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Mechanical Behaviour of a Porous Chalk and Water/Chalk Interaction

Part I: Experimental Study

S. Homand[1] and J.F. Shao[1]*

1 USTL-EUDIL, Laboratory of Mechanics of Lille, URA 1441, Cité scientifique, 59655 Villeneuve-d'Ascq - France
e-mail: Jian-Fu.Shao@eudil.fr

* Author to whom correspondence should be addressed

Résumé — Comportement mécanique d'une craie poreuse et effets de l'interaction eau/craie, 1^re^ partie : Résultats expérimentaux* — Cet article constitue le premier volet d'une étude complète du comportement mécanique d'une craie poreuse et des effets du fluide saturant sur celui-ci. Une campagne expérimentale visant à caractériser le comportement d'une craie poreuse en fonction du fluide saturant a été réalisée. Deux fluides ont été utilisés : l'un mouillant (eau) et l'autre non mouillant (huile) vis-à-vis de la craie.

Cette campagne expérimentale est scindée en deux parties. La première partie consiste à réaliser des essais classiques de type compression hydrostatique et triaxiale sur des échantillons saturés à l'eau et à l'huile. L'influence du comportement de la craie en fonction du fluide saturant est clairement mise en évidence. La seconde partie consiste à effectuer des essais originaux, où de l'eau est injectée dans des échantillons initialement saturés en huile, sous divers états de contraintes hydrostatiques et déviatoriques. Une déformation plastique induite par l'eau est clairement mise en évidence.

Mots-clés : comportement mécanique, plasticité, craie, effets de l'eau, expériences.

Abstract — Mechanical Behaviour of a Porous Chalk and Water/Chalk Interaction, Part I: Experimental Study* — *This paper is the first part of a general work on the mechanical behaviour of a porous chalk and the effect of saturating fluid. It presents an experimental investigation of the behaviour of a porous chalk by taking into account the effects of saturating fluid. Two representative fluids are concerned: a wetting fluid (water) and a non-wetting fluid (oil).*

The laboratory-testing program includes two topics. At first, conventional hydrostatic and triaxial compression tests are carried out on samples, which are respectively saturated with water and oil. The sensitivity of chalk behaviour to saturating fluid is clearly shown. Secondly, specific water injection tests are conducted in which water is injected in chalk samples initially saturated by oil, under different hydrostatic and deviatoric stress conditions. A water induced plastic deformation is observed.

Keywords: mechanical behaviour, plasticity, chalk, water effects, experiments.

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INTRODUCTION

Compaction and induced subsidence problems have been experienced in oil fields like Ekofisk, Valhall. These North Sea reservoirs are made of water sensitive rock such as pure high-porosity chalk (Andersen, 1995).

In order to perform reliable predictions of compaction when water flooding is processed in such reservoirs, it is necessary to take account of the deformations induced by the rock behaviour and also the additional deformations induced by water injection. The previous laboratory investigations have clearly shown a strong sensitivity of chalky rocks to water content (Halleux *et al.*, 1990; Brignoli *et al.*, 1994; Risnes and Garspestad, 1998; Risnes and Kaarigstad, 1996; Monjoie *et al.*, 1995; Schroeder, 1995; Schroeder *et al.*, 1998).

The purpose of this paper is to provide a comprehensive database to characterise the basic behaviour of porous chalk and to quantify the additional plastic deformation due to water flooding under deviatoric stresses. This will be used to define an accurate model in a following paper.

In a first part, conventional and specific hydrostatic and triaxial compression tests have been carried out, respectively on oil and water saturated samples. The results obtained will be used to determine the initial plastic yield surface and its evolution due to material hardening. The influence of saturating fluid will be demonstrated by comparing the results obtained from the two different saturation conditions. In a second part, original water injection tests have been done in initially oil saturated samples under constant hydrostatic and deviatoric stresses.

Concerning the first part, our study will complete and corroborate results which have been obtained recently by Schroeder for the Pasachalk project (Schroeder, 1999), Risnes and Kaarigstad (1996) and Risnes and Garspestad (1996). Concerning the second aspect, there is a lack of experimental published data and the experiments done would be useful for modelling water injection.

