists in using alternatively two loading rates : one slow one ( $10^{-4}$  MPa/s) and one fast ( $2 \cdot 10^{-3}$  MPa/s) followed by a creep at constant load stage (Monjoie et al., 1991)

The most of the tests has been performed using several loading rates but this time, one constant rate per experiment. The loading rates are from  $1 \cdot 10^{-4}$  to  $1 \cdot 10^{-2}$  MPa/s. The results of these tests are summarized by figures II-9 and II-10.

The diagrams show the time influence : the highest the loading rate, the highest the strength. Because of the scattering, the influence of loading rate is more evident for oil saturated samples. Anyway, these tests provide enough information to allow to derive the values of the parameters for the viscous part of the Pasachalk model.



**Figure II-9 :** isotropic compression tests at several loading rates - water saturated samples - stress -strain curves



**Figure II-10 :** isotropic compression tests at several loading rates - oil saturated samples - stress -strain curves

### II.3.2 Partially saturated samples : suction controlled oedometric tests

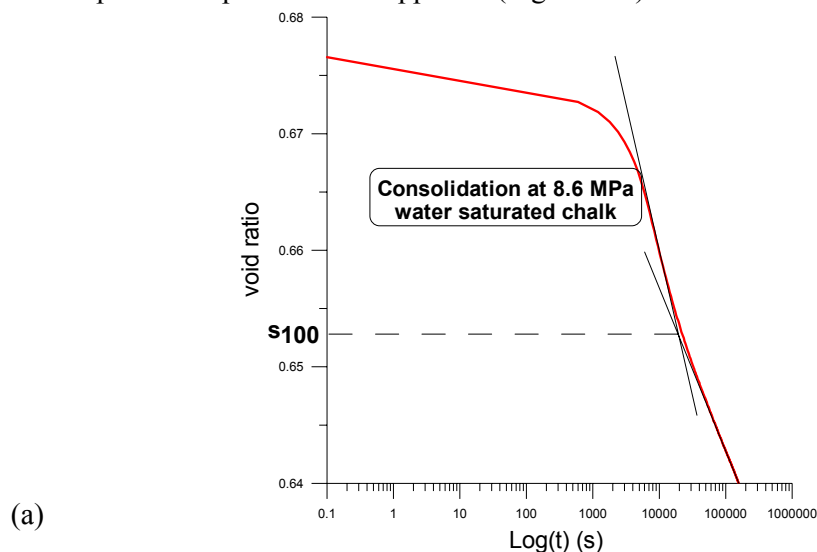
The time-dependent mechanical behaviour of partially saturated chalks during oedometric compression was studied by means of two different tests : (i) Multiple-Stage Loading tests (MSL) and (ii) Constant Rate of Strain (CRS) tests (e.g. Leroueil *et al.* 1985).

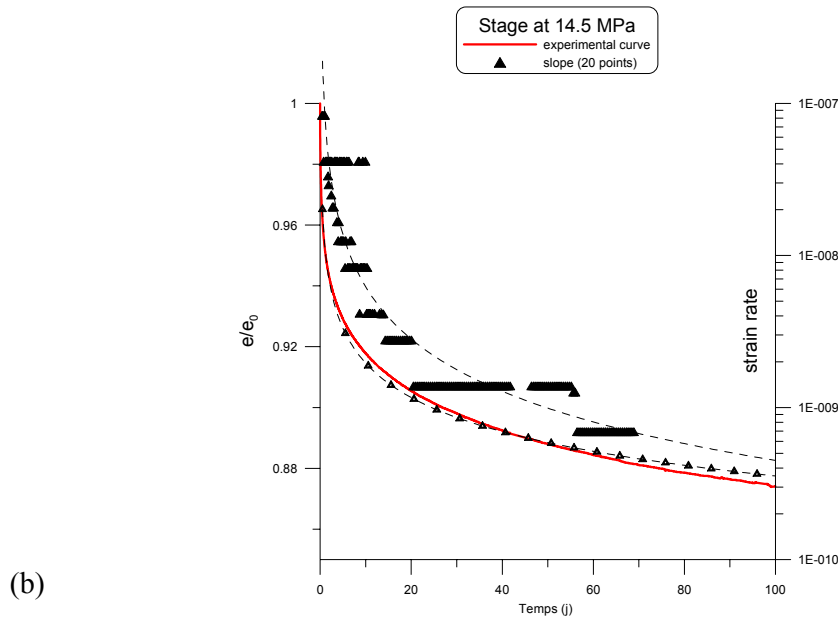
MSL tests allowed to identify the response of the material under sustained constant loading, emphasising the influence of creep effects on the behaviour of chalk. CRS tests permitted to have an insight into the influence of the loading rate and its effect on the material strength. All these tests were performed with the apparatus presented in Annexe 4.

#### Multiple-Stage Loading tests : creep

During MSL tests chalk samples (50 mm diameter and about 20 mm high) were subjected to incremental loading (applied instantaneously) and the evolution of the vertical strain during each loading stage was measured. A double lever arm allowed to apply a maximum vertical stress of approximately 60 MPa. This procedure is well established in soil mechanics. Available methods, based on Terzaghi's consolidation theory (1925) and effective stress principle, allow to define the effective stress-strain relationship, characterising the compressibility of the material (e.g. Lambe and Whitman 1979). This is achieved by analysing the evolution of the vertical strain curve versus time, called "consolidation curve", which permits to identify the representative vertical strain value at a given loading stage. This value of the vertical strain is defined as the strain corresponding to the effective stress state, the state of stress for which the excess pore fluid pressure is zero. In a chalk saturated with oil and water, excess pore pressures of oil and water during consolidation should modify suction ( $s = u_o - u_w$ ) and mean net stress ( $p_{net} = p - u_o$ , being  $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$  the mean total stress). In this case, the actual vertical strain value will correspond to the condition of simultaneous equilibrium of suction and mean net stress.

For chalk, it was possible to verify that such methods are not reliable. Indeed, the analysis of the consolidation curves did not permit to identify any significant point where change in excess pore fluid pressure was apparent (Fig. II-16a).





**Figure II-16.** Consolidation curves of Lixhe chalk during oedometric tests : (a) Casagrande's method, (b) rheological law for creep

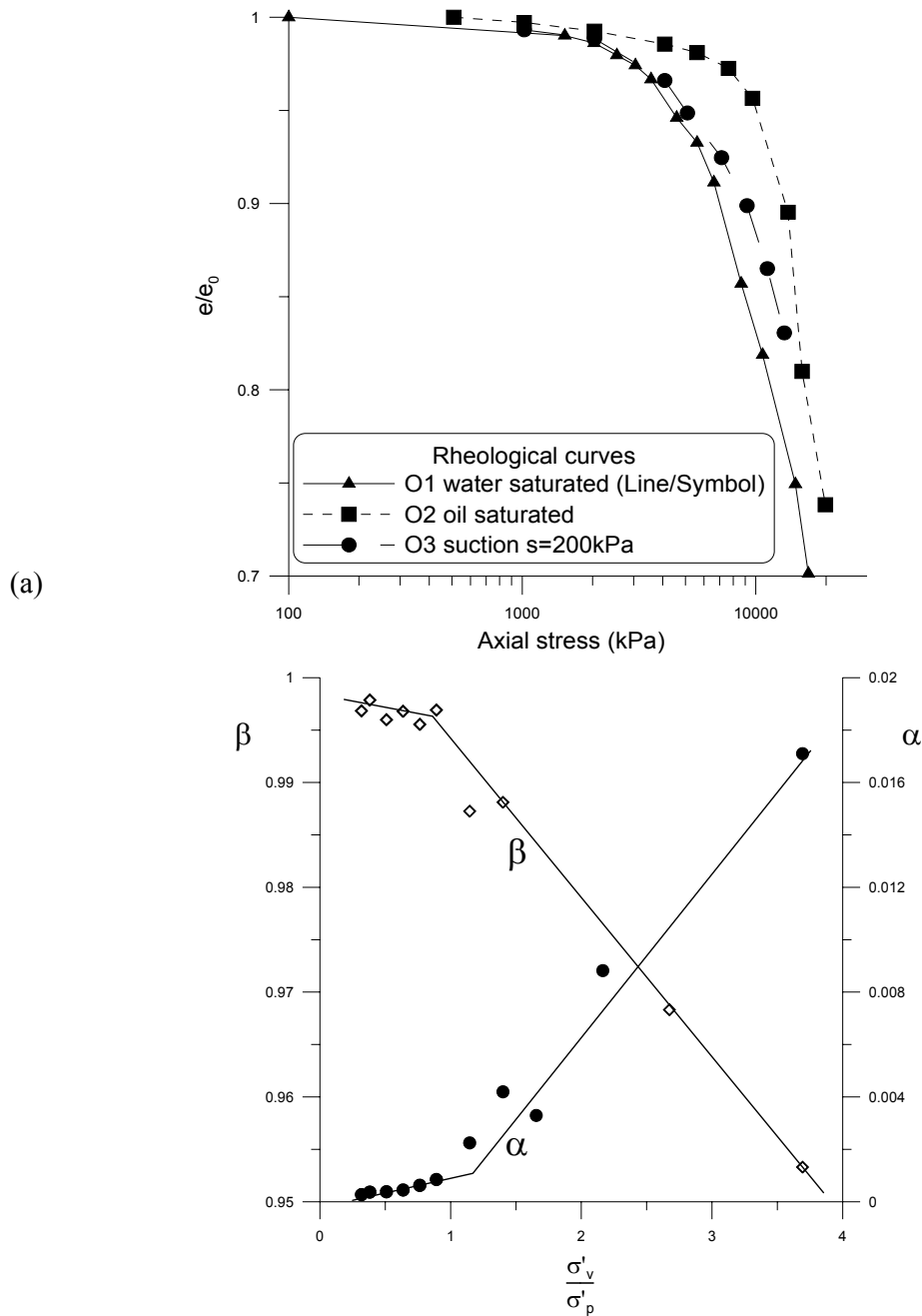
It seems likely that the low compressibility of the soil skeleton (bonding) and the permeability of the soft rock are sufficient in chalk to prevent excess pore fluid pressure generation (Lade and de Boer 1997). If this holds true, the delayed volumetric strain of chalk, as observed during MSL tests, should be highly creep dependent and solid skeleton settles although the excess pore pressure is zero. This results should be corroborated by pore pressure measurements during applied loading. A new methodology was then developed in order to analyze the creep behaviour and define an evolution law of the vertical strain as a function of the loading stage duration. This law reads as follows (Fig. II-16b) :

$$\frac{e}{e_{oi}} = t^{-\alpha_i} + \beta_i \quad (\text{II-6})$$

where  $e_{oi}$  is the void ratio at the beginning of loading stage  $i$ ,  $\beta_i$  represents the instantaneous strain, and  $\alpha_i$  controls the slope of void ratio vs time ( $0 < \alpha_i < 0.02$ ). The stress-strain relation (compressibility curve) obtained is presented in Fig. II-17a. It can be observed that the yield stress increases with increasing suction, i.e. with lower degrees of saturation in water ( $S_{rw}$ ). These results are in accordance with well established results showing a higher yield stress observed on chalk full of oil as compared to chalk full of water (Delage et al. 1996, Schroeder et al. 1998). They are also compatible with the water weakening effect. However, the results of Fig. II-17a complete these observations by also accounting for the gradual effect of partial saturation in both fluids under a controlled suction (200 kPa). In this regard, the change in yield stress with suction is compatible with the conclusions drawn on unsaturated soils by Alonso *et al.* (1987 and 1990) and that founded the notion of LC curve.

As shown in Fig. II-17b, the evolution of parameters  $\alpha$  and  $\beta$  (Eq. II-6) is likely to be a bilinear function of the effective vertical stress normalised with respect to the yield stress (over-stress ratio  $\sigma'_v/\sigma'_p$ ). These parameters describe adequately the viscous-elastic-plastic behaviour of Lixhe chalk. It is worth noting that the evolution of  $\alpha$  and  $\beta$  seems to be independent of the hydraulic configuration (i.e. saturating fluid(s)), and a unique relationship

can be established between creep rate and over-stress ratio (Fig. II-17b). Furthermore, change in creep rate due to suction changes is implicitly accounted for, based on the results presented in Fig. II-17a. Actually, any modification of the yield stress due to suction will modify the over-stress ratio  $\sigma'_v/\sigma'_p$ , and then  $\alpha$ , in Fig. II-17b.



**Figure II-17.** (a) Compressibility curves of Lixhe chalk during oedometric tests, (b) evolution of creep parameters  $\alpha$  and  $\beta$  (data from samples full of oil, full of water or under suction controlled condition)

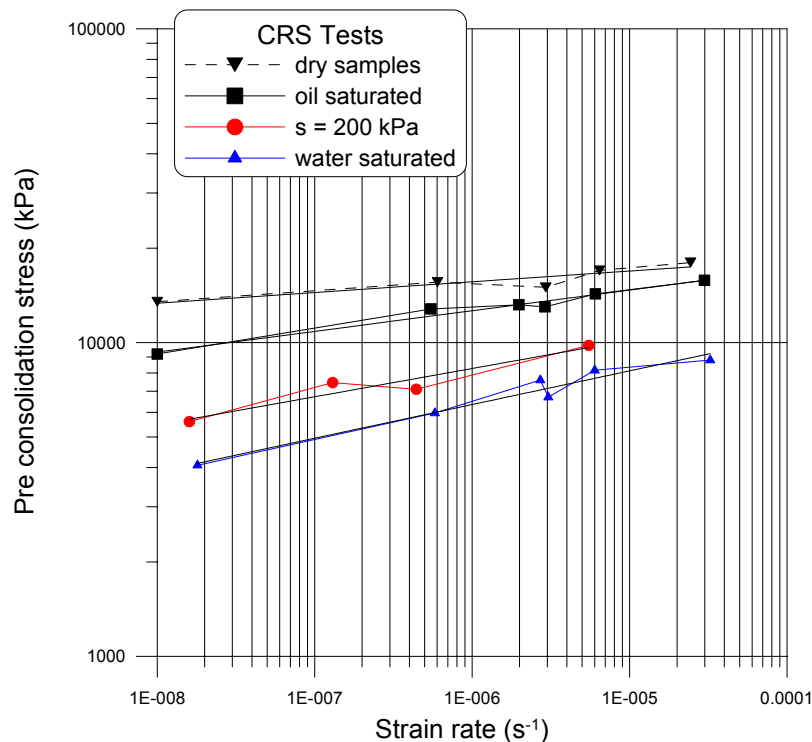
## CRS tests

During CRS tests the double lever arm was replaced by a mechanical loading frame, which allowed to control the rate of the vertical displacement of the base pedestal where the oedometric cell was located. It has long been recognised that the choice of the appropriate stress and/or strain rate during mechanical tests on saturated fine grained soils (i.e. silts, clays) is essential in order to avoid excess pore-water pressure generation and to apply fully effective stresses to the sample (Gibson and Henkel, 1954).

Four different displacement rates were used, with imposed values ranging between 1µm/min and 50µm/min. The strain rate engendered varied between  $5 \times 10^{-6} \text{ s}^{-1}$  and  $8 \times 10^{-5} \text{ s}^{-1}$ . Results of the tests are summarised in Fig. II-18. In a logarithmic plane the yield stress values increase linearly for increasing strain rates and decrease for increasing water saturation degree. Dry samples exhibit similar sensitivity to strain rate, within the range of the explored values. Consequently, it is believed that this behaviour does not depend on undissipated excess pore pressure generated during the tests. Finally, it is interesting to emphasise that data in Fig. II-18 also include the yield stress calculated from MSL tests. The corresponding strain rate was calculated from the total strain divided by the total test duration. The points corresponding to the MSL tests are in good agreement with the results of CRS tests. Based on the results presented in Fig. II-18, the following rheological law can be defined, similar to that proposed by Leroueil et al. (1985):

$$\log \sigma'_p = A + \frac{1}{m'} \log \dot{\epsilon}_1 \quad (\text{II-7})$$

where  $m'$  is the parameter that characterises the viscous behaviour of chalk, and  $A$  is an intrinsic parameter giving the "virtual" limit yield stress.



