

TECHNICAL NOTE

On the collapse behaviour of oil reservoir chalk

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KEYWORDS: chalk; compaction; laboratory tests; offshore engineering; soft rocks; suction

INTRODUCTION

In the past two decades, problems related to seabed subsidence in the Ekofisk oilfield in the North Sea (about 10 m; Nagel, 2001) have required a substantial revision in the production planning, as well as an important structural rehabilitation, of the offshore platforms (Hermansen *et al.*, 2000). Although it is now widely accepted that the main cause of the seabed settlement is the compaction of the 150 m thick layer of reservoir chalk ($n = 30\text{--}48\%$) located at a 3000 m depth below the sea floor, the origin of the compaction is still an open issue. Early studies that related the compaction to increased effective stresses due to reservoir depletion (Johnson & Rhett, 1986; Jones & Leddra, 1989; Leddra *et al.*, 1993) were soon questioned (Jones & Mathiesen, 1993). The depletion phase (1971–1986) was followed in 1987 by an enhanced oil recovery procedure in which cold seawater was injected (waterflooding). Although pressure depletion was stalled, resulting in a constant effective stress, seabed subsidence continued.

Since the early 1980s, the effects of the nature of the pore fluids, of their mutual interaction and of their interaction with the rock skeleton were examined to better interpret the origin of chalk compaction (Newman, 1983; Monjoie *et al.*, 1985; Piau & Maury, 1994; Schroeder *et al.*, 1998; Lord *et al.*, 2002; Risnes *et al.*, 2003). It was proposed to adopt a coupled hydromechanical framework taken from the mechanics of unsaturated soils (containing water and air as a non-wetting fluid) and to adapt it to reservoir chalks (containing water and oil as a non-wetting fluid) (Delage *et al.*, 1996; Collin *et al.*, 2002; De Gennaro *et al.*, 2003). In this framework, it was demonstrated that the compaction induced by waterflooding bore strong similarities to the collapse of unsaturated soils when wetted under a constant load. In both cases, water was considered to be located in menisci in the smaller pores close to the intergrain contacts, remaining the largest available porosity to the non-wetting fluid (air or oil).

In this framework, the oil–water suction s_o was defined by $s_o = u_o - u_w$ (u_o and u_w being the oil and water pressures respectively). As in unsaturated soils (Coleman, 1962; Fredlund & Morgenstern, 1977), two independent stress variables were considered, namely the oil–water suction s_o and the mean net stress $p - u_o$. An extended experimental programme including suction-controlled oedometric and triaxial tests was developed from 1997 to 2003 within

the framework of two European projects (PASACHALK1, 2001; PASACHALK2, 2004). Suction control was achieved by using both the oil overpressure (or axis translation) technique (Richards, 1941; Hilf, 1956) and the osmotic technique (Kassiff & Benschalom, 1971; Delage *et al.*, 1992). Among other things, the effects of physico-chemical chalk–water interactions as a complement of capillarity were evidenced. Finally, a constitutive ‘PASACHALK’ model, derived from the Barcelona Basic Model (Alonso *et al.*, 1990) with time effects added, was adapted to reservoir chalks and successfully used in reservoir simulations (Charlier *et al.*, 2002; Collin *et al.*, 2002).

In this note, some results of oedometer tests carried out on chalk samples under constant (oil–water) suction are presented. Particular emphasis is given to the effect of suction on the compression behaviour. Collapse due to waterflooding (i.e. decreasing the oil–water suction by replacing oil by water) under a constant load is also presented and discussed.

TESTED MATERIAL

Blocks of an outcrop chalk from Belgium called *Lixhe chalk*, corresponding to the same geological layer as the Ekofisk reservoir chalk (Hod formation of the Upper Campanian level, Cretaceous period), were used in this study (Schroeder, 2002).