1 MATERIAL EQUIPMENT AND TEST PROCEDURE

1.1 Tested Material

All the tests have been performed on an outcrop chalk from Upper Campanian age, called *Lixhe chalk* which is sampled in the *CBR* quarry near Liège (Belgium). This chalk has been used because many other experimenters already studied it (Monjoie *et al.*, 1995; Risnes and Kaarigstad, 1996; Andersen, 1995) and have shown that its mechanical behaviour is close to that of reservoir chalks.

It is a relatively homogeneous and isotropic material at the sample scale. It is rather pure (more than 98% $CaCO_3$), almost monomineral and has low quartz content (< 2% SiO_2). Its porosity ranges from 41% to 44% with an average of about 43%. Its permeability is about 1.2 mD ($1.2 * 10^{-15}$ m^2).

The porosity of the chalk has also been measured using a mercury porosimeter. The porosities of the two different blocks used for the following tests, obtained by using this method, are very close: 42.43% and 42.18%.

1.2 Sample Preparation

The outcrop chalk is cored and machine turned in order to get the requested shape for the cell (36 mm diameter by 72 mm length). The saturating method is classical: samples have been oven dried at 105°C to constant weight (at least 24 h drying) before being saturated under vacuum (at least 6 h with a pressure in the vacuum vessel between 3-4 MPa), with water or with oil. Then the plugs have been placed in the triaxial cell where they have been submitted to an additional flow (until constant flow is obtained) to insure "perfect" saturation.

The fluid used for oil saturation is Soltrol 170^{TM} and in all the following of this article, *oil* and *soltrol* have the same meaning. The fluid used for water saturation is distilled water mixed with crushed chalk and then filtered for it to be in chemical equilibrium with chalk in order to avoid dissolution phenomenon.

1.3 Test Equipment

1.3.1 Cell Equipment

The triaxial cell used for this test program is hydraulically operated. This cell is schematically presented in Figure 1.

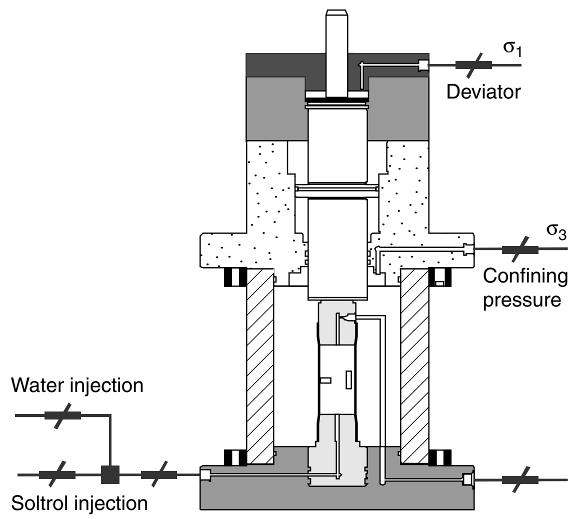

Figure 1

Schematic presentation of the autocompensated triaxial cell.

The cell is operated with two high-pressure pumps limited to 60 MPa, one for the deviator and one for the confining pressure. This cell is autocompensated: it means that the confining pressure is also applied axially and that the axial loading is directly the deviator. In that way, the confining pressure is purely hydrostatic during all the test, which is very difficult to obtain with a classical cell. The axial pistons can be pumped both downward for compression tests and upward for extension tests.

1.3.2 Measurement Equipment

In order to measure quite large deformations expected for the tests, special gauges and special glue have been used. These gauges and this glue allow to accurately measure strains until 10%. Moreover, small size gauges (5 mm) have been used in order to measure deformation as locally as possible. Further, in order to compare two different measurement techniques, eight LVDTs (Linear Variable Differential Transformer) are also used in the cell to measure the sample displacements. Four are placed in the axial direction and four are fixed on a ring in a 90° phasing in the radial direction. Pumps and LVDTs are connected to a computer to control and record the experiments. Note that the value of the injected water volume by the high-pressure pumps is also available, which is an interesting data for the water injection.