**Figure II-18.** Evolution of the pre-consolidation pressure versus strain rate



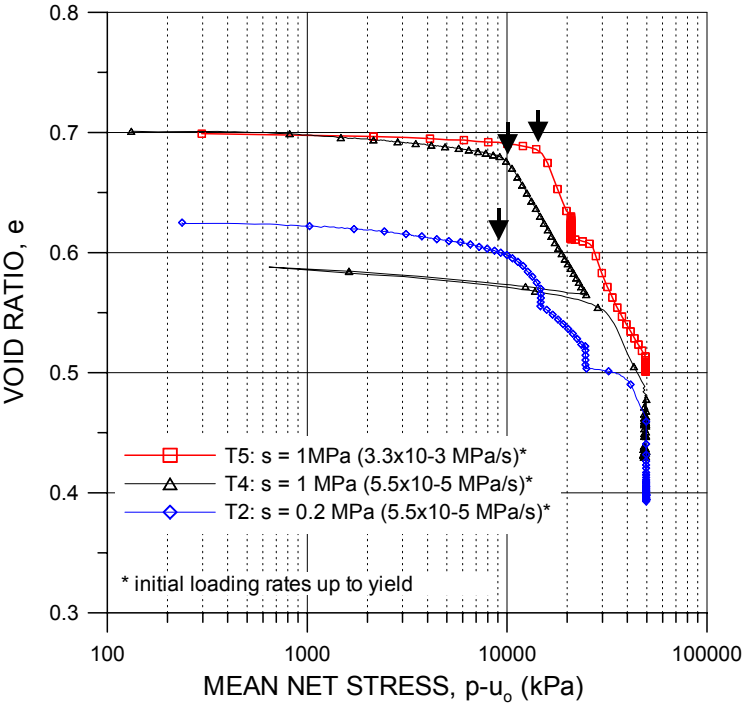
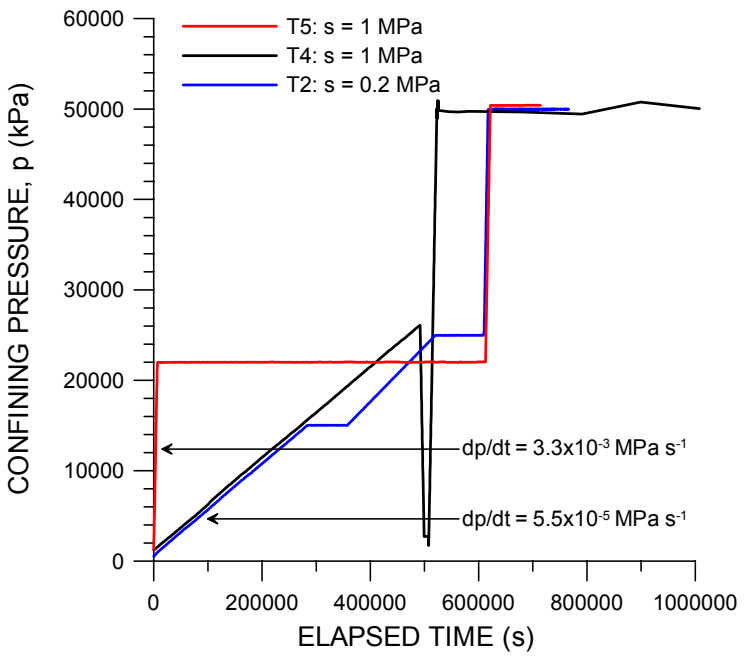
### *II.3.3 Partially saturated samples : suction controlled triaxial tests*

The triaxial tests presented in this section have been run following a load controlled procedure. There are not enough data related to the admissible loading rates in chalks. Axial strain rates of about 0.1 %/h (i.e.  $2.7 \times 10^{-7} \text{ s}^{-1}$ ) have been used on chalks almost full of oil ( $S_{rw} \cong 5\%$ ) and reputed slow enough to avoid excess oil-pressure generation (Havmøller and Foged, 1998). Deviator loading rates of about  $1.6 \times 10^{-4} \text{ MPa s}^{-1}$  have been applied during triaxial tests at constant confining pressure in order to prevent excess pore pressure (Homand and Shao, 2000). Based on previous findings, two isotropic loading rates have been retained in this study, namely:  $3.3 \times 10^{-3} \text{ MPa/s}$  (fast rate) and  $5.5 \times 10^{-5} \text{ MPa/s}$  (slow rate). Hereinafter we will use exclusively the terms "slow rate" and "fast rate". As previously introduced, obviously this is a crucial point of the experimentation.

All the tests were run in a way to collect the higher number of information with respect to two specific factors, namely: suction dependency and time dependency (loading rate and creep). To this aim, initial loading phases at slow rate or fast rate up to yield were performed, followed by successive phases of creep, during which the mean total stress was maintained constant, and reloading at fast or slow rate. All the samples were submitted to a preliminary equalisation stage (osmotic technique), in order to bring them to the corresponding level of imposed suction. As shown previously (section II.1.3), suction control during the triaxial tests was achieved by means of the overpressure technique. A total of 25 tests have been performed, in the following we summarise the typical results obtained.

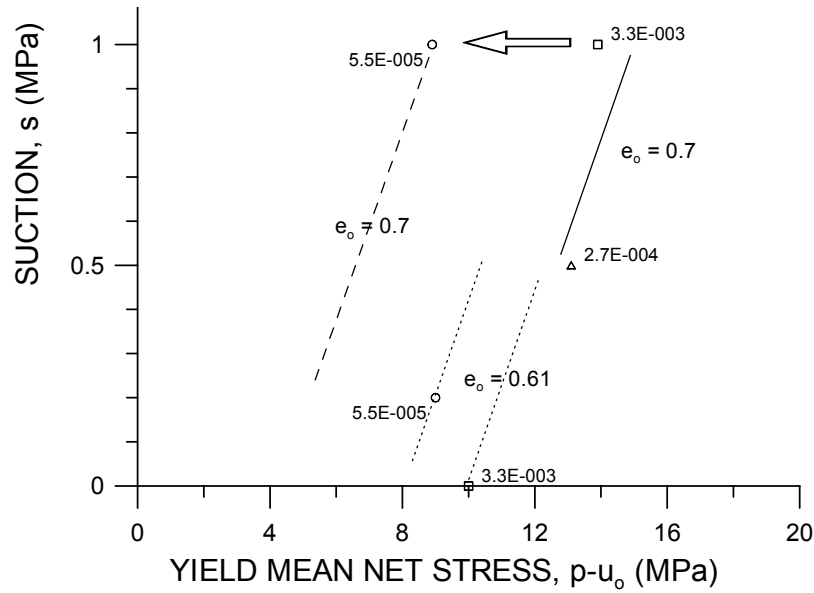
#### Suction controlled isotropic compression tests

Typical results of three isotropic compression tests are presented in Fig. II-19. The loading program imposed for each of the tested chalk specimens is shown in Fig. II-19a. Increasing confining pressure up to yield was applied at slow or fast rate. Isotropic compression test results are presented in Fig. II-19b. Within the natural variability of the outcrop block porosity, two main "families" of void ratios are distinguishable, namely:  $e_o \cong 0.6$  (denser samples) and  $e_o \cong 0.7$  (looser samples). Both suction effects and loading rate effects are legible: at a given suction, the higher the loading rate, the higher is the mean total stress at yield (e.g. arrows on test curves T4 and T5) and the stiffer is the elastic response of the material. On the other hand, increasing suction induces a progressive passage from a "water-like" behaviour to a "oil-like" behaviour. Generally this corresponds to a stiffer response in the elastic regime (e.g. test T2 and T4), an increase of the mean total stress at yield (see arrows on test curves T2 and T4, Fig. II-19b) and a more pronounced transition from elastic to elastic-plastic regime when yielding occurs. These observations are summarised in Fig. II-20 in terms of mean net stress values at yielding and bulk modulus values, respectively.

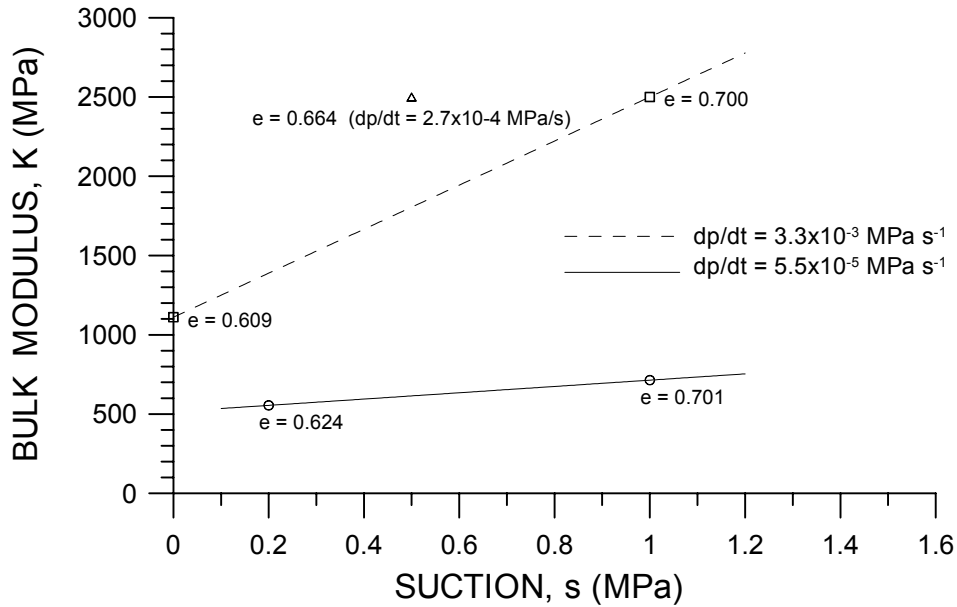


(b)

Figure II-19. Typical results of isotropic triaxial compression tests: (a) loading program, (b) test results



(a)



(b)

**Figure II-20.** (a) variation of mean net stress at yielding (preconsolidation stress) with suction and loading rates, (b) variation of bulk modulus with suction and loading rates

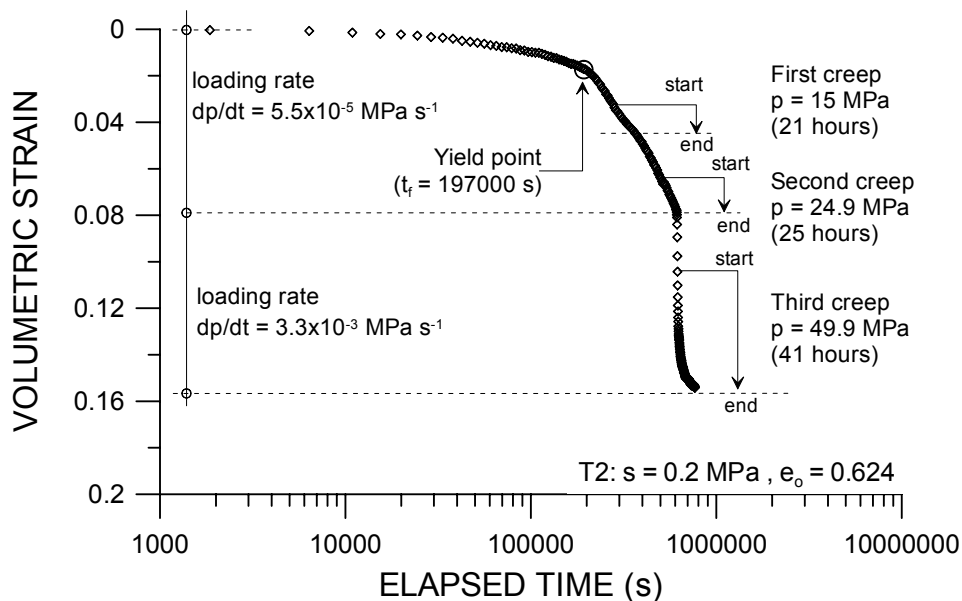
In this respect, we draw reader's attention to the influence of the porosity on the test results. In fact, from the experience on this chalk, the difference in mean total stress at yielding between the two extreme limits of "oil-like" state and "water-like" state should be more pronounced than what is observed (about 6 MPa, cf. Fig. II-19b). Unfortunately, sample at low suction level is also the denser, hence suction effects are partially hidden by the increasing stiffness due to the reduced compressibility of the material. It is worth noting that the results in Fig. II-20a confirm the approach proposed by Alonso *et al.* (1990) for unsaturated soils, where the change in yield stress with suction allows to define the LC (Loading Collapse) curve. This approach will be developed further in this report, in Section III (Constitutive Modelling).

### Loading rate effects

The effect of the loading rate on the mean net stress at yielding and on the bulk modulus has been introduced in discussing results in Fig. II-20.

Since no measurements of water and oil pore pressures were performed during the tests, some conjectures arise on whether all these tests can be considered fully drained or not depending on the loading rate. Based on a classical approach following Terzaghi's consolidation theory, De Gennaro et al. (2003) defined a limit (maximum) value of the volumetric strain rate of about  $3 \times 10^{-7} \text{ s}^{-1}$  to admit fully drained conditions (no excess pore pressure) during the tests. The limit of such an approach has been discussed in section II.3.1 (oedometric CRS tests). In particular, oedometric tests on dry samples showed that within the same range of volumetric strain rates, yield stress was rate sensitive, independently of the presence of the saturating fluid (Fig. II-18).

The sensitivity of the tests upon the loading rate is also illustrated via the evolution of the volumetric strain versus time for test T2 (Fig. II-16). Change in volumetric strain rate during this test occurs at yield and sometimes passing from a loading phase to a creep phase. Considering for instance the branch of the curve after the yield point. It is likely that the induced volumetric strain rate under a mean total stress  $p$  which is continuously increasing is equal to the volumetric strain rate during the first two creep phases, where  $p$  is constant. Oppositely, the passage from the second creep to reloading at fast rate induces a bright change in the volumetric strain rate.

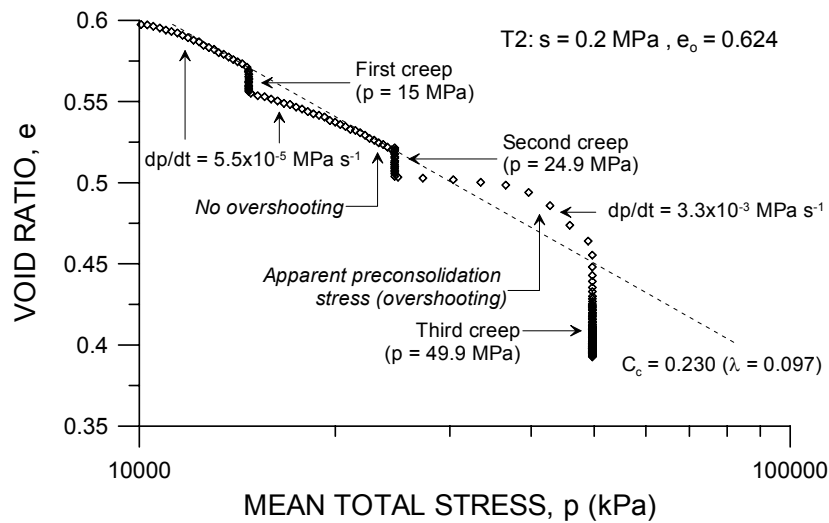


**Figure II-16.** Volumetric strain variation for isotropic triaxial tests on Lixhe chalk

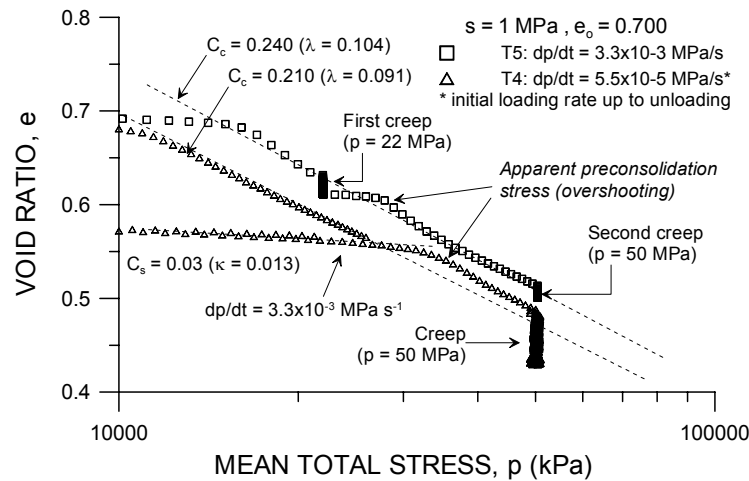
The existence of such a behaviour for Lixhe chalk is confirmed by the results shown in Fig. II-17, which gives some details of the isotropic compression tests already presented in Fig. II-19b. During test T2 (Fig. II-17a), performed at initial slow loading rate, a first creep phase of about 21 hours has been allowed to develop after the yield point, under a constant mean total stress of 15 MPa. After that, a second loading phase at same slow rate has been run. As it can be observed, the reloading curve rejoins the original initial loading curve without any temporary overshooting of the apparent preconsolidation stress. It is a type of behaviour very similar to the temporary strengthening of the links of the clay structure (Bjerrum 1967), most geotechnical engineers could be aware of. Time effect could lead to the development of additional strength related to a chemo-mechanical coupling associated to the

precipitation of cementing agents like calcite. The importance of chemistry on the mechanical behaviour of chalk has been recently emphasised by Hellmann and co-workers (Hellmann et al. 2002a, Hellmann et al. 2002b). Therefore the results presented herein seem to corroborate the idea that chemistry could play an important role in characterising the time-dependent behaviour of chalk. After the reloading which follows the first creep phase, a second creep phase (at 24.9 MPa) and a new reloading at faster rate ( $3.3 \times 10^{-3} \text{ MPa s}^{-1}$ ) were done. In this case the response of the sample is quite different, and a clear overshooting of the apparent preconsolidation stress can be observed, associated to the fast loading. Finally the reloading curve rejoins the original initial loading curve at higher stresses before the beginning of the third creep.