SEM observation highlighted the remains of coccoliths (skeletal debris of unicellular algae), which are present in small plates of about 1–10 μm dimensions (Fig. 1). Between the calcite grains, the voids (dimensions 1–5 μm) represent about half of the total volume, with an average porosity of about 40%. This value was corroborated by a series of mercury intrusion porosimetry (MIP) tests that characterised a quite well-defined population of large pores with an average entrance radius of about 0.37 μm (Fig. 2). In the natural deposit, voids are filled with water in chemical equilibrium with the chalk, saturated in CaCO_3 . In the oil reservoir, chalk was initially filled by water a long time ago (35 million years for Cretaceous chalks), and oil has afterwards infiltrated part of the pore space, expelling part of the water. Constant-head permeability measurements (PASACHALK1, 2001) gave a value of intrinsic permeability K of about $1 \times 10^{-14} \text{ m}^2$ (corresponding to water and oil permeability respectively equal to $k_{\text{water}} \approx 1 \times 10^{-8} \text{ m/s}$, $k_{\text{oil}} \approx 7 \times 10^{-9} \text{ m/s}$).

A non-polar and non-toxic immiscible organic liquid called Soltrol 170[®] ($\text{C}_{12}\text{--}\text{C}_{14}$ isoalkanes, Phillips Petroleum Co.) was used in this study to simulate oil. Soltrol 170[®] has also been selected for its very low solubility in water ($\ll 1 \text{ mg/l}$ at 20°C) and very low volatility in air ($\ll 4 \times 10^{-2} \text{ mm}^3/\text{h}$ at 20°C). Soltrol 170[®] has a dynamic viscosity $\eta_o = 2.028 \text{ cP}$ and a density $\rho_o = 0.78 \text{ Mg/m}^3$.

EXPERIMENTAL INVESTIGATION

The pressure discontinuity ($u_o - u_w$) through the interface separating the two immiscible fluids (oil and water) gives

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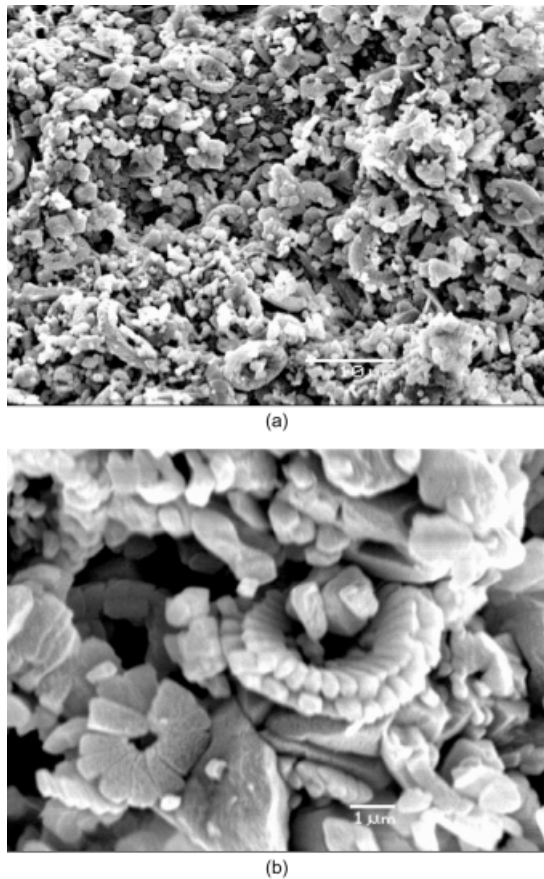


Fig. 1. SEM pictures of Lixhe chalk at various magnifications: (a) 10 µm; (b) 1 µm

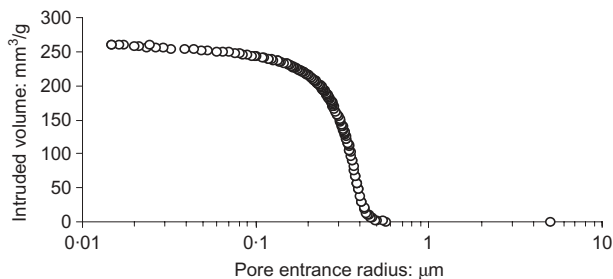


Fig. 2. Pore size distribution curve of Lixhe chalk

rise to the capillary pressure (Laplace, 1806; in Morrow, 1970), which depends on the fluid interfacial tension and on the pore geometry. In clayey soils, additional physico-chemical fluid–mineral interactions exist. Both capillary and physico-chemical interactions contribute to the suction. This concept is considered to be valid in multiphase chalk.