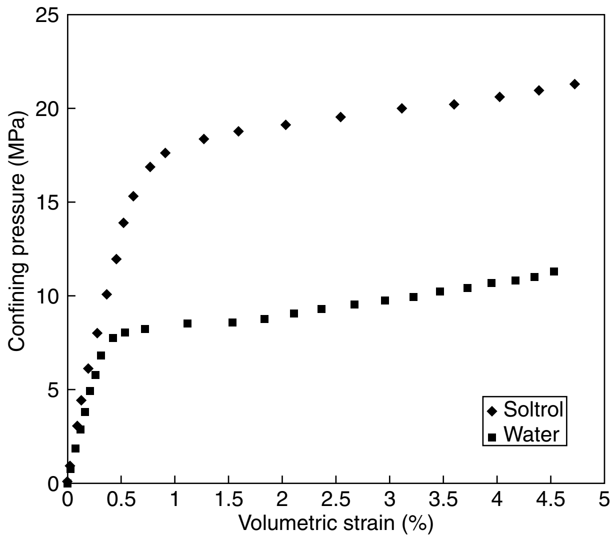

Figure 2

Typical stress volumetric strain curves obtained in hydrostatic compression tests: comparisons between the experimental results for water and soltrol saturated chalk samples.

1.4 Test Procedures

The tests are performed in drained condition. This hypothesis implies to choose a loading rate which prevents excessive pore pressure increase. Moreover, because of the creep in this material and in order to be able to compare our experiments it is necessary to run all the tests with the same loading rate. We decided to fix this loading rate to 0.01 MPa/min.

2 BASIC MECHANICAL BEHAVIOUR

2.1 Definition of the Initial Yield Surfaces

In order to define the initial yield surface for intact chalk as a function of the saturating fluid, two sets of classical triaxial and hydrostatic tests have been performed, one set with water as saturating fluid and one set with oil saturating fluid. For water saturated samples, five triaxial tests (with confining pressures of 0.5, 1, 2, 5 and 7 MPa) and one hydrostatic test have been performed. For oil saturated samples, five triaxial tests (with confining pressures of 1, 3, 4, 7 and 10 MPa) and one hydrostatic test have been performed. The results of these tests are given in Figures 2-6.

By looking at the stress strain curves obtained in hydrostatic compression tests *(Fig. 2)*, the water sensitivity of chalk behaviour is clearly shown. The plastic yield stress is drastically reduced when chalk is saturated with a water-like fluid.

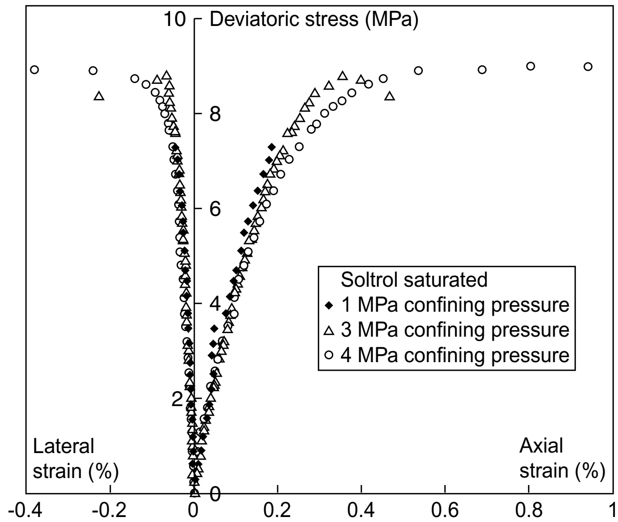

Figure 3

Stress strain curves obtained in triaxial compression test with "low" confining pressure (1, 3 and 4 MPa) on soltrol saturated samples.