By comparison between test T2 and T5 (Fig. II-17) it is evident that the temporary increase of the apparent preconsolidation stress upon reloading after creep is associated to the faster loading rate. This is corroborated by the results of test T4 (Fig. II-17b), where the apparent preconsolidation stress overshooting follows an unloading phase. As a concluding remark, based on the values obtained for the coefficients of compressibility  $C_c$ , it is possible to recognise that the effect of the loading rate on the overall compressibility of the chalk seems to be negligible (i.e. nearly constant  $C_c$  values).



(a)



(b)

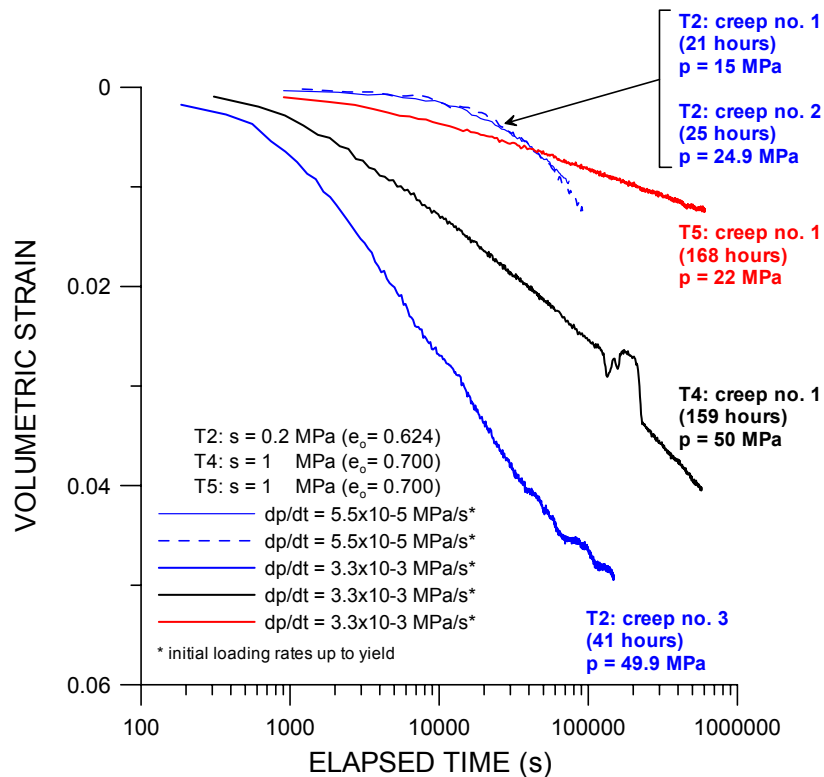
**Figure II-17.** Volumetric strain variation for isotropic triaxial tests on Lixhe chalk

*Creep effects*

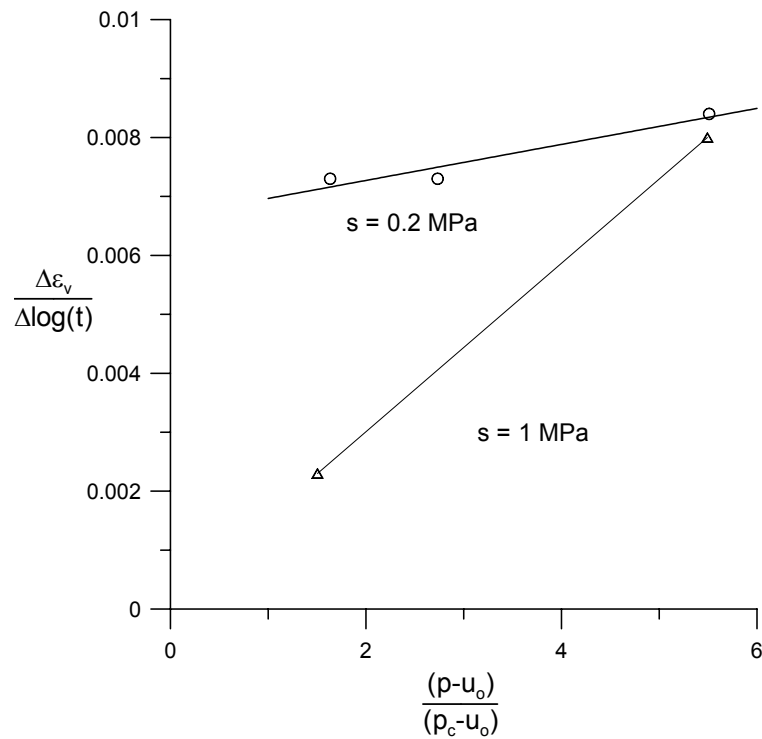
The evolutions of creep phases of Lixhe chalk at various suction levels and constant mean total stresses are summarised in Fig. II-18a. Results are presented in terms of volumetric strain versus time in log scale. Various trends are depicted, it can be observed that:

- for creep test at low stress levels (approximately when  $p < 25$  MPa) volumetric strain curves increase smoothly with increasing time;
- high stress levels change the shape of the curve, inducing at the beginning of the test a rapid increase in the volumetric strain;
- at same applied stress levels the higher the suction, the lower is the amount of induced volumetric strain (e.g. tests T2 and T4 at  $p \cong 50$  MPa).

The effect of the suction level on the evolution of creep phases is presented in Fig. II-18b. Values of the slope of the final branch of the creep curve as a function of the mean net stress normalised with respect to the mean net stress at yield are presented. The amount of volumetric strain rate increases when suction decreases. Whereas at same suction level the volumetric strain rate increases when the stress ratio  $(p-u_0)/(p_c-u_0)$  increases.



**Figure II-18.** (a) Analysis of creep phases on Lixhe chalk at various suction levels



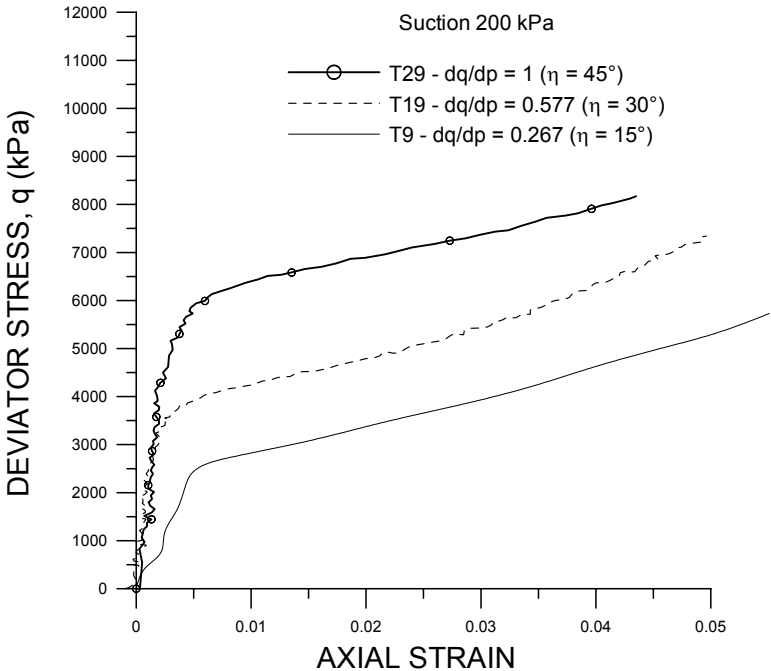
**Figure II-18.** (b) Analysis of creep phases on Lixhe chalk at various suction levels

#### Suction controlled deviatoric compression tests

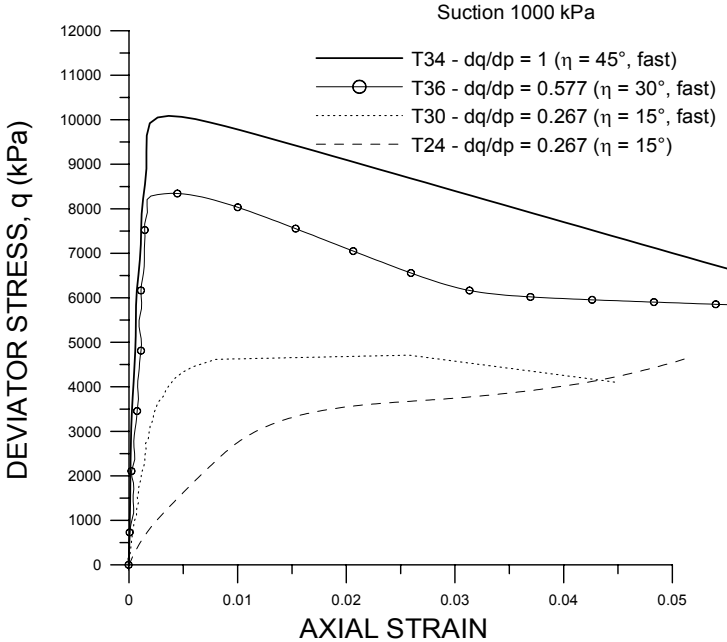
Results of deviatoric compression tests performed at different loading rates are presented in Fig. II-18 and II-19. Results refer to tests performed following proportional stress paths (i.e.  $dq/dp = \text{constant}$ ) and focus on the effect of suction and loading rate.

##### *Suction and loading path effects*

Like during isotropic compression tests, the value of the yield deviator stress is suction dependent. A comparison can be done between the deviator stress at yielding during tests T9 (Fig. II-19a,  $s = 200$  kPa) and test T24 (Fig. II.14b,  $s = 1000$  kPa), a suction increase strengthens the chalk.



(a)



(b)

**Figure II-19.** Typical results of deviatoric compression tests: (a) tests at slow loading rate, (b) tests at slow and fast loading rates

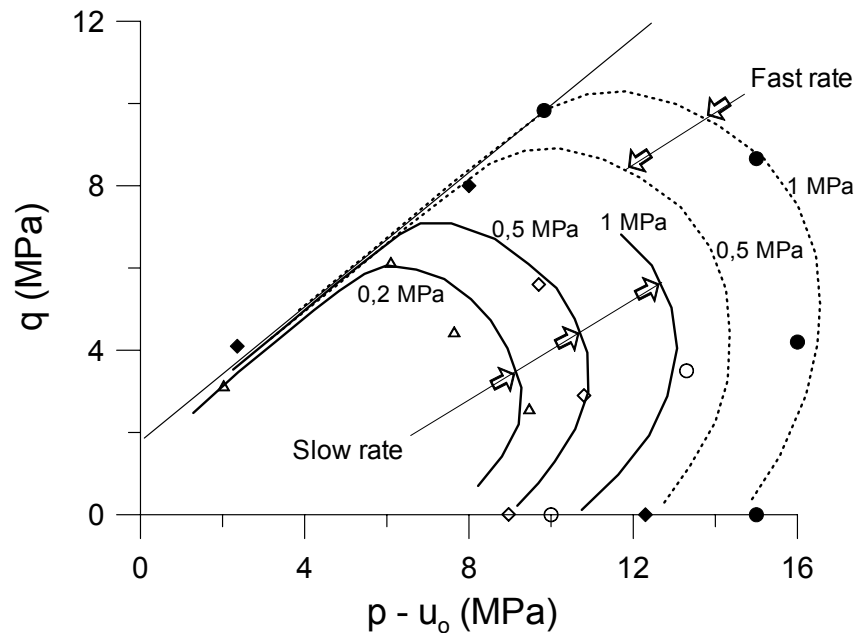
As shown in Fig. II-19a, it also evident that chalk shear resistance increases when the proportional path approaches  $45^\circ$  ( $dq/dp = 1$ ), in accordance with the progressive increase in mean net stress.



### Loading rate effects

At a given suction level, the higher the loading rate, the higher is the deviator stress at yielding and the stiffer is the elastic response of the material (tests T24 and T30, Fig. II-19b). Furthermore, it seems likely that the effect of the loading rate affect significantly the type of induced failure: brittle failures seem to be associated to fast loading rates (Fig. II-19b), whereas slow loading rates show a relatively stable behaviour with increasing values of deviator stress at large axial strain (Fig. II-19a and test T24 in Fig. II-19b).

A summary of the effects of previous parameters on the chalk strength is given in Fig. II-20, where the yield loci at various suction levels and different loading rates are presented. Again, high loading rates seem to expand the elastic domain of the material, in a way similar to that observed by Graham *et al.* (1983) on less sensitive plastic soft clays.



**Figure II-20.** Typical results of deviatoric triaxial compression tests: tests at slow loading rate, tests at slow and fast loading rates

### II.3.4 Chalk fluid interaction

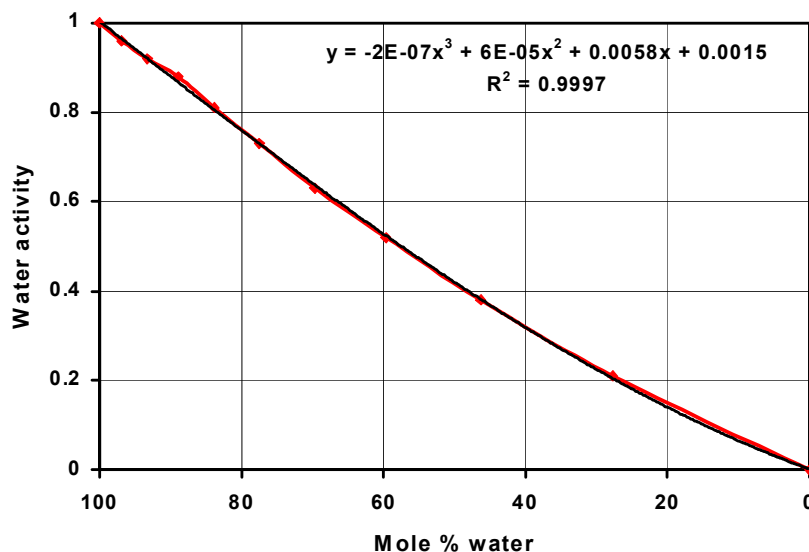
This aspect has been studied by the Stavanger College (Prof. R. Risnes) who jointed the partnership on behalf of Total Exploration Norway. These studies give a new perspective on the physico-chemical interaction that produce the "suction". Initially, "suction" was considered as mainly produced by capillary effects. The experiments performed (Risnes et al. 2002) with a fluid that is miscible with water (glycol) and with different brines show the response of the mechanical behaviour of chalk to changes in chemical composition of the saturated fluid.

To address this problem, several series of tests have been performed with glycol (ethylene-glycol) and high concentration brines as saturating fluids.

There are three properties that make ethylene glycol an interesting fluid in the study of chalk behaviour : in many aspects it resembles oil, it will hardly dissolve calcite and it is fully miscible with water. The first property allows to compare with the results obtained on Soltrol saturated samples, the second property makes it possible to neglect any chemical reaction, while the latter assures no capillary effects if some water should remain in the chalk before saturation. These properties are also shared with fluids like methanol, and methanol-saturated chalk has been shown to be stronger than water-saturated chalk (Risnes & Flaageng 1999)

Compared to dry chalk, both oil and glycol make the chalk somewhat weaker, but this weakening effect is much less than with water.