The control of suction was accomplished using the osmotic technique (Delage *et al.*, 1992; Dineen & Burland, 1995; Cui & Delage, 1996). This technique consists in putting the sample in contact with a regenerated cellulose semi-permeable membrane behind which a solution of large molecules of polyethylene glycol (PEG) is circulated. As the large PEG molecules cannot go through the semi-permeable membrane, an osmotic suction that increases with the PEG concentration is imposed on the sample through the membrane. Note that direct suction measurements carried out by Dineen & Burland (1995) using the IC suction sensor (Ridley & Burland, 1993) on samples in which the suction was osmotically imposed showed some deviations from the standard calibration of Williams & Shaykewich (1969).

Some preliminary tests showed an excellent behaviour of the semi-permeable membrane when put in contact with Soltrol, with no apparent chemical reaction, no membrane damage and no resulting PEG leaks through the membrane. This was confirmed by careful examination made on the sample at the end of the tests, where no evidence of PEG infiltration (PEG infiltration in samples due to membrane breakdown are clearly apparent) was observed. The validity of the osmotic technique was particularly interesting in the case of oedometer testing, where the use of the osmotic technique is easier than that of the overpressure technique. Owing to the difficulty of a simultaneous direct measurement of suction, the Williams & Shaykewich (1969) calibration curve was used. This will probably result in an uncertainty at high suction levels, estimated at a maximum value of about 200 kPa when considering the Dineen & Burland (1995) measurements for suction values ranging between 0 MPa and 1.5 MPa. However, as will be seen below, the range of this uncertainty will not significantly affect the conclusions regarding suction effects on the compression behaviour of the chalk.

Sample preparation

Chalk samples were cored from a block of chalk and then shaped on a lathe at the required size. Samples about 50 mm in diameter and 15 mm high were used for the oedometer tests (Table 1). For the retention tests, the samples had a diameter of about 20 mm and their height ranged between 20 and 25 mm (De Gennaro *et al.*, 2003). All the samples were oven-dried at 105°C, put under vacuum (approximately –94 kPa for 24 h) and oil-saturated under vacuum. The oil-saturated state is to be related to a ‘dry’ state of the chalk (with no water inside) with very high values of suction s_0 .

Subsequent wetting down to controlled values of suction was made using the osmotic technique. Samples full of oil were inserted in a cylinder-shaped semi-permeable membrane that was subsequently plunged in a PEG solution at the desired concentration (see Cui & Delage, 1996). When doing so, a good contact between the membrane and the sample should be ensured. Owing to the higher surface tension of water as compared with that of oil, water coming through the membrane progressively infiltrated the sample, giving rise to oil expulsion out of the sample. Visual

Table 1. Physical properties of chalk samples (oedometric tests)

Sample	D : mm	H : mm	W_s : g	W_{sat} : g	S_{rw} : %	e_o^*	s_0 : MPa
1	49.89	17.11	52.41	63.26	98.6	0.704	Oil sat.
2	49.84	13.64	43.11	–	–	0.649	Dry
3	49.91	13.46	42.23	50.47	98.3	0.665	0.8
4	49.84	14.19	43.43	52.28	97.4	0.702	0.4
5	49.47	12.51	37.43	45.31	98.7	0.715	0.1

*Calculated with $G_s = 2.71$.

observation showed that the expelled oil remained inside the membrane. This technique of imposing a suction when no stress application is required appeared quite convenient and inexpensive to treat many samples at the same time. Note that the infiltration of water in an oil-saturated chalk is comparable to the waterflooding carried out in the oil reservoir chalk to enhance oil recovery.

Retention properties of Lixhe chalk

The wetting path of the retention curve of the Lixhe chalk containing oil and water is presented in Fig. 3 in a $\log s_o : S_{rw}$ diagram, where S_{rw} is the degree of saturation in water. At high suctions (s_o higher than 0.5 MPa), large changes in suction induce small changes in expelled oil volume, whereas the same suction changes at lower suction involve a significantly larger expelled volume, leading to a residual degree of saturation in water of 70% (average) at zero suction.