From these tests we can note two kinds of behaviour depending on the confining pressure. For low confining pressure (say lower than 4 MPa for water saturated samples and 6 MPa for oil saturated ones) we have a small hardening

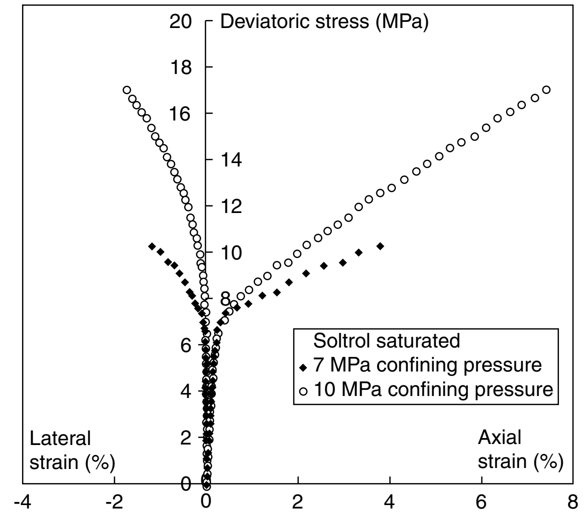

Figure 4

Stress strain curves obtained in triaxial compression test with “high” confining pressure (7 and 10 MPa) on soltrol saturated samples.

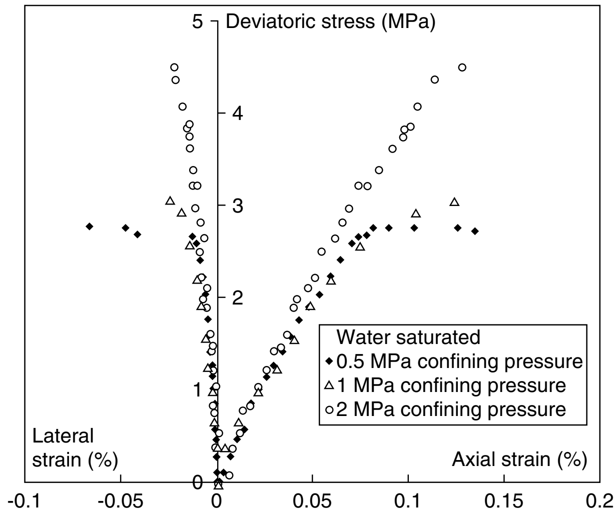

Figure 5

Stress strain curves obtained in triaxial compression test with “low” confining pressure (0.5, 1 and 2 MPa) on water saturated samples.

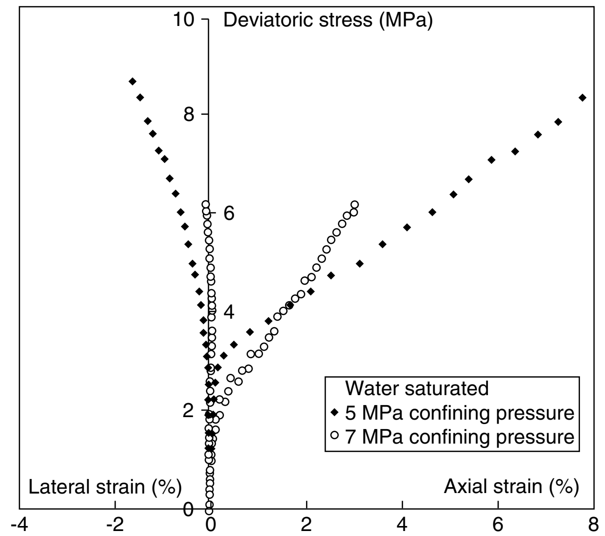

Figure 6

Stress strain curves obtained in triaxial compression test with “high” confining pressure (5 and 7 MPa) on water saturated samples.

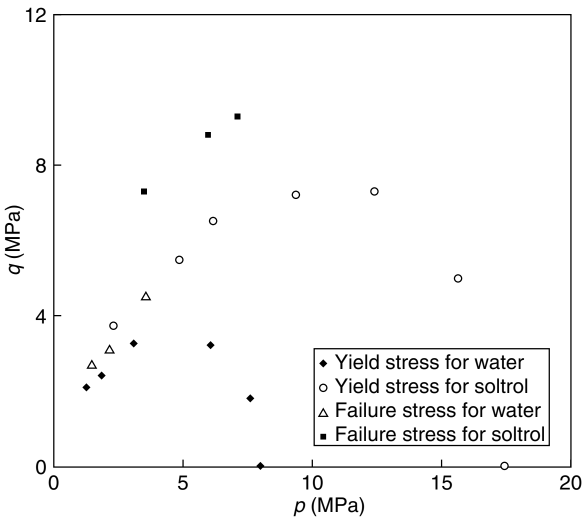

Figure 7

Initial plastic yield surfaces and rupture locus of chalk respectively in soltrol and water saturated samples.

