Hydromechanical characterization of the behaviour of Chateau-Landon chalk

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ABSTRACT

This paper presents an experimental investigation on the hydromechanical behaviour of a partially saturated soft rock (a porous chalk), the Chateau-Landon chalk. Such conditions correspond to those of a chalk mine known as Royer located in the North-centre of France in Paris basin, subjected to shrinking, drying and potential flooding cycles. To study this rock, we apply a method usually used in soils whose hydromechanical behaviour is strongly modified by changes in suction, according to the degree of water saturation. Different degrees of saturation are imposed by controlled relative humidity conditions with continuous measurement of physical parameters. Hydrostatic compression and conventional triaxial compression tests are performed under drained conditions for saturation degrees up to 100% under low confining pressures. The obtained results have allowed to show fundamental aspects of the chalk behaviour. Correlations between water saturation degree, confining pressure and the mechanical behaviour of the chalk are discussed.

Keywords: Porous chalk; Hydromechanical behaviour; Water saturation.

1. Introduction

In France, catastrophic collapses of abandoned mines have occurred, particularly chalk mines in the Paris basin: Château-Landon (7 deaths in 1910), Clamart (21 deaths in 1961), La Rivière (1 death in 1984), Saumur (1 death in 1967) (Conil et al. 2022).

One of the major objectives of the hydromechanical behaviour researches in geological formations is studying their stability and performance under fluctuating hygrometry atmospheres. These perturbations can induce opening of cracks in the site, and loss of confinement properties of the geological barrier.

The hydromechanical behaviour of chalk rocks related to their stability has been studied by many authors. Those studies have shown that the mechanical strength of chalk is reduced under high saturated conditions and high porosity (Bell et al. 1990). Senfaute et al. 2005 showed that chalk rocks present a particular mechanical behaviour which is intermediate between a rock and a soil. Doremus (1978) also showed that dry chalk under low confining stress shows elastic–brittle or elastoplastic–brittle behaviours. Failure occurs without permanent deformation at the end of the linear phase of the stress– strain curve. Under low confining stress (from 0.5 to 2 MPa), water-saturated chalk also shows a linear phase in the stress – strain curve (Homand and Shao 2000), while under high confining stress, the slope of the stress–strain curve increases continuously with a concave shape due to pore collapse, leading to an increase in the contact surfaces and plastic hardening. Under very high confining stress, the failure is characterised by a complete destruction of the pore structure, transforming the cohesive chalk into a compacted powder (Homand and Shao 2000; Xie and Shao 2006). When the stress is high, with a volumetric component larger than the deviatoric stress, chalk behaviour is elasto-visco-plastic.

The aim of this paper is to study the hydro-mechanical behaviour of a partially saturated porous chalk under low confining stress, replicating the natural conditions of a chalk mine. To understand the effects of the hygrometric conditions on the chalk rock, an experimental program is conducted to determine the effects of water saturation on the mechanical behaviour of the Chateau-Landon chalk. To obtain different water saturations degrees (from dry to saturated atmospheres), chalk samples were put in equilibrium with atmospheres whose relative humidity was controlled.

2. Project background

In January 1910, the mine known as "Beaulieu", located in the commune of Château Landon in France (Fig. 1), collapsed after a series of rainfalls and the heavy flooding of the Loing river, located at the bottom of the mine. The lowest parts were then submerged by groundwater and gradually the whole structure weakened and collapsed. This event has generated a major landslide taking away several houses and killing 7 people.

The various scenarios of climate change in France in the 21st century envisage a serious modification of the rainfall regime likely to generate increased fluctuations of water tables.

Important scientific gaps remain, particularly concerning the mechanical effects of seasonal fluctuations in water levels on potentially unstable underground cavities.

In 2011, The French National Institute for Industrial Environment and Risks (Ineris) considered it useful to take an interest in the Royer mine, which is still accessible and located less than 500 m from the collapsed Beaulieu mine (Fig. 1) and presents characteristics quite similar to the latter. This mine also showed signs of instability evolving in 2016 following the exceptional climatic events in the region. It was instrumented to be studied (Conil et al. 2022). Cracks can also be observed; they seem governed by the de-saturation and re-saturation of the chalk material due to the seasonal variations of temperature and humidity in the gallery.

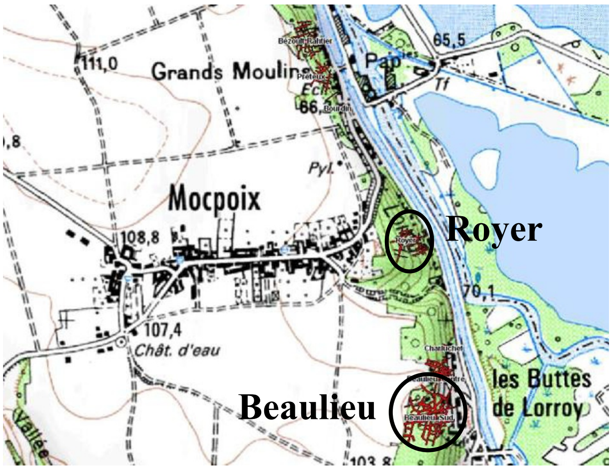

Figure 1. Localization of Beaulieu and Royer mines

The objective here is to better understand the 1910 collapse but also to determine whether a similar incident may occur in the surrounding mine or in other mines with the same configuration as in the Paris Basin.