This high residual degree of saturation in water shows the high water wettability of this chalk. Similar data are used in the Amott quantification of water wettability of reservoir rocks (Amott, 1959). Other North Sea chalks, as for instance in the Valhall oilfield (Andersen, 1995), present a hydrophobic behaviour. The origin of such a behaviour can be either adsorption of organic molecules along the coccolithe surfaces, due to the contact that occurred between oil and chalk minerals during a very long period of time of the reservoir history at elevated temperature (between 130°C and 150°C) and pore pressure (44.5 MPa at 2400 m depth), or surface alteration due to oil-based drilling mud. It is most probable that the degree of wettability or non-wettability to water of chalks is of utmost importance in the coupled hydromechanical behaviour of chalks.

Suction-controlled oedometer

The samples were tested in the osmotic oedometer cell presented in Fig. 4. 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 through visual observation of the water level in the graduated tube placed in the bottle that contains the PEG solution. Water exchanges were in general very slow, and it was observed that a period of time of about 15 days was necessary to reach equilibrium after imposing the desired suction.

In order to reach the desired net vertical stress, the sample was loaded using a high-pressure oedometer frame with a double lever arm that allowed a maximum vertical stress of approximately 60 MPa to be applied to a 50 mm diameter sample (Marcial *et al.*, 2002). A standard step-loading procedure was adopted. At each stage the stabilisation of the PEG level in the tube was checked.

TEST RESULTS AND DISCUSSION

Figure 5 shows the results of four compression tests performed on chalk samples submitted to various oil–water suctions: 0.1, 0.4 MPa (Fig. 5(a)) and 0.8 MPa and dry sample (Fig. 5(b)). Owing to the overall importance of the initial void ratio for the compression behaviour, compression curves have been grouped according to their initial void ratio to facilitate comparisons. Data of samples with higher initial void ratios (0.715 at 0.1 MPa and 0.702 at 0.4 MPa) are presented in Fig. 5(a) and those with lower void ratios (0.665 at 0.8 MPa and 0.649 in dry state) in Fig. 5(b). All samples were loaded up to 10 MPa, submitted to an unloading–reloading cycle, and subsequently loaded up to a maximum vertical stress that was selected depending on the suction applied (20 MPa for the sample at $s_o = 0.1$ MPa, 30 MPa for the sample at $s_o = 0.4$ MPa, 40 MPa for the sample at $s_o = 0.8$ MPa and for the dry sample). The corresponding void ratio was calculated from the volumetric strain obtained after 24 h of applied constant loading.

The initial water saturation degrees (S_{rw}) of the samples can reasonably be estimated from the retention curve of Fig. 3, giving respectively $S_{rw} = 50\%$, 20% and 10% for the samples at 0.1, 0.4 and 0.8 MPa respectively.

It can be observed in Fig. 5 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 with 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. 5 complete these observations by also accounting for the gradual effect of partial saturation in both fluids under a controlled suction. In this regard, the change in yield stress with suction is compatible with the conclusions drawn for unsaturated soils by Alonso *et al.* (1987, 1990), which founded the notion of an LC (loading collapse) curve. Note that the results of the four tests presented here cannot be plotted together to determine an LC curve because of the effects of the change in void ratios; the increased density also has a significant effect on the yield stress. However, unlike unsaturated soils, the slope in the plastic zone does not appear to be suction dependent. Conversely, as in unsaturated soils, the elastic response investigated by the unloading–reloading sequences does not show any significant suction effect.

The collapse phenomenon of an oil-saturated chalk sample due to waterflooding has been investigated in the framework of unsaturated soil mechanics by infiltration of water under a vertical load of 10 MPa, as shown in Fig. 6. In this test, the initial (theoretically) infinite oil–water suction was reduced to zero. In the absence of an available water-saturated compression test at the same initial void ratio, a test at low suction (0.1 MPa) has been plotted, together with the collapse test. As mentioned earlier, the initial degree of water