zone followed by a sample failure characterised by a net peak deviatoric stress. The chalk behaviour is rather brittle with a small volume compaction obtained. One could argue that when the mean stress is under a certain limit value, the plastic deformation of chalk is essentially due to matrix shearing (dislocation type mechanism) activated by the applied deviatoric stress. The sample failure is obtained through localised shear bands. The active mechanism is called *deviatoric mechanism*. While for higher confining pressure the chalk behaviour becomes clearly different. An important plastic hardening zone is obtained and no apparent macroscopic failure of sample is observed until relatively large values of strain (10% for example). There is an important compaction of chalk. The main active mechanism is then called *pore collapse mechanism*.

In order to determine the initial elastic domain and failure surface of the chalk with respect to saturating fluid, the initial yield stresses and failure stresses are calculated from the previous tests. The initial yield stress is theoretically defined as the onset point of irreversible plastic strain. However, it is often not easy to accurately detect such a point on a stress-strain curve because the non-linearity generally occurs progressively. In this study, we have used the so-called *straight line method* which consists in simulating the material elastic response by a straight line and then considering the first deviation point from this line as the initial yield stress. The failure stress is assimilated to the peak stress. By using this method, the previous set of twelve triaxial tests allows to define for the two saturating fluids the initial yield surfaces of the two mechanisms and the failure surface of the deviatoric mechanism *(Fig. 7)*. We can note that the initial elastic domain is largely reduced in water saturated chalk. The water saturation seems to affect essentially the plastic pore collapse mechanism. Indeed, for the yield surface of the deviatoric mechanism, the difference seems much smaller between the two material states.

So, when a constitutive model is used to a porous chalk, two distinct sets of material parameters should be used respectively in "water" and "oil" saturated conditions.

2.2 Characterisation of the Yield Surface Evolution

If the initial yield surfaces are currently well known, the evolutions of these surfaces have poorly been investigated. The aim of the following tests is to characterise the evolution of the yield surface of the pore collapse mechanism. All the tests described in this section have been performed on oil saturated chalk samples.

The loading path in the *p-q* plan is represented in Figure 8. All the samples were loaded hydrostatically to 25 MPa (OA). Following the hydrostatic preloading phase, the samples were unloaded to different hydrostatic pressures (AB) (10, 14, 17 and 20 MPa) and then tested in standard triaxial compression tests (BC). The yield surface after the hydrostatic preloading is compared to the initial yield surface *(Fig. 9)*. These results allow to consider that the assumption of isotropic hardening for the pore collapse mechanism is fully justified.

Another important result from these hardening experiments is that the two mechanisms are independent. The two failure points obtained from the triaxial tests performed with respectively 10 and 14 MPa confining pressure after the hardening loading are lined up with those obtained from virgin samples; it means that the movement of the cap surface (pore collapse mechanism) does not affect the deviatoric mechanism.

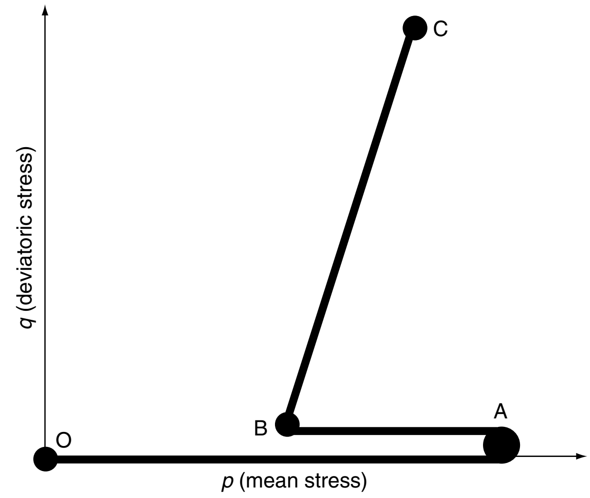

Figure 8

Stress loading path followed in plastic hardening tests.