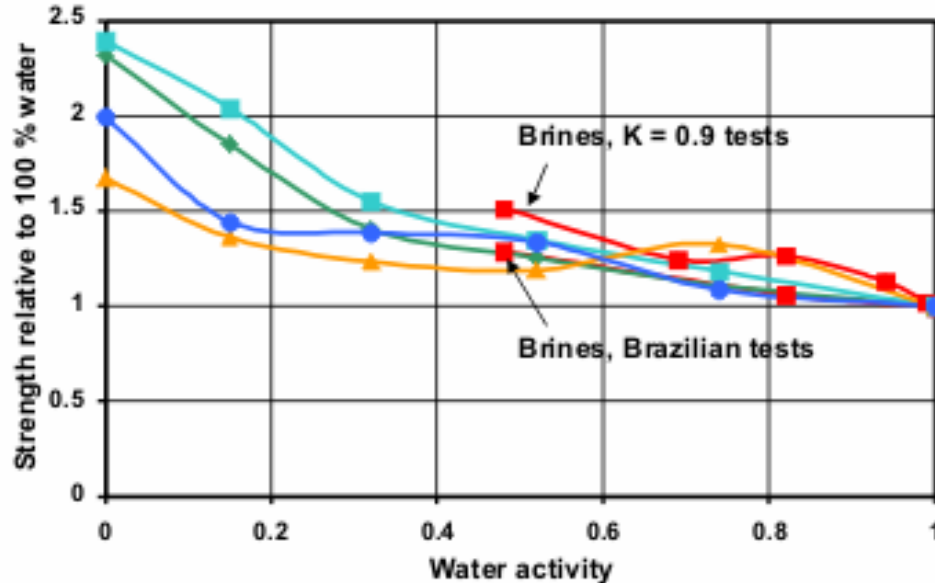
For the interpretation of the results in physico-chemical terms, the parameter "activity" has been chosen. The figure II-21 shows the variation of this parameter as a function of glycol concentration.



**Figure II-21.** Water activity in water-glycol mixtures (Risnes et al. 2002)

On the other hand, several series of tests with brines with high concentrations of calcium chloride or sodium chloride show that the water-weakening effect is considerably reduced in high ionic strength solutions. Most tests were performed as quasi- hydrostatic tests, with a constant stress ratio of 0.9. In such tests the yield point marks the onset of accelerated pore collapse, and the yield value is close to the hydrostatic yield stress. In addition to these compressive tests, a series of Brazilian tests were performed, revealing the same trend. The variations in mechanical strength have been correlated with the activity of water in the brines (ranging from 0.4 to 1).

Within the experimental accuracy of the compressive tests, there is a linear trend between reduction of water activity and the corresponding increase in strength as shown on figure II-22 where the results of tests with glycol and brines are grouped. The strength is given as a relative value compared to the strength of water saturated chalk. The trend is evident, as well for the glycol mixture (whose activity ranges from 0 to 1) as for the brines (activity ranging from 0.5 to 1).



**Figure II-22.** Relative strength function of water activity (Risnes et al. 2002)

It also can be seen that the relationship is not linear with a change in the slope for the low water content values. Other experiments indicate that there may be a threshold value of around 5 mole % water to mobilize the water weakening effect.

From these experiences with chalk, glycol and brines emerges the hypothesis that the water activity may be a key parameter in the water-weakening mechanism. This suggests that the water-weakening effect is basically a chemical or physico-chemical phenomenon. It could be related to chemical dissolution, and/or to adsorption of water at the chalk surfaces. The assumption that the process of water weakening is largely reversible, indicates that the second mechanism is probably the more important one.

This conclusion also indicates that water weakening may be a special case of general chalk fluid interactions where the degree of weakening depends on the strength of adsorption of the fluid molecules to the calcite surfaces.

The hypothesis of the role of the fluid activity makes the phenomenon more readily accessible to general thermodynamic considerations. Temperature and pressure effects in mechanical properties may be more easily predictable, as fluid and solid skeleton to some extent can be treated separately.

The conclusions of these experiments give a more detailed comprehension of the chemophysical mechanisms that govern the chalk behaviour and show the way for the future researches. On the modelling point of view, the concept of "suction" remain fully valid and is applicable to the modelling of the experiments. The only condition is to establish the relationship between the value of the "suction" and this of the "activity" of the fluids.

## II.4 Conclusions

The experimental work provides the stuff for the construction of the "elasto - visco- plastic law with suction" , the Pasachalk law.

**In a first stage**, the main lines of the model were established carrying experiments at constant loading rate on fully oil or water saturates samples, on one hand, and on the other hand on partially saturated samples, what means at controlled suction level.

This allows to build the Pasachalk model, elasto-plastic (with suction).

**In a second stage**, the problem of the stress-strain time-dependent mechanical behaviour of a multiphase saturated chalk has been studied.

A first set of parameters has been deduced from experiments performed on fully oil or water saturated samples.

Moving from the hypothesis that the mechanical behaviour of a chalk containing a variable proportion of oil and water can be described following the same experimental and theoretical approach proposed for unsaturated soils, the relevant developments allowing for chalk mechanical testing under oil-water suction control have been described. This investigation required a preliminary assessment of the wettability characteristics (retention properties) of Lixhe chalk. This was achieved adopting three methodologies : the osmotic technique, the overpressure method and the mercury intrusion porosimetry. The viability of this approach allowed to define satisfactory the retention properties of the material, the complementary use of the three methodologies has also been demonstrated.

It has been recognised that oil-water suction influences the mechanical response of the material. Increasing suction levels induce stiffer response in the elastic regime, increase the mean total stress at yield and lead to a more pronounced transition from elastic to elastic-plastic regime when yielding occurs.

The new perspective opened by the experiments performed with glycol and brines increase the field of application of the model. The physico-chemo-mechanics is the next step of the research.

As far as time-dependent behaviour is concerned, both affects of loading rate and creep have been considered. The effect of loading rate has been analysed with regards to the multiphase nature of the material tested. The analysis of creep phases under controlled suction conditions indicates that suction influences the evolution of creep. In particular, it has been observed that suction decrease causes increasing volumetric strain rate and a progressive early dominance of creep.

The whole of these results allowed to perform the modelling work that is presented in the next chapters.

### III. CONSTITUTIVE MODELLING

The different experiment presented in the previous part of this report show clearly the time-dependent behaviour of chalk. Indeed, the material response during testing depend on the stress/strain rate: higher the rate is, higher the strength of chalk will be. Moreover, during creep phase (constant stress state path), evolving strains with time appear.

All these phenomena have to be reproduced by a constitutive law. Few models have been already presented in the literature but the originality of our work is to include suction effects into an elasto-visco-plastic model. It is able to reproduce the time-dependent behaviour of chalk saturated either by oil or by water.

Another task has appeared to be necessary during the project, but was not initially planned. The idea is to compare Lagamine code to reservoir simulator (namely ECLIPSE in this case) in order to show the ability of our code to model fluid exchanges in an oil reservoir. This work has been achieved in close collaboration with TotalFinaElf Norway a/s.

#### III.1 Elasto-viscoplastic model

In civil and petroleum engineering, the description of the complex and time-dependent behaviour of soft porous rocks is very important for the understanding of various geomechanical problems, such well bore stability, subsidence and hydraulic fracturing. There are three mains approaches in mathematical modelling of creep or time depending inelastic phenomena [Flavigny *et al.*, 1990] :

- Empirical flow laws or formulation of creep laws simply describing in analytical form the observed experimental results;
- Rheological model;
- Constitutive laws describing the behaviour of the soil in principle and under any possible loading conditions.

The basic limit of empirical flow laws is that the proposed equations are valid only for the stress conditions identical to those of the test from which they have been derived. Without further hypotheses they are not applicable for more general loading conditions. Models using rheological elements help to give a better understanding of viscoplastic behaviour [Dusseault *et al.*, 1993]. However, these models have deficiencies, because they do not account for shear and normal stress and intrinsic structure. Only models for soft porous rocks based on the last approach will be discussed in the general overview.

##### III.1.1 General overview

Among continuum mechanics based mathematical models for rocks time dependent behaviour, the following main approaches may be distinguished:

(A) : general constitutive equation theory, proposed by Critescu first for low porosity rocks (Critescu *et al.* 1998), and adapted for chalk in (Dahou *et al.* 1990) and (Datcheva 2001). In this theory, strains are divided into two parts:

$$\underline{\dot{\epsilon}} = \underline{\dot{\epsilon}}^e + \underline{\dot{\epsilon}}^{vp} \quad (\text{III-1})$$

where

$$\underline{\dot{\sigma}} = \underline{C}^e (\underline{\dot{\epsilon}} - \underline{\dot{\epsilon}}^{vp}) \quad (\text{III-2})$$

$$\underline{\dot{\epsilon}}^{vp} = k \left\langle 1 - \frac{W^I(t)}{H(p,q)} \right\rangle \frac{\partial F}{\partial \underline{\sigma}} \quad (\text{III-3})$$

$F$  is the creep potential function,  $W^I(t)$  is the irreversible stress work and  $H(p,q)$  loading function such that:

$$H(p,q) = W^I(t)_{t \rightarrow \infty} \quad (\text{III-4})$$

(B) : argotropy models, for example see [Chambon *et al.*, 1994] and, in particular for chalk [Shao *et al.*, 1993]. Argotropy means rate-dependence [Kolymbas, 1991], i.e. non invariance of the stress with respect to the changes of time scale of deformation history. Related to hypoplasticity, in order to describe argotropy, rate-independent evolution equation must be extended by terms containing the strain tensor  $\underline{\epsilon}$ . The following general form is proposed [Kolymbas, 1991]:

$$\underline{\sigma}^\circ = h(\underline{\sigma}, \underline{\dot{\epsilon}}, \underline{\pi}) + g(\underline{\sigma}, \underline{\dot{\epsilon}}, \underline{\ddot{\epsilon}}, \underline{\pi}) \quad (\text{III-5})$$

(C) : Perzyna's viscoplasticity – a modification of plasticity models introducing time-rate flow rule employing a plastic yield function [Katona, 1992], [Shao *et al.*, 1993]:

$$\underline{\dot{\epsilon}} = \underline{\dot{\epsilon}}^e + \underline{\dot{\epsilon}}^{vp} \quad (\text{III-6})$$

$$\underline{\dot{\sigma}} = \underline{C}^e (\underline{\dot{\epsilon}} - \underline{\dot{\epsilon}}^{vp}) \quad (\text{III-7})$$

The irreversible strain may be described as normal to some potential  $g$ :

$$\underline{\dot{\epsilon}}^{vp} = \gamma \langle \phi(f) \rangle \frac{\partial g}{\partial \underline{\sigma}} \quad (\text{III-8})$$

$\gamma$  is the fluidity parameter,  $\phi$  is the viscous flow potential,  $g$  is the creep potential and  $f$  is any valid plasticity function playing the role of loading surface.

### III.1.2 Presentation of the Pasachalk model

During the first research phase PASACHALK 1, attention was focused on the elastoplastic behaviour of a partly saturated chalk. The cap model developed in the PASACHALK 1 project takes into account of the chalk compaction thanks to the CamClay – critical model concepts, and to frictional behaviour thanks to a Mohr – Coulomb like model. Partly saturated state induces capillary pressures or suction. Their influence on the mechanical behaviour is modelled thanks to the Barcelona concepts, developed by [Alonso *et al.*, 1990], in a series of models for unsaturated clays.

Different strategies have been proposed in the literature for elasto-visco-plasticity constitutive modelling. However, the important results obtained during the first PASACHALK project should be a basis for our new developments. Based on these ideas, it has been decided to use the Perzina constitutive models framework for our developments. The idea is to use the yield surfaces of an elastoplastic model in the definition of potential surfaces for the description of

viscous effects, whose amplitude is depending on the stress point distance to the potential surface.

The Perzyna's elastic viscoplastic theory has been thus adopted based on the following motivations:

- the formulation is well accepted and well used;
- the generality of the time-rate flow rule offers the capability of simulating time-dependent behaviour over a wide range of loading;
- it gives a possibility to take advantage of the inviscid multisurface cap-failure-tension model, developed for elastoplasticity modelling ;
- the formulation is readily adaptable to a numerical algorithm suitable for finite element procedure.

This approach has been adopted, because it is probably the most understandable for geomechanicians mainly involved in elastoplasticity. Moreover, it allows us to develop the new constitutive model on the basis of preceding works done in PASACHALK 1, and so to ensure continuity in our work. The yield surface of this first model is compound of three models:

#### 1. Cam-Clay pore collapse model

The Cam-Clay yield surface is defined by the following expression:

$$f_1 \equiv II_{\hat{\sigma}}^2 + m^2 \left( I_{\sigma} + \frac{3c(s)}{\tan \phi_C} \right) (I_{\sigma} - 3p_0) = 0 \quad (\text{III-9})$$

where  $c$  is the cohesion,  $\phi_C$  is the friction angle in compression path,  $p_0$  is the preconsolidation pressure which defines the size of the yield surface, and  $m$  is a coefficient introduced to take into account the effect of the third stress invariant. The coefficient  $m$  is defined by:

$$m = a(1 + b \sin 3\beta)^n \quad (\text{III-10})$$

where the parameters  $a$ ,  $b$  and  $n$  must verify some convexity conditions (Van Eekelen, 1980). Assuming associated plastic flow, the preconsolidation pressure  $p_0$  is related to the volumetric plastic strain  $d\varepsilon^{vp}$  following the kinematic equation:

$$dp_0 = \frac{1+e}{\lambda - \kappa} p_0 d\varepsilon_v^p \quad (\text{III-11})$$

where  $\lambda$  is the compression coefficient and  $\kappa$  is the elastic coefficient. Expression (III-11) allows us to account for both hardening or softening according to the sign of the volumetric plastic strain. However, in the cap model, the softening zone will not be considered. On the other hand, it should be noted that the irreversible volumetric strain includes the coupled effect of mechanical and suction changes.

## 2. Internal friction model

In order to formulate a friction model based on a Mohr-Coulomb type failure criterion with a smoothed plastic surface, the Van Eekelen's (1980) formulation has been adopted. The latter is based on a modification of the Drucker-Prager's failure cone, by introducing a dependence on the Lode's angle  $\beta$ . With this assumptions, the failure criterion can be written as:

$$f_2 \equiv II_{\dot{\sigma}} - m \left( I_{\sigma} + \frac{3c}{\tan \phi_C} \right) = 0 \quad (\text{III-12})$$

As for the cap model (Cam-Clay), associated plasticity is considered also for the friction model.

## 3. Suction effect on yield surface (BBM model)

Several phenomena are usually evidenced for unsaturated soils:

- The preconsolidation pressure  $p_0$  and the material stiffness increase with suction. In BBM (**B**arcelona **B**asic **M**odel - Alonso et al., 1990), this is described by the *LC curve*, which formulation has been adapted for chalk material:

$$p_0(s) = p_0(0) + \Delta p_0 \frac{s}{s + s^*} \quad (\text{III-13})$$

where  $p_0(0)$  is the preconsolidation pressure for  $s = 0$ ,  $\Delta p_0$  is the variation of  $p_0$  between water and oil saturated sample, and  $s^*$  is a parameter controlling the shape of the *LC curve*.

- Cohesion increases with suction, this is modelled using Eq. (19). The influence of suction on friction angle depends on the material studied. Experiment on chalk shows that friction angle is independent of the saturating fluid.

$$c(s) = c(0) + k s \quad (\text{III-14})$$

where  $k$  is a material constant,  $c(0)$  is the cohesion at water saturated state.

## 4. Mechanical elastoviscoplastic model

As it has been shown, viscous effects in chalk may be relevant during triaxial tests performed at various stress rates and involving creep stages. Time-dependent behaviour modelling of chalk is here introduced based on the elastoviscoplastic approach proposed by Perzyna (1964).