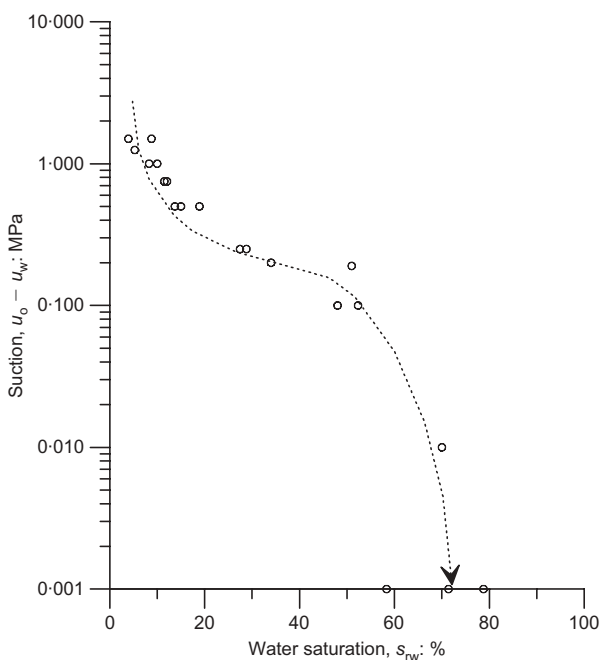


Fig. 3. Retention curve (wetting path) of Lixhe chalk

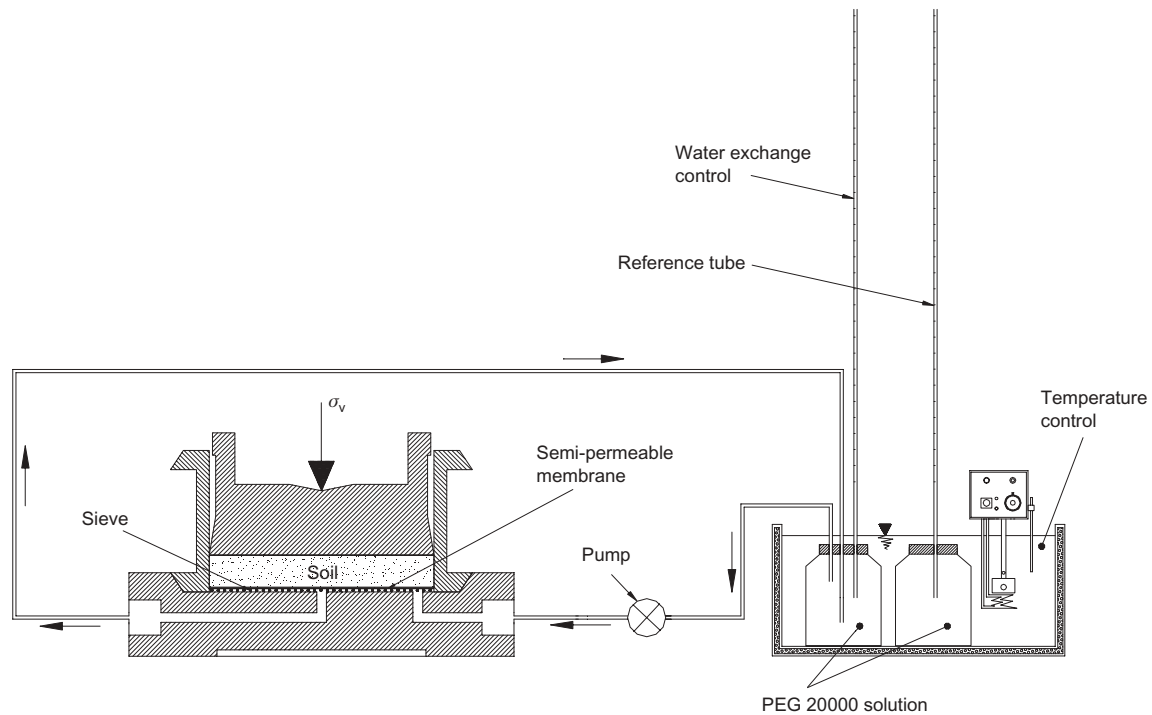


Fig. 4. Suction-controlled oedometer

saturation of this sample is about 5%, as compared with the average value of 70% observed on samples saturated under a zero suction (see Fig. 3).