In the context of climate change, which is associated with an increased number of severe hydrometeorological events, it seems essential to better understand the instability factors for this type of mine through an in-depth analysis of the site conditions as well as an appropriate laboratory characterization of the hydromechanical behaviour from an unsaturated state to a saturated one.

3. Tested Material and Testing Procedure

3.1. General description of Royer's chalk

The Royer's chalk comes from a chalk mine in the Parisian Basin, from Santonian age. The tested samples were collected from drill cores carried out in one pillar in the mine.

This chalk is a micritic limestone with some bioclasts and spartite grains as well as some rare opaque minerals. It has a mudstone-like texture. Calcite is the predominant carbonate (97%) with just 2% to 4% of other minerals. The degree of saturation is to be 0.90–0.95 (or relative humidity values exceeding 97%) with a high porosity close to 45%.

3.2. Preparation of specimens

Rock specimens cored from the Royer mine are mainly chalk. Cylindrical specimens with diameters of 50 to 100 mm are drilled, wrapped in plastic film, and stored in airtight bags (Fig. 2).

Figure 2. Chalk cores drilled from the Royer mine

Once in the laboratory, the rock specimens are cored with water, cut, and processed into standard cylindrical specimens with a diameter of 36 mm and a height of 72 mm, following the standard testing method recommended by ISRM (International Society for Rock Mechanics and Rock Engineering). Based on the average mineral grain size, this specimen size appears to be large enough to be a representative volume element of the chalk.

To obtain different degrees of water saturation, standard methods used in soil mechanics were used during this testing program (Delage et al. 1998). Rock specimens are put in climatic chambers whose humidity are controlled; no mechanical loading is applied. Different saline solutions were selected to cover the range of relative humidity chosen and the water saturation degree calculated using the physical characteristics of the chalk (Table 1). When the weight evolution is stabilized, the specimen is assumed to be in equilibrium with the controlled humidity atmosphere.

For each sample, the weight is recorded, the water content (w) and the degree of saturation (S) are estimated. All the results are presented as a function of the degree of saturation.

Table 1. Controlled relative humidity and saturations

Relative humidity (%RH)	**Initial state**	**55**	**89**	**97**	**-**
Saline solution	-	NaBr	KCl	K_2SO_4	-
Water content w (%)	27.8	9.8	17	26	29.3
Saturation degree S (%)	95	35	60	90	100

3.3. Experiment scheme

To complete the existing experimental data on the behaviour of the Royer chalk (Lafrance and al. 2016), an experimental program presented in Table 2 was designed to study the influence of the water saturation degree on the mechanical behaviour of the chalk. Short term tests are carried out for different saturation degree (ranging from a dry state corresponding to 35% to a saturated state of the material).

The calculated actual in situ stress obtained is 1 MPa and the in situ relative humidity measured inside the chalk mine is between to 97% and 100%.

Table 2. Experiment scheme

	Confining pressure (MPa)	Saturation degree (%)
Hydrostatic test	-	35, 60, 90, 100
Triaxial test	0.5 1 1.5 2 3	100

3.4. Experimental device

The specimen is inserted inside a rubber jacket and isolated from the confining fluid. It is placed between two porous steel pads, to obtain a uniform distribution of fluid pressure at the inlet and outlet of the specimen. After the application of the confining pressure and for the saturated tests only, the saturation of the specimen is done by a water injection procedure. All tests are conducted in drained conditions and carried out under an isothermal condition with an average room temperature of 20 ± 2 °C.

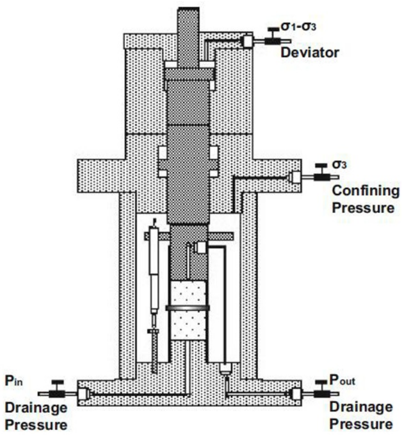

Figure 3. Schematic representation of an auto-compensated triaxial testing system

All tests are conducted by using an auto-compensated triaxial testing system where the schematic illustration is shown in Fig. 3. It is composed of a cylindrical cell and three high pressure generators with a maximum capacity of 60 MPa each, the first one is used for the confining pressure, the second one for the deviatoric stress loading. There are two pressure transducers, respectively for measuring confining pressure, deviatoric stress. The axial strain is measured by two LVDT transducers, which are placed between the top and the bottom platens inside the cell. The lateral strain is measured using a home-designed strain ring placed at the middle height of the sample.