Hence, the strains are divided in reversible and irreversible parts (related mechanical and suction loading):

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^{m,e} + \dot{\epsilon}_{ij}^{s,e} + \dot{\epsilon}_{ij}^{m,vp} + \dot{\epsilon}_{ij}^{s,p} \quad (\text{III-15})$$

During the PASACHALK 1 project, it has been observed that suction variations do not evolve permanent strains. Moreover, it is assumed that reversible strain related to suction are not time-dependent. The following relationship is taken [Alonso *et al.*, 1990]:

$$\dot{\epsilon}_{ij}^{s,e} = \frac{\kappa_s}{(1+e)} \frac{\dot{s}}{(s + p_{at})} \delta_{ij} = h_{ij}^e \dot{s} \quad (\text{III-16})$$



The stress increment can thus be expressed as follow:

$$\underline{\dot{\sigma}} = \underline{C}^e(s) (\underline{\dot{\varepsilon}} - \underline{\dot{\varepsilon}}^{s,e} - \underline{\dot{\varepsilon}}^{m,vp}) \quad (\text{III-17})$$

The irreversible strain may be described as normal to some potential  $g$ :

$$\underline{\dot{\varepsilon}}^{m,vp} = \gamma \langle \phi(f) \rangle \frac{\partial g}{\partial \underline{\sigma}} \quad (\text{III-18})$$

This formulation is rather similar to the elastoplastic one, but it is not based on the consistency condition. The amount of strain rate is described with respect to a reference surface  $f$ , similar to the yield surface. Then, we may define two irreversible mechanisms, one dedicated to the pore collapse, the second to the friction failure.

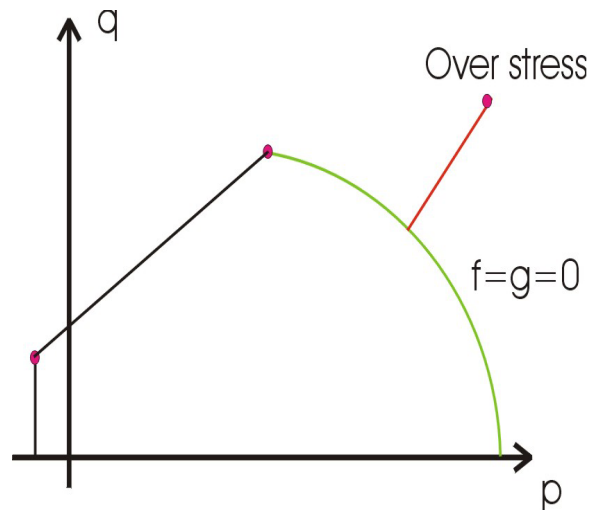
Concerning the pore collapse mechanism, the creep potential is based on the following equations:

$$\langle \phi_c(f_c) \rangle = \left( \frac{f_c}{3p_0^2} \right)^{\alpha_c} \quad (\text{III-19})$$

and (Shao *et al.*, 1993):

$$\gamma = \omega \left( \frac{I_\sigma}{p_a} \right)^i \quad (\text{III-20})$$

where the reference surface  $f_c$  is similar to the yield surface of the Pasachalk model (III-9). The function  $f_c$  may here be analysed as an overstress, or a measure of the amount of the stress state going outside the yield or reference surface. Moreover, the overstress is only positive when the stress state is outside the yield – reference surface (Fig. III-1). As the Macaulay's brackets are used in equations (III-18) and (III-19), the irreversible strains exist only in this peculiar situation. The more the overstress, the more is the irreversible strain rate. Obviously, a hardening rule has to be defined, and the plastic hardening rule (III-11) is here adopted. For the friction failure, a similar development may be considered and implemented without major difficulties.



**Figure III-1.** Overstress with respect to the reference surface

### III.2 Verification of the model

The constitutive model is developed but we have now to determine its parameters and validate the law against some numerical modelling of experiment. Thanks to all the tests performed during the two PASACHALK projects, a very important experimental database has been achieved and allows us to determine all the parameters of the model.

The validation of the constitutive relationship has been performed by modelling some complex loading path experiment. These tests are composed of different stress rates loading path and some creep phases.

#### III.2.1 Definition and determination of model parameters

In the PASACHALK model, only the irreversible behaviour is time-dependent. That means that the elastic moduli determined during the previous project are still consistent. In the table 1 are recalled the values of the moduli defining the Hook's law.

	<i>Water</i>	<i>Oil</i>
$K$ [MPa]	612	726
$G$ [MPa]	500	700
$E$ [MPa]	1180	1590
$\nu$ [-]	0.18	0.14

**Table III-1.** Mean elastic parameters

In the model, elastic parameters are suction dependent. The following expression have been chosen for the cubic and shear moduli:

$$K(s) = K_0^{eau} + k_s \cdot s \quad (\text{III-21})$$

$$G(s) = G_0^{eau} + g_s \cdot s \quad (\text{III-22})$$

where  $k_s$  and  $g_s$  are determined up to values given in the upper table and are equal to 38 and 66,67 respectively.

The parameter defining the yield surface of the elasto-plastic model are given in the following table to remind you the size of the elastic domain in an elasto-plastic framework for a stress rate of  $10^{-3}$  MPa/s.

	Water	Oil
Friction angle $\phi$ [°]	22	22
Cohesion $c$ [MPa]	1,5	2,0
Pre-consolidation $p_0$ [MPa]	10	21
Compressibility index $\lambda$	0,195	0,195

**Table III-2.** Yield surface parameters of the elasto-plastic model

The viscous parameters concern mainly the pore collapse mechanism because the failure criterion is assumed to be time-independent. That means that we have to determine the viscous parameters  $\gamma$  (fluidity parameter), the reference surface  $f_c$  and the exponent  $\alpha$  of visco-plastic strain relation. Experiment have shown that pre-consolidation pressure  $p_0$

depends directly on the stress-rate. This relation is not defined directly in the model : this effect (of rate dependence) comes as a result of the visco-plastic formulation we have chosen. First of all, we have to define the reference surface related to the pore collapse mechanism. This reference surface represents the elasto-plastic yield surface you should define based on a hypothetical experiment with an infinitely low rate. The other viscous parameters have been determined by trial and error in order to fit the hydrostatic experiment on saturated (oil and water) chalk.

As shear failure is assumed to be time independent, only the preconsolidation pressure of the pore collapse reference surface has to be adapted. The final value of all the parameters are given in the table 3. Surprisingly, it is not necessary to chose different values of viscous parameters ( $\alpha, \omega, \iota$ ) for oil or water saturated samples. Suction influence is taken into account on the preconsolidation pressure only.

	Water	Oil
Pre-consolidation $p_0$ [MPa]	2	5
Parameter $\alpha$	5	5
Parameter $\omega$	$5,1 \cdot 10^{-7}$	$5,1 \cdot 10^{-7}$
Parameter $\iota$	0,0	0,0

**Table III-3.** Viscous parameters of the model

For intermediate saturation degree, we assume to keep the same shape for the *LC curve* than the one used previously in the elasto-plastic model. We use thus the following relationship:

$$p_0(s) = p_0(0) + \Delta p_0 \frac{s}{s + s^*} \quad (\text{III-23})$$

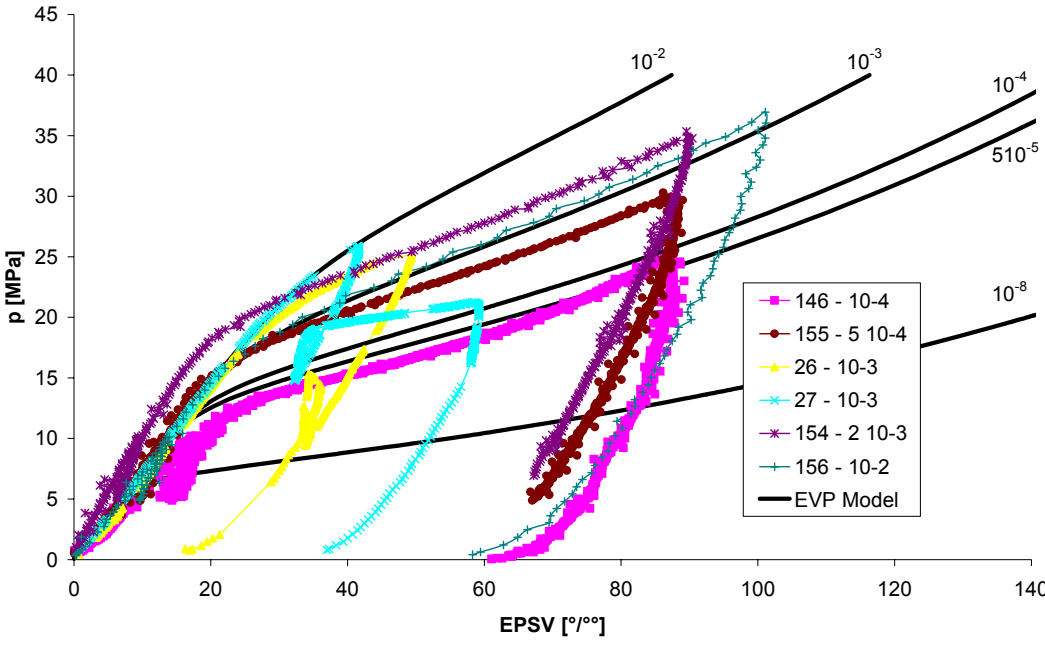
where  $\Delta p_0 = 3$  MPa,  $p_0(0) = 2$  MPa et  $s^* = 0.2$  MPa. It is important to notice that we have kept the same value of the compressibility index  $\lambda$  for the definition of the hardening law in the viscoplastic model.

### III.2.2 Laboratory test modelling

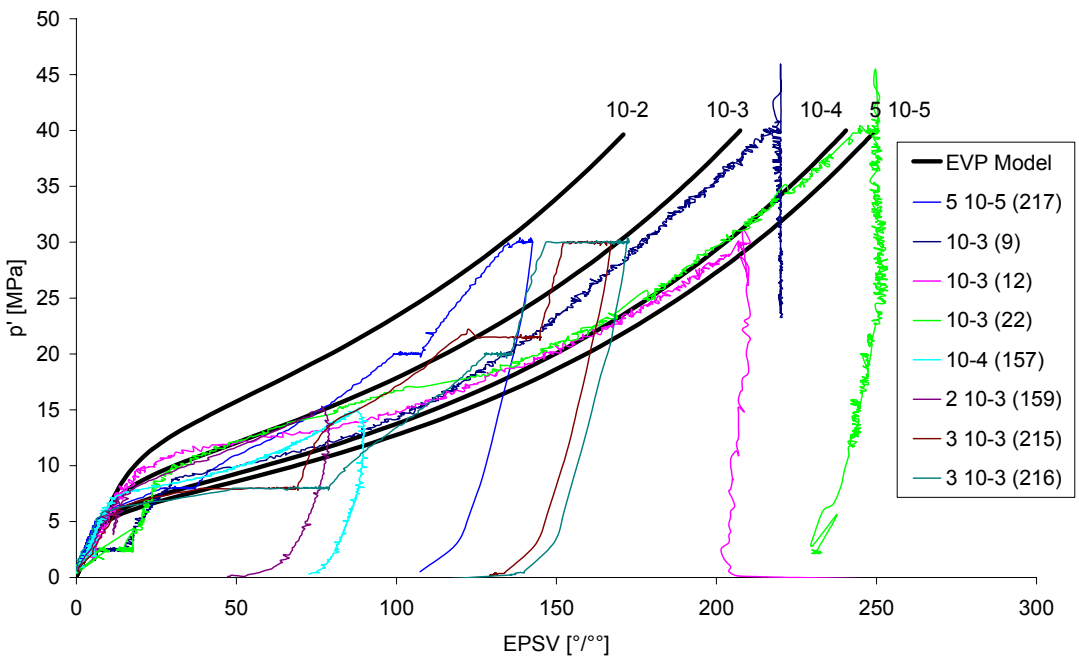
In the experimental part of this report, numerous results of experimental testing have been presented: isotropic and triaxial tests on saturated chalk (water or oil) or suction controlled experiment.

We present here some of laboratory tests modelling: first isotropic stress rate controlled experiment (on saturated chalk). These experiments have allowed us to calibrate to constitutive law. Secondly, we have modelled a complex loading path test. It is composed of three parts : a stress rate controlled loading, then a creep phase and eventually a stress rate controlled loading.

Finally we have also modelled a De Wall experiment in order to show the ability of the constitutive law to represent qualitatively experimental results on this kind of loading path. De Wall model assumes the existence of a unique loading curve for a given stress rate loading. Moreover, when one increases the loading rate starting from a given point of a loading curve, the material response tends to the curve corresponding to the higher stress rate. In the opposite way, when one performs a creep phase (coming from a loading curve at a given stress) and then a loading path at a lower stress rate, the chalk behaviour tends to the loading curve corresponding to this new stress rate.



(a) (b)  
**Figure III-2.** Isotropic tests at different stress rate : Oil saturated sampl



**Figure III-3.** Isotropic tests at different stress rate : Water saturated samples.

In Figures III-2 and III-3 are plotted the experimental curves of saturated samples for different stress rates. Even if results are slightly scattered, the model is able to well reproduce the chalk behaviour for both saturation conditions. It is important to notice that these computations have been performed with only one set of parameters for all the cases. That is to say that this constitutive relationship is able to take into account for influence of suction and stress rate at the same time. In figure III-2, a simulation have been plotted, corresponding to an estimated stress rate in the reservoir ( $10^{-8}$  MPa/s).

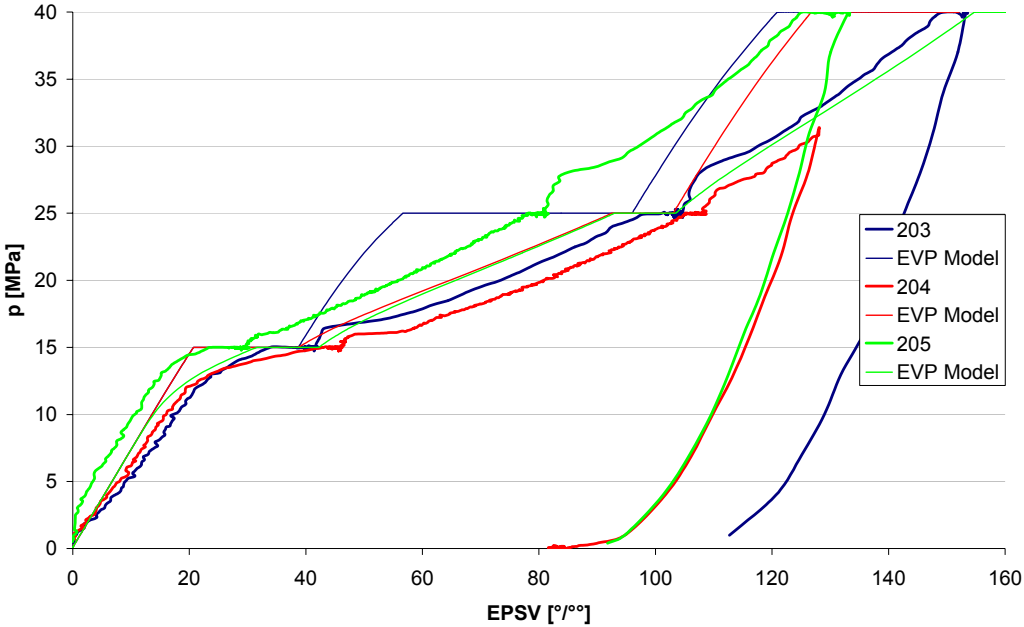


Figure III-4. Complex loading path with creep phase on oil saturated sample.