Water was infiltrated using the same system that allowed PEG solutions to be circulated during suction-controlled tests (Fig. 4). Thus the circulation of pure water at the bottom of the chalk sample was ensured by the peristaltic pump shown in Fig. 4. However, with respect to the apparatus layout shown in the same figure, neither PEG solution nor cellulosic semi-permeable membrane were necessary. The final point in Fig. 6 (point B) has been obtained after one week of continuous water circulation, and defines a total decrease of 0.025 in void ratio (path AB). This variation of the void ratio corresponds to a compressive volumetric strain of about 1.5%. Some creep may also have affected this volume decrease (Ruddy *et al.*, 1989; De Gennaro *et al.*, 2003). It is worth noting that the induced volumetric strain due to wetting results from a natural infiltration process, developing from the bottom to the top of the sample. Unlike in waterflooding, during which the soft rock is soaked by water injection under pressure and suction may attain negative values (i.e. $u_w > u_o$, forced imbibition) and residual oil saturation, infiltration requires much more time to achieve the water saturation degree corresponding to the complete suction release down to zero (i.e. S_{rw} of about 70%). Consequently, it is believed that higher volumetric strain would have been induced if water was injected at constant pressure. Nevertheless, the collapse observed in Fig. 6 is significant and comparable to earlier data of Newman (1983) on chalk samples from the Cora, Dan and Gorm North Sea oilfields. Comparison with the 0.1 MPa compression curve shows that point B is not located on or below the 0.1 MPa compression curve, as could have been expected referring to well-established results in unsaturated soils as shown through the double oedometer approach of Jennings & Knight (1957) and the state surface of Matyas & Radhakrishna (1968). This difference is, however, often observed in natural soils, and is not surprising in this natural chalk.

In unsaturated soils, collapse is interpreted as a breakdown of an open porous metastable granular structure whose

stability was ensured in the unsaturated state by capillary menisci at intergranular contacts. Here, some questions arise owing to the initial dry state of the chalk before oil saturation and to the existence of capillary menisci in such conditions. It seems more probable that the strongest intergranular links existing in the oil-saturated sample (which, if not capillary, have a significant physico-chemical component due to the high reactivity of carbonate) are progressively weakened by the infiltration of water through the smallest pores (i.e. at the intergrain contacts), giving rise to collapse.

CONCLUSIONS

An interpretation of the collapse mechanism induced by waterflooding in chalk reservoir rocks has been proposed in this note, based on the use of a framework taken from the mechanics of unsaturated soils. The relevant developments allowing for chalk mechanical testing under oil–water suction control have been described.

The osmotic technique has been used to control oil–water suction during retention tests following a wetting path. Its reliability in controlling suction in chalk has been verified. A series of suction-controlled tests in the osmotic oedometer cell, performed on chalk samples having different relative saturation in oil and water, provided information on the mechanical behaviour of multiphase chalk under K_0 conditions and controlled suction. Owing to the presence of two immiscible pore fluids (oil and water) of different surface tension properties, the volume change behaviour of oil reservoir chalk appears to present various similarities with that of unsaturated soils. Experimental results highlight the influence of oil–water suction on the mechanical response of the material.

As in unsaturated soils, the elastic behaviour of chalk is not affected by suction. Conversely, increasing suction induces an increase of the vertical stress at yielding. Suction decrease has been recognised to play a major role in interpreting the collapse due to wetting under constant load. This situation is comparable to that encountered in oilfields when waterflooding is used to enhance oil production. Water