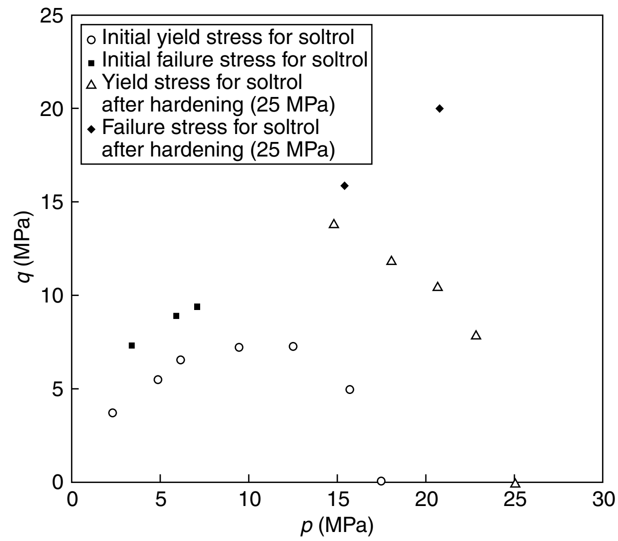

Figure 9

Evolution of yield and failure surfaces during plastic hardening of chalk in soltrol saturated samples.

These results are in perfect accordance with those obtained by Schroeder in the framework of the European project Pasachalk (Schroeder, 1999). Indeed, the same kind of tests have been done on chalk samples saturated with water and a similar conclusion has been obtained (Schroeder, 1999).

3 WATER INJECTION TESTS

In above investigations, the sensitivity of chalk behaviour to saturating fluid is studied through laboratory tests separately performed on water and oil saturated samples. However, in many practical cases, water is injected into initially oil saturated chalk and the key concern is to predict additional plastic deformation caused by water injection. Some previous experiments have been performed by Schroeder (1998) on the Lixhe chalk but these tests were limited to hydrostatic stresses. The purpose of the present tests is to quantify the axial and radial plastic strains induced by water injection under different constant deviatoric stress states. It is important to point out that such experimental data are essential for the formulation and validation of constitutive models devoted to the modelling of chalk responses during water injection process. This feature will be addressed in the numerical modelling study (Homand and Shao, 2000).

3.1 Test Procedure

The loading procedure is defined as follows: an initially oil saturated sample is first subject to a hydrostatic stress level and the deviatoric stress is then applied. Both the axial and radial stresses are maintained constant when water is injected into the sample. The axial and lateral strains are monitored during the injection at different levels along the sample *(Fig. 10)*. The water is injected to the bottom face of the sample with a pressure of 1 to 3 MPa. Two porous metal plates are placed on the top and bottom of the sample for a good distribution of water flow. Eight water injection tests have been performed: four under constant hydrostatic stresses and four under constant deviatoric stresses. The applied stress levels and the test designation are summarised in Table 1.

TABLE 1

Applied stress states for water injection tests

Test designation	Confining pressure (MPa)	Deviatoric stress (MPa)
SLIX1INJ	17	9
SLIX2INJ	14	4.5
SLIX3INJ	17	3.5
SLIX4INJ	25	0
SLIX5INJ	20	3.1
SLIX6INJ	30	0
SLIX7INJ	35	0
SLIX8INJ	50	0

The test SLIX3INJ is fully instrumented and is presented with more details. To determine if the deformations due to water injection are localised and instantaneous, small size gauges (5 mm) have been used in order to measure deformation as locally as possible. In order to observe the phenomenon of "piston-like" water flooding, three gauge levels have been glued. Moreover, these three level gauges allow to observe if the deformations (induced by water injection) are homogeneous in all the sample. The instrumented sample SLIX3INJ is presented in Figure 10.