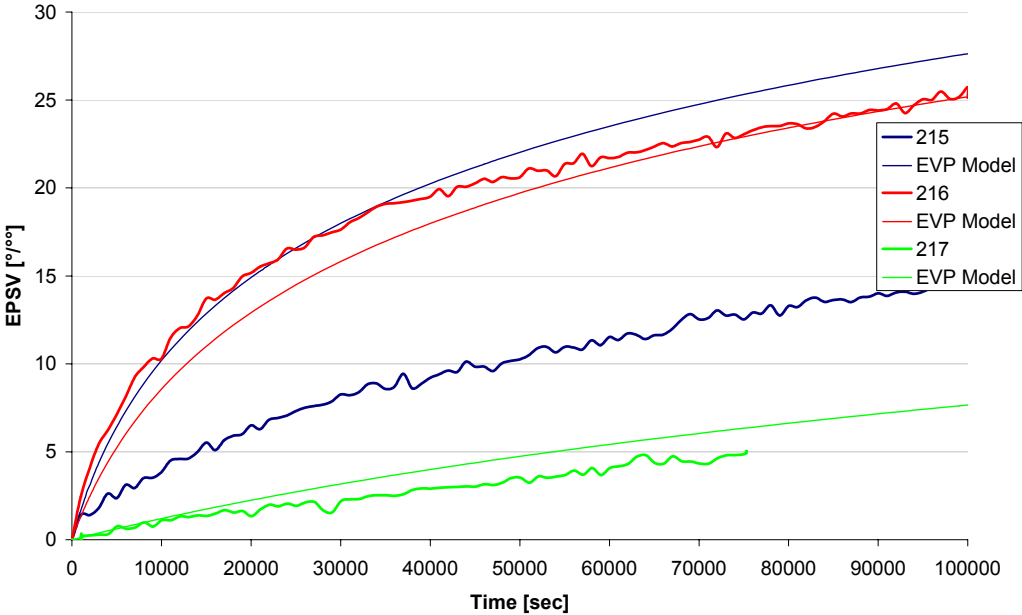
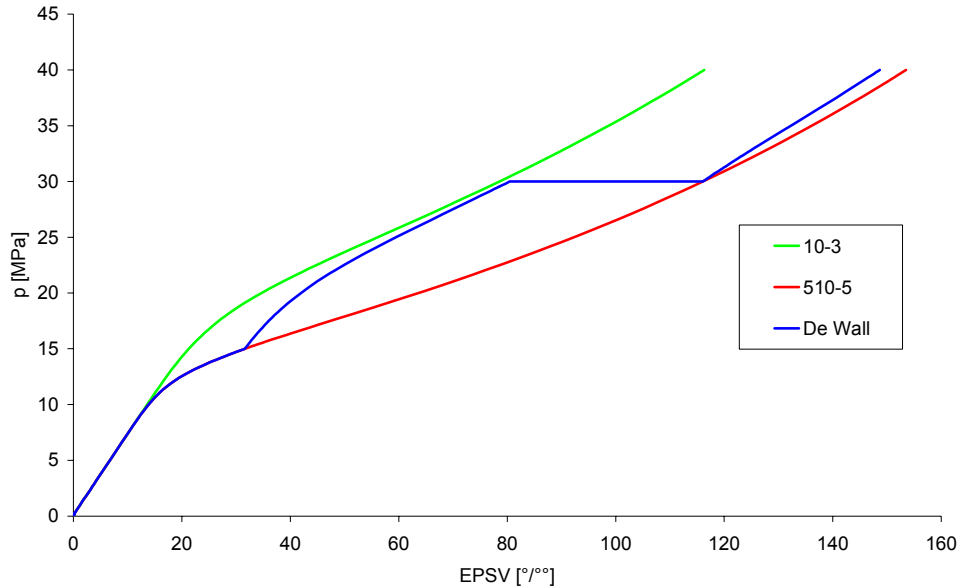
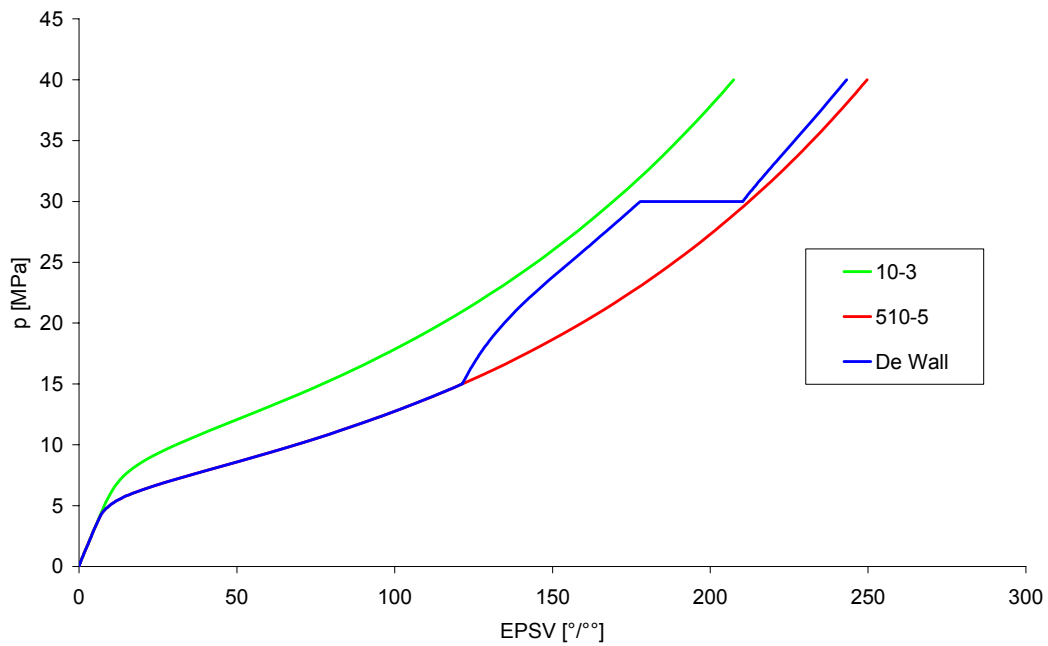


Figure III-5. Creep phase on water saturated sample

In Figure III-4 and III-5, we show the comparison between experiment and numerical modelling for the complex loading path. For oil saturated samples, all the phases of the tests are represented. One can see a qualitative agreement with experimental results even if the scattering of the results is important. For water saturated samples, only one creep phase is represented: we observe a very good agreement between the model and the experiment. Figure III-6 and III-7 confirm the ability of the model to reproduce De Wall model. On these two graphs, the green and the red curves correspond to a stress rate of  $10^{-3}$  and  $5 \cdot 10^{-5}$  MPa/s respectively. The third curve corresponds to the De Wall path.



**Figure III-6.** De Wall loading path on oil saturated sample



**Figure III-7.** De Wall loading path on water saturated sample

### III.3 Applications: reservoir simulation

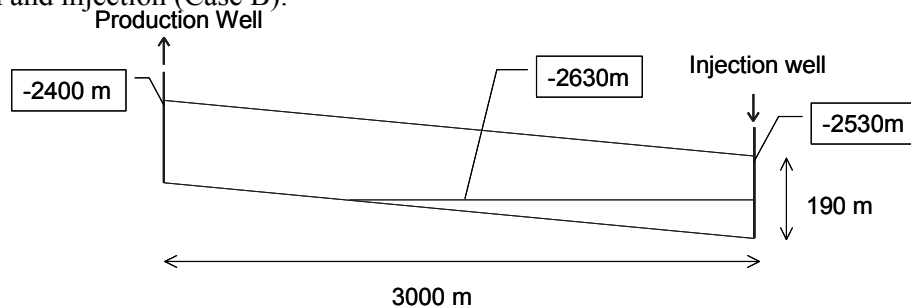
The final objective of Pasachalk 2 is to get a reliable model able to compete with the existing commercial ones. For this, the aim is to understand and to manage the oil field operations, and especially the depletion / injection compaction / subsidence scheme.

A “benchmark”, comparison between the Pasachalk model and the models generally used by the oil companies has been performed, according to the remarks of the Scientific Advisory committee. The idea is to compare ECLIPSE and LAGAMINE simulations results. The work is a highly cooperative one, between TotalFinaElf Norway and Liege University. A number of discussion and of information exchanges have been achieved.

Benchmark are performed on two reservoir models. On one hand, a 2D plane strain multi-layer reservoir is used with one injection and one production well. On the other hand, a 3D reservoir model has been developed in order to compare the results of TFE simulation. This reservoir model is not an academic reservoir : six production wells, two injection wells, five layers with anisotropic properties and complex production scheme.

#### III.3.1 2D Reservoir simulation

A simplified model of a reservoir has been proposed by TotalFinaElf Norway a/s. The model is a simplified 2D model of the Valhall field, taking into account the heterogeneity of the properties of this reservoir and the presence of only two fluids: water and oil. No compaction effects are considered. Two strategies are possible : one case corresponds to a production of 20 years without any injection (Case A) and the second case is performed with simultaneous production and injection (Case B).



**Figure III-8.** Geometry of the 2D reservoir

The reservoir is composed of six layers, which properties are given in table 4. Horizontal permeability is much more higher than vertical one. Moreover, the first layer is approximately 100 times more pervious than the others. The production and injection flows are both equal to 3000 Sm<sup>3</sup>/day (10 MPa and 90 MPa of bottom pressure at production and injection well respectively).

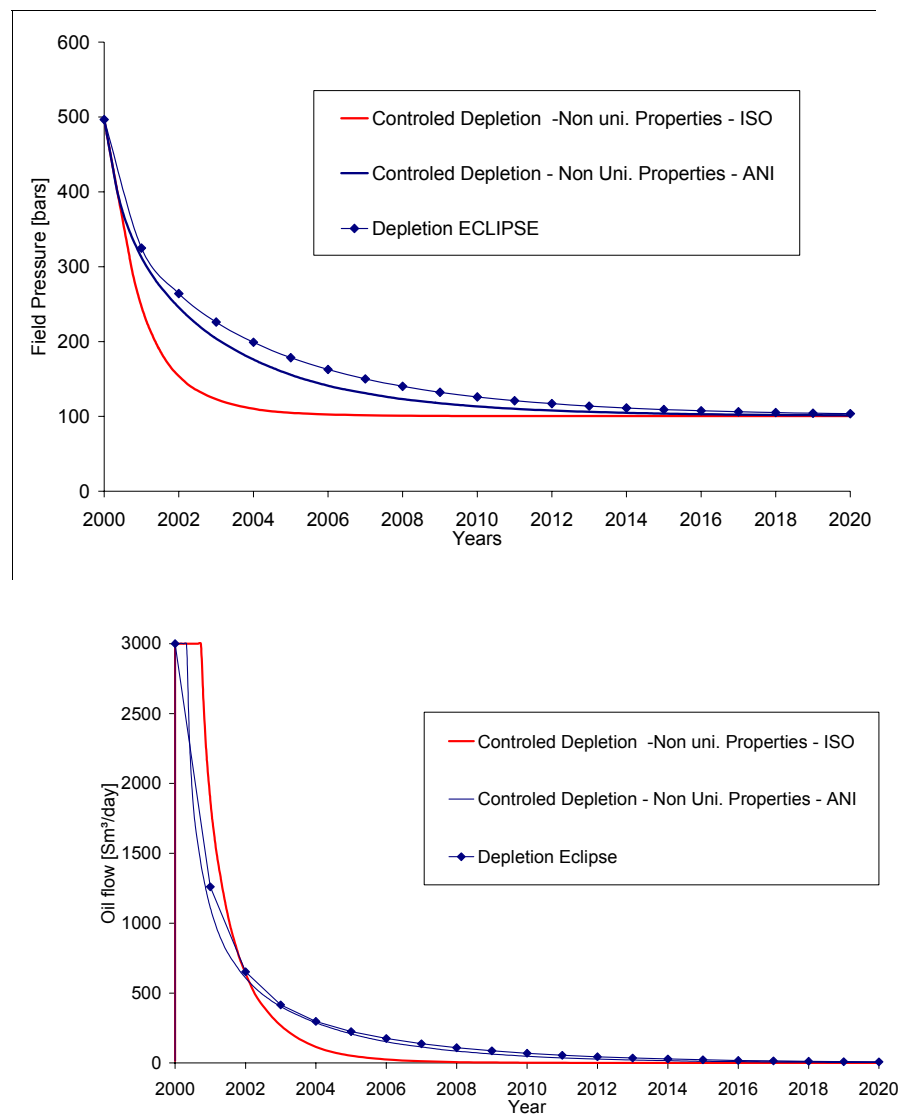
Layer	Formation	Thickness <i>m</i>	Porosity <i>Fraction</i>	H. permeability <i>mD</i>	V. permeability <i>mD</i>
1	Tor-1 (fracturated)	40	0.45	100	0.42
2	Tor-2	10	0.4	1.3	0.13
3	Barrière	5	0.3	0.3	0.001
4	Hod 1-3	45	0.3	0.3	0.03
5	Hod 4	30	0.33	1.7	0.17
6	Hod 5-6	60	0.25	0.2	0.02

**Table 4.** Properties of the reservoir layers

On figure III-9 are plotted the results corresponding to case A. The field pressure first decreases fast due to the oil flow at the production well. But after a given time, the field pressure stabilises to a value equal to the bottom pressure at the well. Indeed, due to production, the well pressure decreases and one has to decrease the imposed oil flow to respect the minimum bottom pressure at the production well.

Moreover, pressure evolution depends deeply on the permeability anisotropy. Therefore we have drawn the results corresponding to isotropic (ISO) and anisotropic (ANI) case. In the latter case, it takes more time to reach the stabilisation pressure. The conclusions are confirmed by the evolution of the oil flow at the production well.

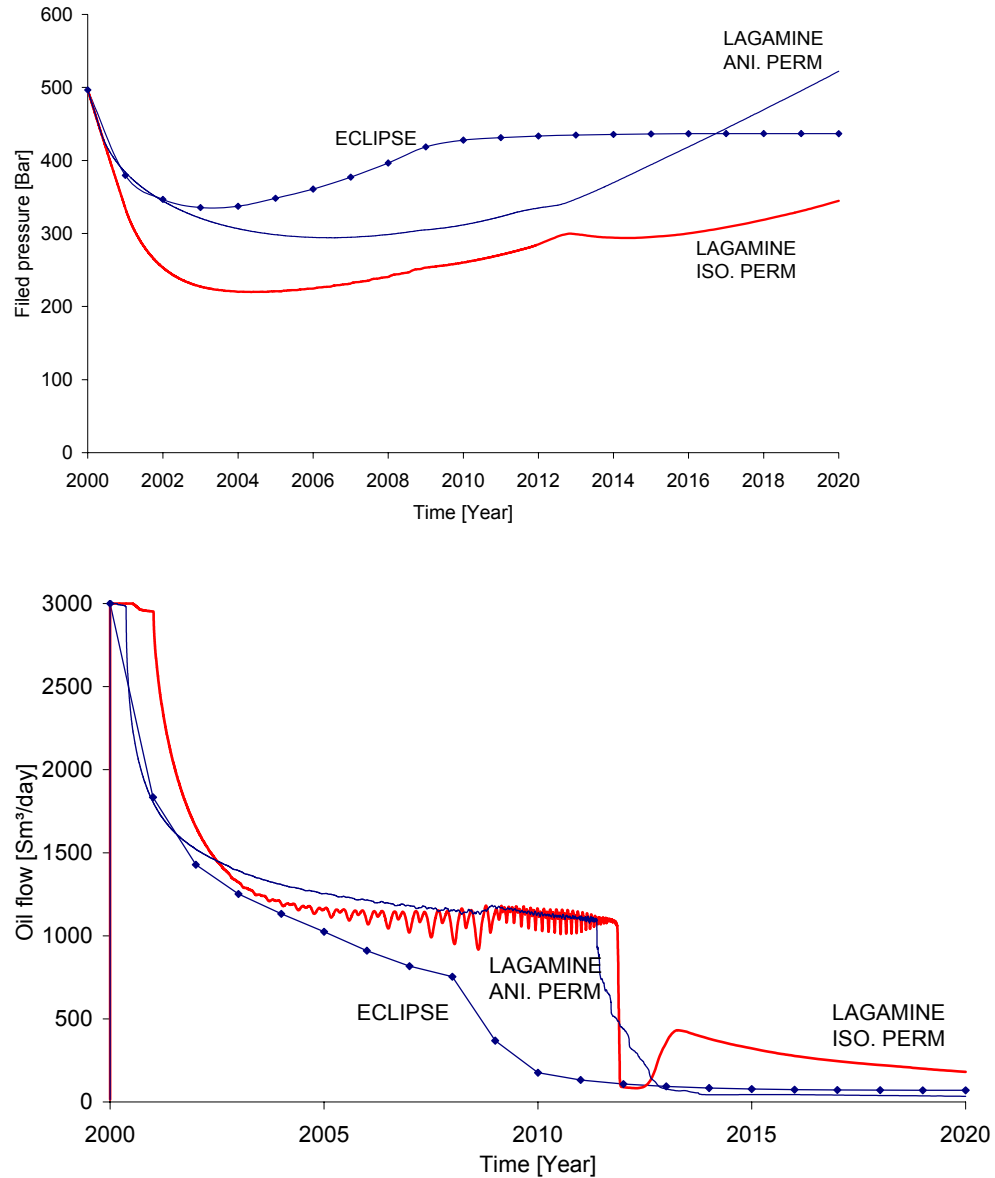
One can also observe the very good agreement between Lagamine and ECLIPSE model in this first simulation. In the case B (Figure III-10), the evolution of field pressure is different: it first decreases as in the previous case, but after a given time, the field pressure increases. This phenomenon has to be related to injection flow, which tends to repressurize the reservoir.