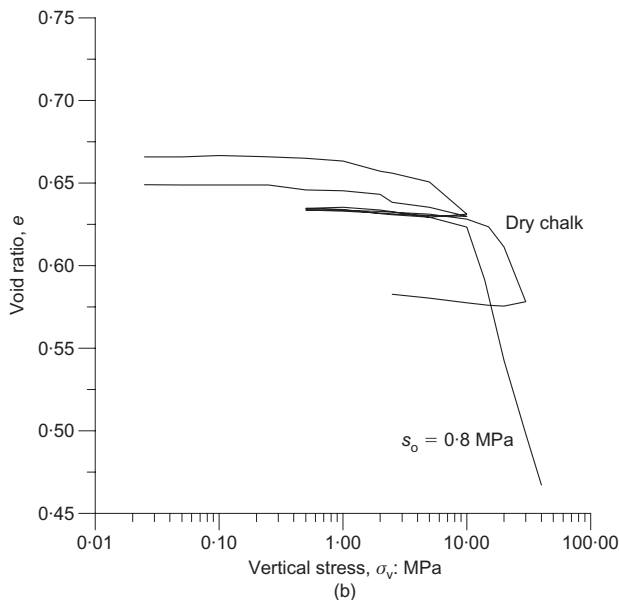
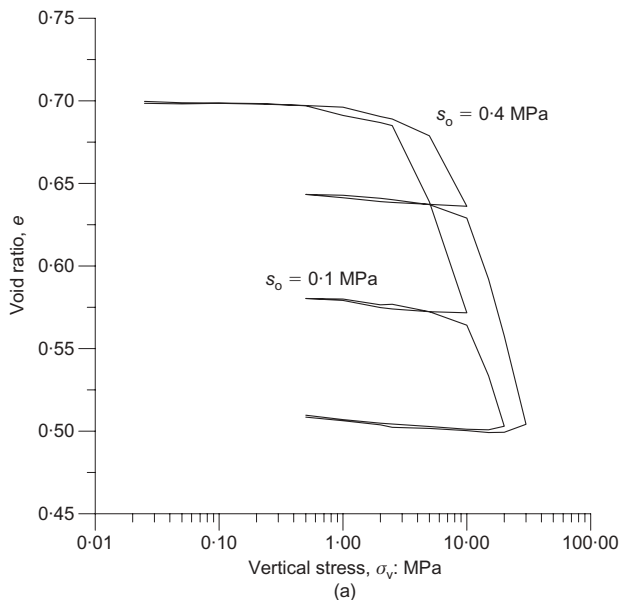


Fig. 5. Suction-controlled oedometer tests on Lixhe chalk: (a) $e_0 \approx 0.7$; (b) $e_0 \approx 0.65$

weakening effects and chalk compaction (collapse) seem likely to occur through the loss of strength of the intergranular links existing in the oil-saturated sample. The nature of these links includes both capillary and physico-chemical fluid–chalk interactions, and is well represented by the oil–water suction.

On the other hand, some differences can be mentioned in comparison with unsaturated soil behaviour, namely the lack of dependence of the slope of the virgin compressibility curve of the chalk on the suction values and the stress independence of the collapse phenomenon.

The time-dependent behaviour of oil reservoir chalks, including the analysis and elucidation of suction effects on creep, is currently the object of further research in this area.

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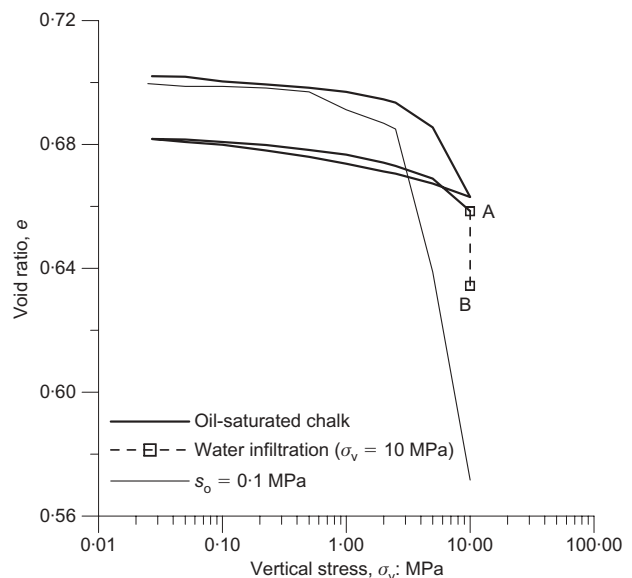


Fig. 6. Wetting-induced collapse of oil-saturated Lixhe chalk sample

2 (contract No. ENK6–2000–00089) carried out jointly by the University of Liege (Dpt GeomaC, Belgium), the Ecole Nationale des Ponts et Chaussées (ENPC, Dpt CERMES, Paris, France) and TotaFinaElf oil company (Drs Ph. Keul and A. Onaisi). The collaboration of Dr B. Chen during his PhD stage at CERMES is also acknowledged.

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