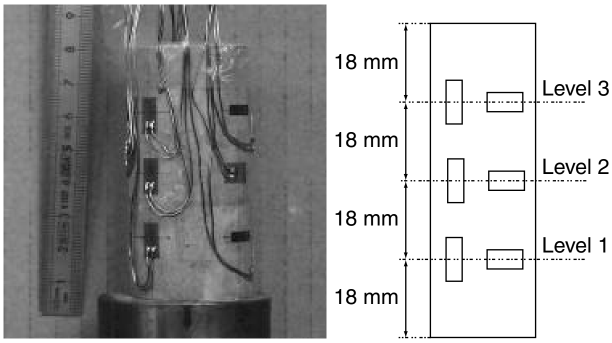

Figure 10

Position of strain gauges on chalk samples used in water injection tests.

3.2 Results

The detailed results obtained from the previous tests are given in Homand (2000). Only the experimental results of the tests SLIX3INJ, SLIX1INJ and SLIX4INJ are presented respectively in Figures 11-13. These figures give the axial and lateral strains recorded at each gauge level as a function of injection time. Note that the lateral strain gauges respond later than the axial one because of their different orientation. The water front reaches the axial gauges before the lateral ones. From the results obtained from these tests, the following remarks can be drawn up:

- note that two gauges are glued respectively in the axial and lateral directions at each height level. The results obtained show that the two gauges in the same orientation at each level respond at the quasi same time when the water injection front passes *(Figs. 11 and 13)*. That means that the assumption of "piston-like" water flooding process is confirmed;
- additional strains due to water injection are clearly localised and instantaneous in nature (it is impossible to have a completely instantaneous strain jump because of the finite size of gauges). The induced volumetric strain is largely compressive;
- in the tests under deviatoric stress state, the water injection induced axial strain is much higher than the radial one, and this difference increases when the stress deviator is higher. This confirms the role of the deviatoric stress in enhancement of chalk pore collapse;
- in the tests where water induced strains are measured at several levels (see for example Figure 11 for the test SLIX3INJ), one can note that the magnitude of induced strain measured by the gauges near the sample top (gauge 3 for instance) is higher than that measured by the gauges near the sample bottom (gauge 1 for example). Such a difference is a consequence of memory effect. In fact,

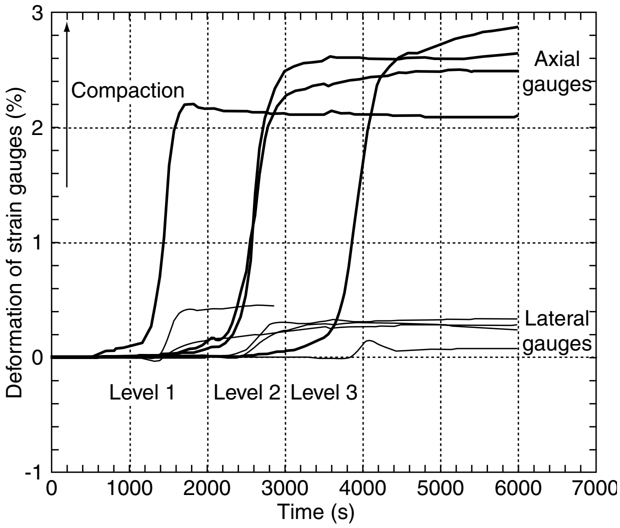

Figure 11

Strain evolutions at three levels of the sample as a function of time during water injection test SLIX3INJ.

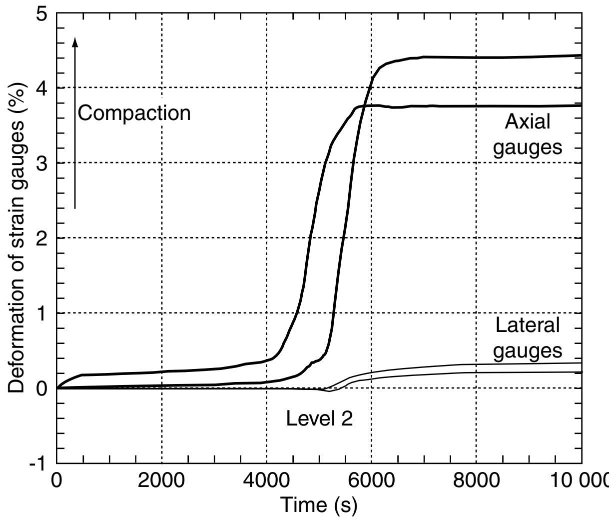

Figure 12

Strain evolutions at the middle point of the sample as a function of time during water injection test SLIX1INJ.