**Figure III-9.** Field pressure and oil flow at the production well (Case A)



It is also interesting to see the results in terms of oil flow. One observes that at a given time, oil flows decreases fast. This corresponds to the incoming of water at production well. When water arrives at the well, quite no more oil is produced.



**Figure III-10.** Field pressure and oil flow at the production well (Case B)

The comparison is quantitatively good for Case A simulations: field pressure and oil production rate are well captured. When injection well is open, comparisons are not so good even if the overall behaviour is reproduced.

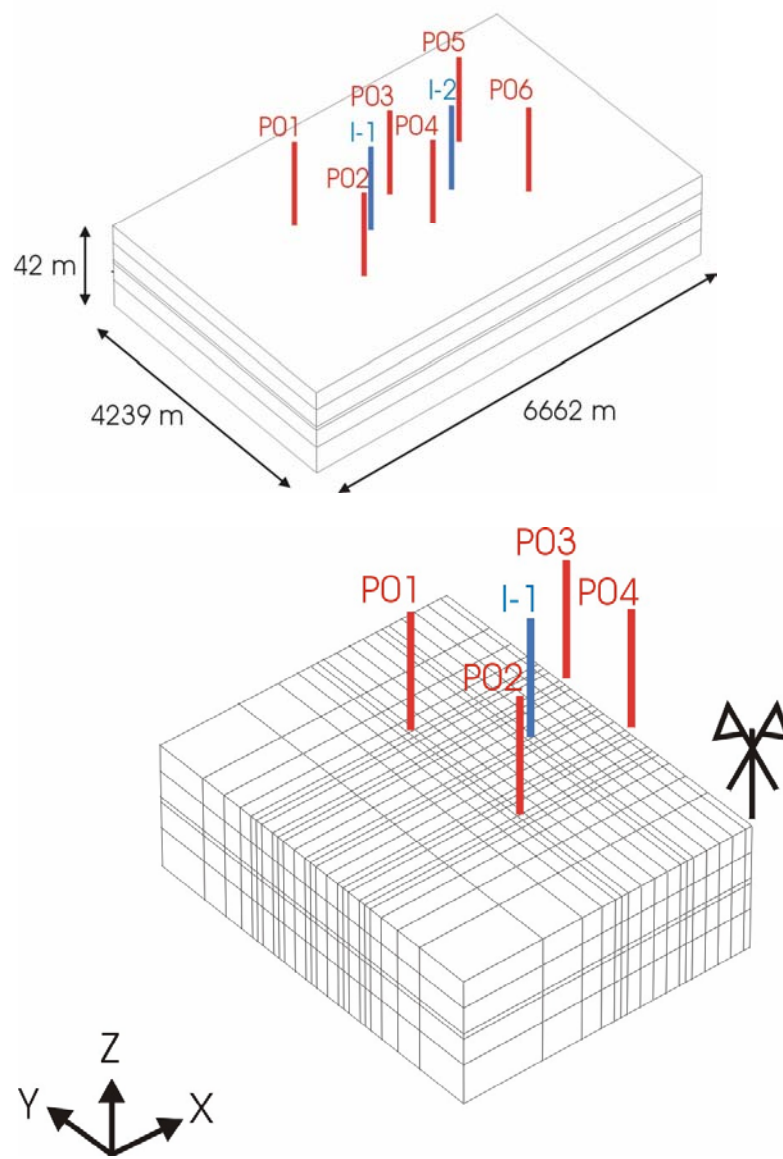
### III.3.2 3D Reservoir simulation

This model proposed by TFE Norway a/s is a synthetic 3D model of Ekofisk. The reservoir is composed of five layers with the same pattern of permeability (See table 5). Except the third layer called Tight zone, which has a vertical permeability ten times lower than the others. A sketch of the geometry and the mesh used for the computation are given in Figure III-11. Owing the symmetry of the problem, the mesh is composed of 2733 nodes, 2040 8-nodes

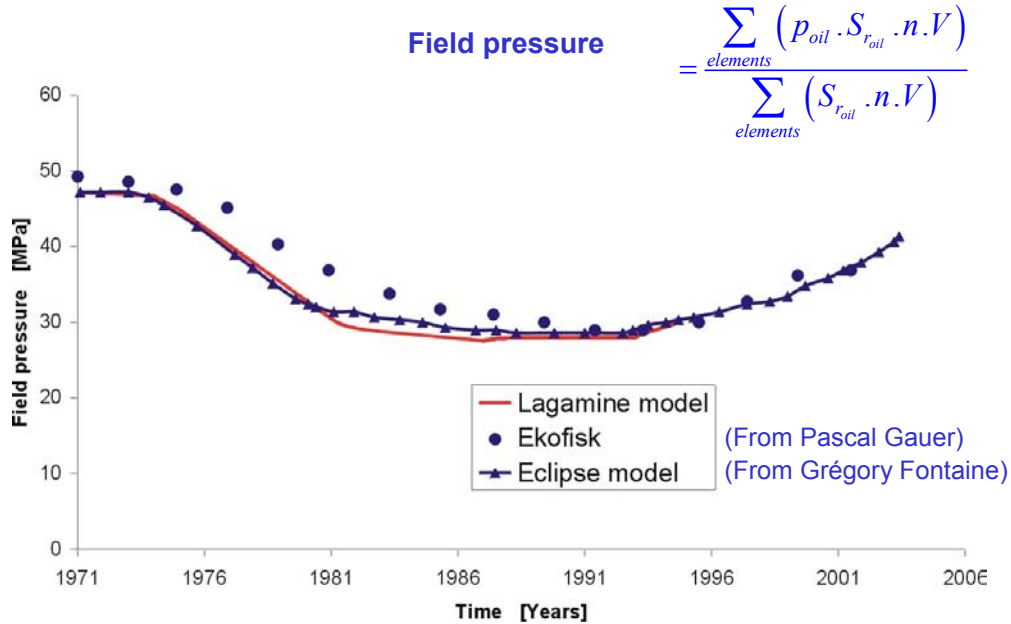
coupled elements MWAT3. These computations have needed new development: 3D multiphase flow model, 3D fully coupled isoparametric finite element. The well elements (WEPRO elements) have also been adapted for 3D simulations.

Layer	Formation	Thickness <i>m</i>	Porosity <i>Fraction</i>	H. permeability <i>mD</i>	V. permeability <i>mD</i>
1	Ekofisk	100	0.40	100	2.5
2	Ekofisk	100	0.40	100	2.5
3	Tight zone	20	0.20	100	0.25
4	Tor	100	0.38	100	2.5
5	Tor	150	0.38	100	2.5

*Table 5. Properties of the reservoir layers*



*Figure III-11. Reservoir geometry and mesh used*



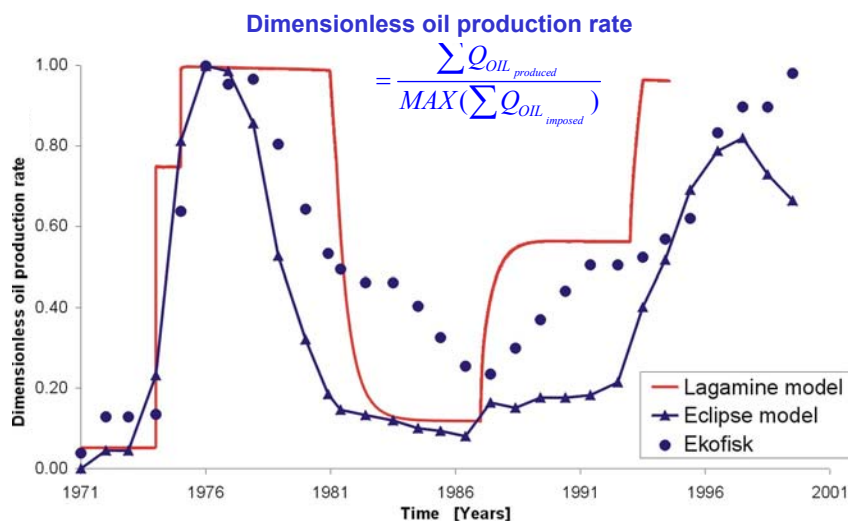
**Figure III-12.** Field pressure in the Ekofisk field

At the beginning of the simulation, only production wells are open : the field pressure decreases first and stabilizes after around ten years of production (Figure III-12). Up to 1987, water injection begins and repressurizes the reservoir: the field pressure increases progressively.

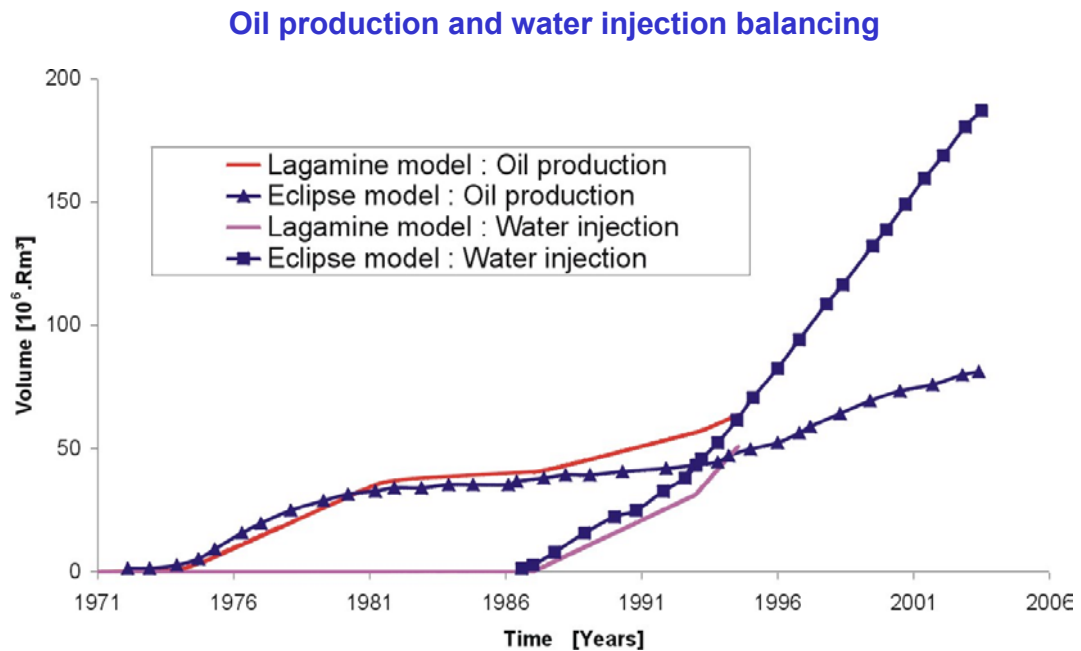
The comparison between ECLIPSE and Lagamine are in a good agreement. We have to specify here that ECLIPSE model has been performed with three fluid phases (oil, water and gas). This is not the case in the Lagamine flow model where only water and oil are considered. This could be a reason why some differences will appear hereafter.

Figure III-13 shows the dimensionless oil production rate. It corresponds to the sum of all the oil flows produced at a given time, normalised by all the oil flows, which should be produced if there were no control of the bottom hole pressure. This figure shows the complexity of the exploitation scheme. These results confirm the conclusions dealt from the pressure field curve.

The comparison with the ECLIPSE results is not so good as in the previous figure. However, the overall evolution of the oil flows is well captured by the code.



**Figure III-13.** Dimensionless oil production rate



**Figure III-14.** Oil production and water injection balancing

On the Figure III-14, one can compare the cumulated volume of produced oil and injected water, predicted by both codes. The general trends are the same for ECLIPSE and Lagamine. The results are very closed during the production phase but a slight difference appears progressively up to the injection phase.

### III.4 Conclusions

The modelling tasks, performed by ULg-GeomaC and comprises two main aspects :

- development of an elasto-visco-plastic law was first performed in saturated conditions (D atcheva, 2001) and then extended in unsaturated cases (Collin, 2003). The model follows guidelines of Perzyna's approach: a potential function is defined; it gives orientation and amplitude of visco-plastic deformations. This work has been implemented in the PASACHALK model in order to take also suction effects into account: this gives the possibility to model within one single constitutive law the water sensivity and long term aspect of chalk behaviour;
- calibration and determination of model parameters. This has been achieved thanks to the experiment performed in the laboratories (CERMES, GeomaC).

The benchmark between ECLIPSE and Lagamine confirms the ability of ULg code to capture correctly the main features of a reservoir code. The FE code is still not able to model the whole of the concepts implemented in reservoir simulator. However, the model responses are good enough to be able to study the couplings (between flows and rock mechanics) appearing in a reservoir.

#### IV. CONCLUDING REMARKS

The Pasachalk has reached the major part of the objectives :

**Theoretical** and phenomenological insight that allowed to improve the basic knowledge of the mechanical behaviour of the chalk

**Experimental** work that reached the main two objectives

- application, set-up and tune-up, of the unsaturated soil mechanics techniques and procedures to the experimentation of oil/water saturated chalk (at different "suction" levels
- performing of set of tests in order to study, calibrate and validate the general elasto-visco-plastic (with suction) constitutive law of the chalk

Some aspects merit to be studied more in details in the future, for example, the wettability whose study could only be started in this framework, the temperature effect that is the scope of the JCRIV project, the physico-chemical interactions, including the solid state dissolution-recrystallisation phenomenon etc.

The **modelling** tasks is completed and has allowed the development of an elasto-visco-plastic law including the effects of the partial saturation (oil/water) "suction" This constitutive law, Pasachalk model' offers then the possibility to model within one single constitutive law the water sensitivity and long term aspect of chalk behaviour. The calibration and determination of model parameters been achieved thanks to the experiment performed in the experimental part. The Pasachalk law has been implemented in a FE code developed by ULg (Lagamine).

To test its ability, a benchmark has been made between the ECLIPSE™ code, usually used by the oil companies, and Lagamine. This benchmark has confirmed the ability of ULg code to capture correctly the main features of a reservoir code. The FE code is still not able to model the whole of the concepts implemented in reservoir simulator. However, the model responses are good enough to be able to study the couplings (between flows and rock mechanics) appearing in a reservoir. So, it appears to be able in the future to compete with the existing commercial codes usually used in the oil industry.

The help of the industrial partner for disseminating the results and promoting the code is of crucial importance. The international workshop that is currently organized will surely contribute greatly to the dissemination of the obtained results and to the promotion of the final product, the Pasachalk law implemented in the Lagamine FE code. It will also give the opportunity to present the future developments in basic insight of the chalk behaviour including the thermal and physico-chemical aspects, in modelling (3D, chemo - thermo coupling...) and in the related experimental works.

It is not because the Pasachalk2 ended successfully that chalk is no more a "terra incognita"... it is in fact the opposite and, even if the basic mechanisms and micromechanisms are now relatively well described, explained and modelled, it is an evidence that the more chalk is known, more it appears that many unexpected aspects are still to be investigated.

As final remark, it has to be pointed out that Pasachalk is an integrated experimental, theoretical and numerical project. All along the work, a continuous dialog was established among the partners and especially, it has been noted that the experiments were not conducted independently from the modelling work. On the opposite, the testing procedures established by the experimentators always took into account the requirement of the numericians and vice-versa. This close collaboration between two worlds too often separated, is seldom enough to be mentioned.

On the other hand, the constant involvement of the industrial partner allowed to reorientate the scopes in order to better fit the companies requirements. The follow-up was permanent and the participation of the experts from Total extremely constructive.