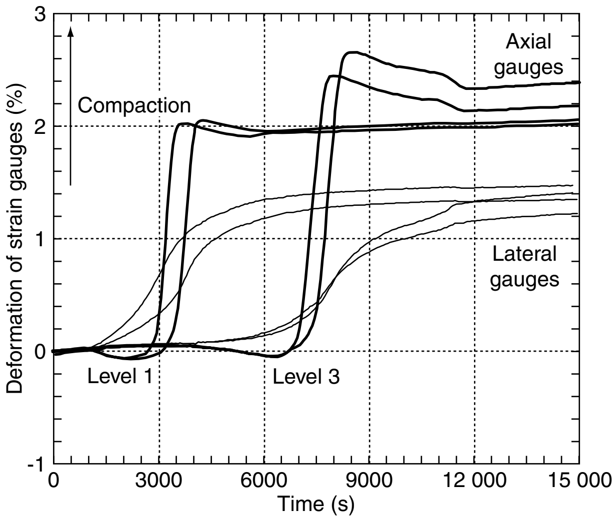

Figure 13

Strain evolutions at two levels of the sample as a function of time during water injection test SLIX4INJ.

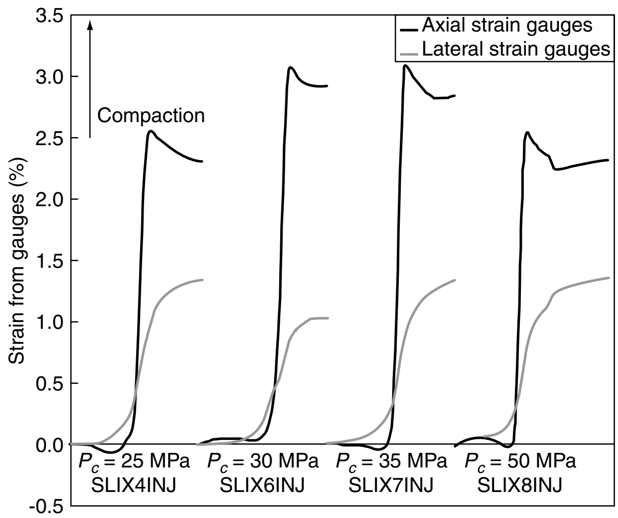

Figure 14

Water induced deformations under four different levels of hydrostatic stress states.

after the passage of the water front, the part of the sample flooded by water changes its mechanical behaviour and behaves like the chalk saturated with water;

– the results from the tests under constant hydrostatic stresses (see test SLIX4INJ, Figure 13 for example) show that the water induced strains are not isotropic, and the axial strain is higher than the radial one. This may be explained by some geometric effects because the plastic strains induced by water flooding are not uniform in the sample.

The four water injection tests under four constant hydrostatic stresses are presented in Figure 14. One can note that the water induced strains are apparently independent of the hydrostatic stress level. This result will be useful in modelling for the choice of fluid-dependent parameters for the pore collapse mechanism.

CONCLUSION

An original experimental investigation has been presented in order to study the water sensitivity of a porous chalk. Two series of experiments have been performed. In the first series, the basic mechanical behaviour of the chalk is investigated in oil and water saturated conditions. It has been noted that the basic plastic behaviour of the porous chalk could be characterised by two distinct mechanisms which are respectively related to matrix shearing and pore collapse. The water sensitivity essentially concerns the pore collapse mechanism. It seems to exist a critical water saturation degree at which a sudden transition from "oil saturated" to "water saturated" behaviour takes place. Partially physical explanations can be issued in connection with the diagenes and microscopic structure of the chalk. In the second series, original water injection tests in initially oil saturated samples have been carried out under different hydrostatic and deviatoric stresses. The results obtained made it possible to evaluate the additional plastic strains induced by water flooding.

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