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The Pasachalk2 project could not be completed without the support and the help of many organisms, companies and people

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**PASACHALK2**  
**FINAL TECHNICAL REPORT**

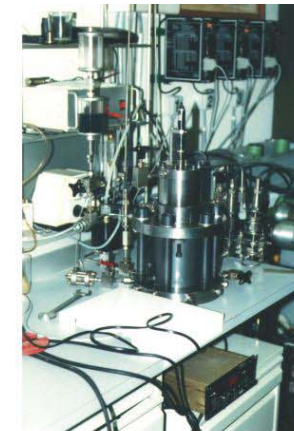
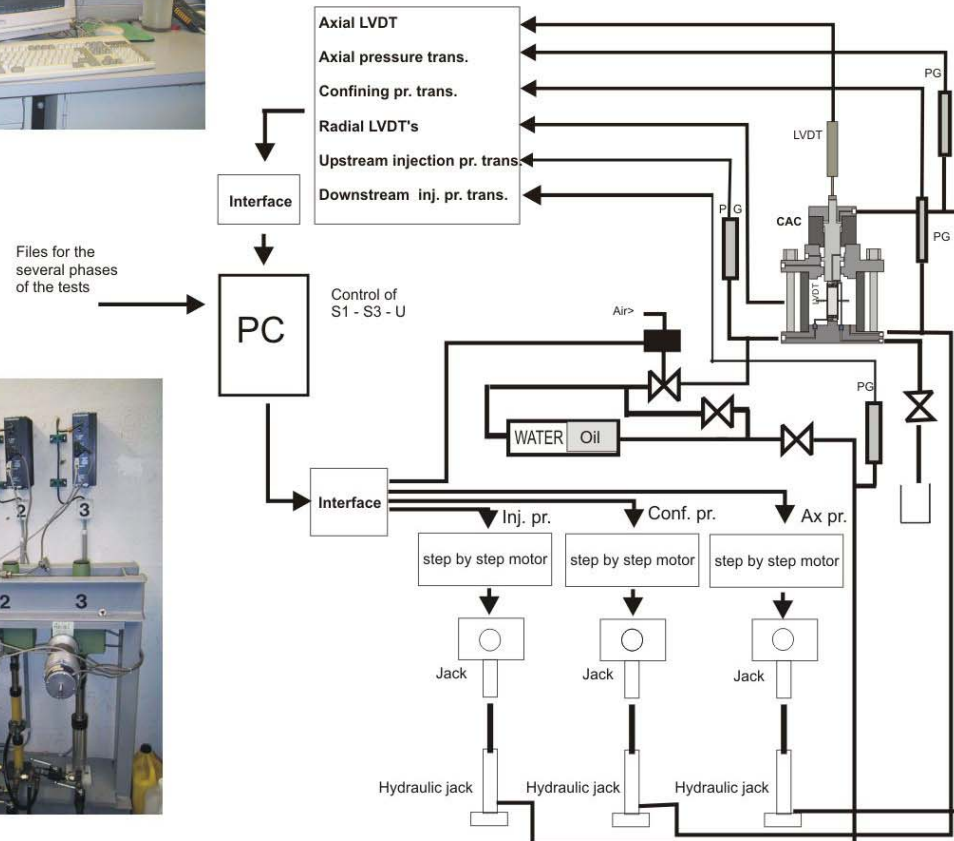
**APPENDICES**

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(1998-2002)**

## ANNEXE 1 : The auto-compensated cell<sup>2</sup>



### Triaxial - permeameter multi - stress paths equipment



CAC : autocompensated triaxial cell

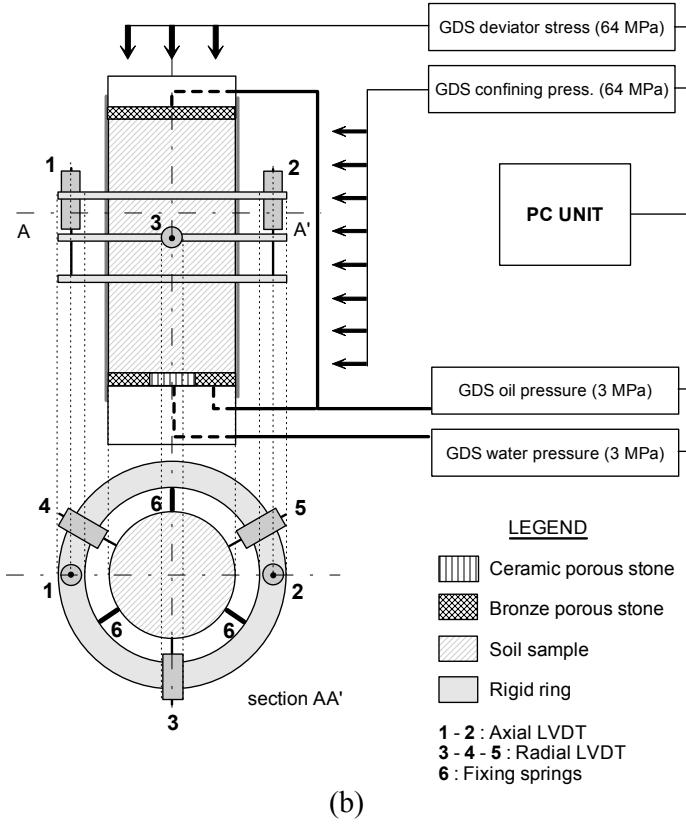
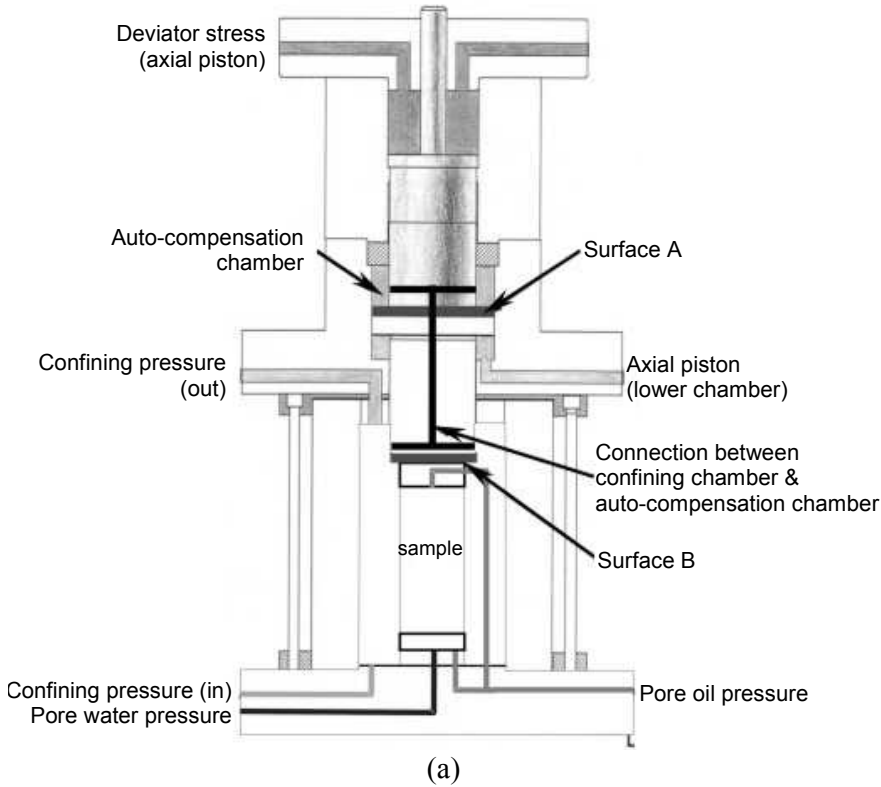
LVDT : displacement transducer

PG : pressure gauge 50 MPa



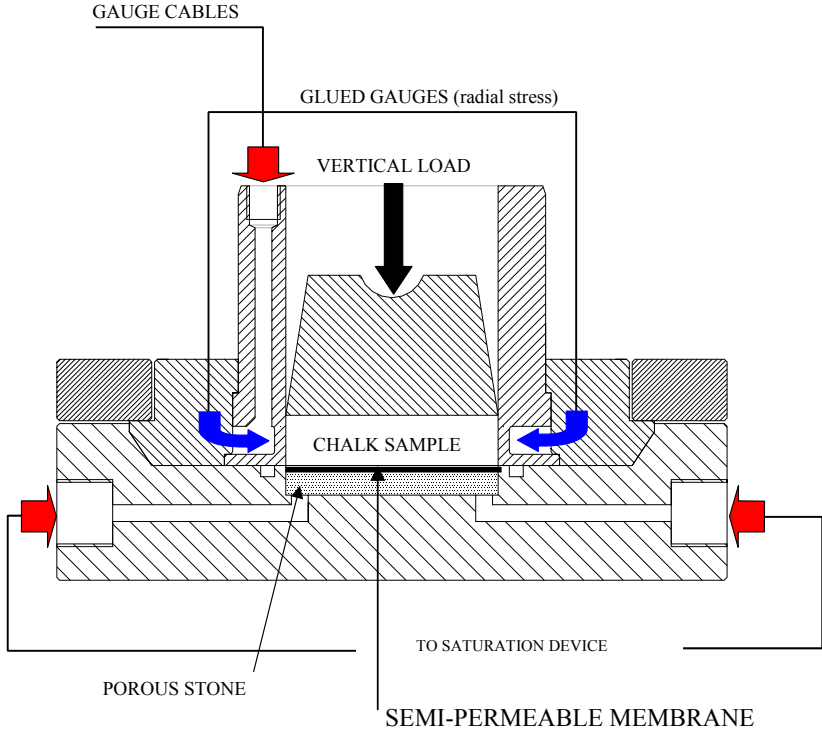
*The auto-compensated suction controlled triaxial cell : general layout of the control system*

**ANNEXE 2 : The suction controlled triaxial cell**

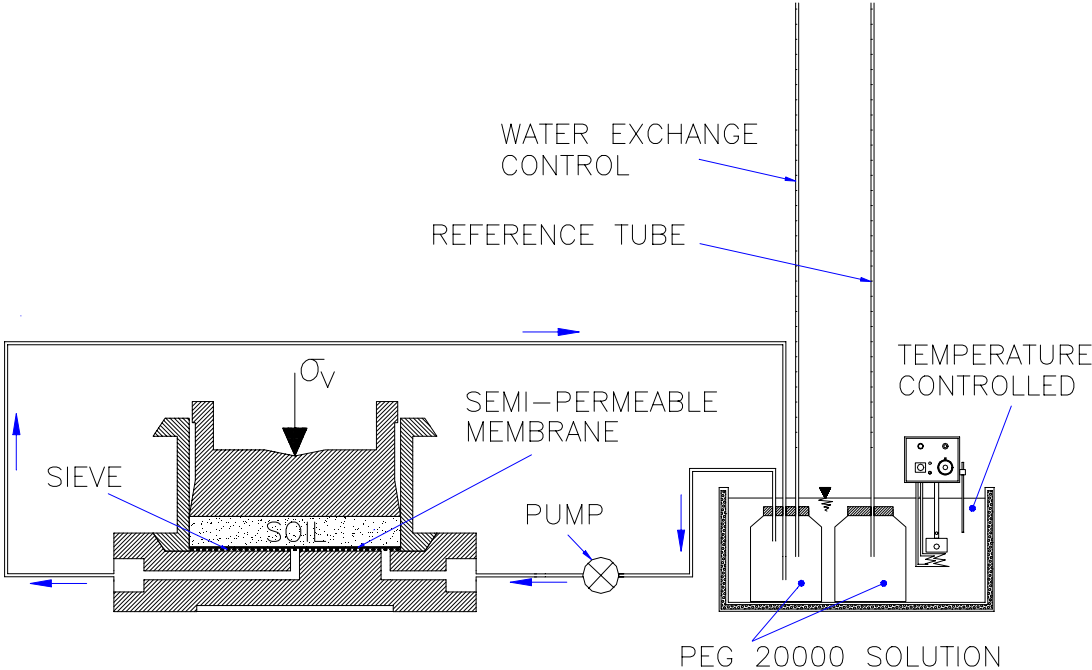


*The auto-compensated suction controlled triaxial cell: (a) schematic layout of the apparatus, (b) acquisition/piloting system and local measurements system*

**ANNEXE 3 : The osmotic  $K_o$  - oedometer**



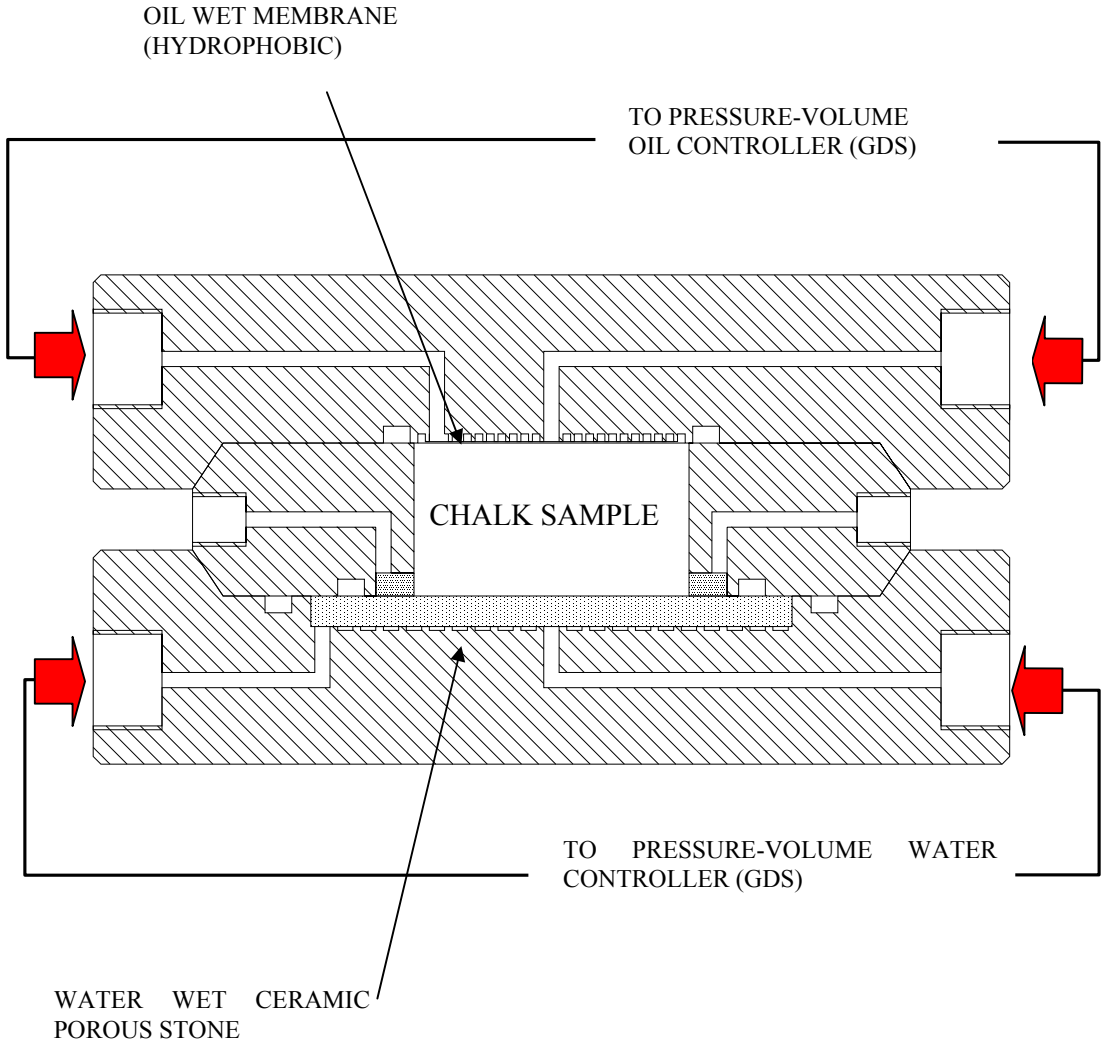
(a)



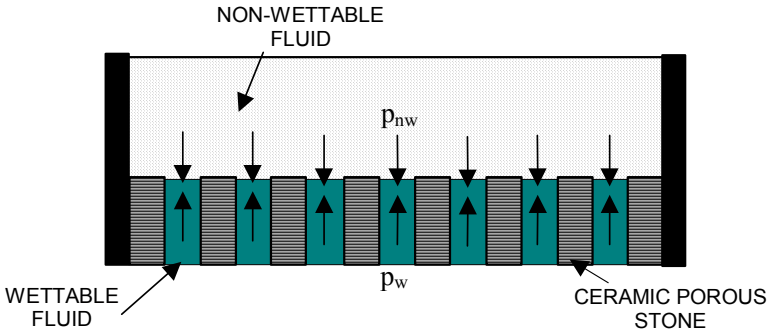
(b)

*The osmotic  $K_o$  - oedometer: (a) schematic layout of the apparatus, (b) suction control by osmotic technique (principle)*

### ANNEXE 4 : The multiphase cell



(a)



(b)

The multiphase cell: (a) schematic layout of the apparatus, (b) capillary pressure in the ceramic porous stone, non-wettable fluid passes if  $p_{nw} > (p_w + p_c)$ , where  $p_c$  is the capillary pressure of the ceramic porous stone