3.5. Hydrostatic and Triaxial Compression Testing procedure

The drained hydrostatic compression tests are performed to determine the bulk compressibility and the variation of the pore collapse of the chalk under different water saturation degrees. The test is conducted in by increasing the confining pressure to a desired value with a prescribed rate.

The drained triaxial tests are performed in two steps (three for the saturated tests).

First a low confining pressure is applied up to a desired value (0.5 MPa). Then the sample is saturated and finally the deviatoric stress is increased with a desired axial strain rate until sample failure or a large axial strain while the confining pressure is kept at a constant value.

4. Experimental results

In this section, the main results obtained from hydrostatic and triaxial compression tests are presented.

4.1. Drained hydrostatic compression tests

The drained hydrostatic tests are realized with different saturation degrees, from a dry state corresponding to 35% of water saturation degree to 100% saturation degree. The loading rate of the hydrostatic rate is 4×10^{-4} MPa/s. The volumetric strain (ε_v) is calculated from the measured values of the axial and lateral strains ($\varepsilon_1, \varepsilon_3$). The obtained stress-strain curves are shown in Fig. 4.

The basic response of the porous chalk under hydrostatic compression can be decomposed into three phases. After the first quasi-linear phase, which represents the elastic compressibility of chalk skeleton, the hydrostatic stress reaches the pore collapse yield stress where an irreversible volumetric strain corresponding to the plastic collapse of porous microstructure occurs. The plastic pore collapse induces an increase in contact surfaces between solid grains; this leads to a plastic hardening phase with a decreasing volumetric strain rate, which is like plastic consolidation in soil mechanics.

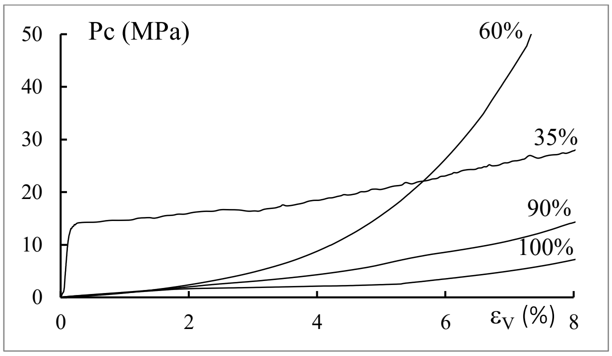

Figure 4. Stress-strain curves of Chateau-Landon chalk obtained in hydrostatic compression tests under different saturation degrees

4.2. Drained triaxial tests

To study the mechanical behaviour of the porous chalk subjected to deviatoric stresses, conventional triaxial compression tests are carried out under an axial strain-controlled condition. The axial strain rate is $5 \times 10^{-6}/s$ which is considered low enough to avoid excessive interstitial overpressure. The obtained stress-strains responses are shown in Fig. 5 and 6.

It is seen that, because of the high porosity, the behaviour of the chalk is strongly dependent on confining pressure.

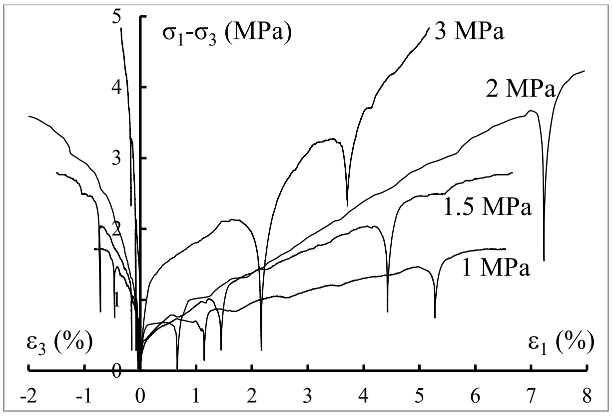

Figure 5. Stress-strain curves of saturated Chateau-Landon chalk obtained in triaxial compression tests under different confining pressures

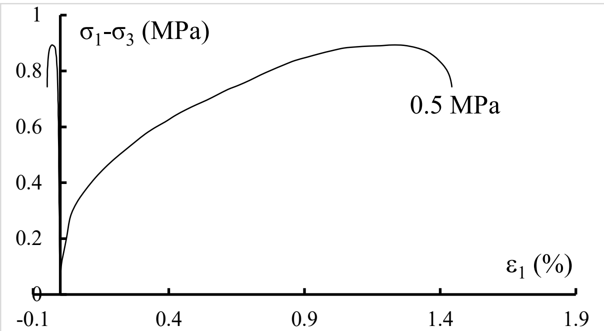

Figure 6. Stress-strain curves of saturated Chateau-Landon chalk obtained in triaxial compression tests for a confining pressure of 0.5 MPa

5. Discussions - Effect of confining pressure and water saturation on plastic deformation process

Based on the experimental results presented above, some specific features are discussed here. It is proposed to investigate the effects of the confining pressure and water saturation degree on the plastic deformation process.

5.1. Plastic deformation under hydrostatic compression

According to previous studies on different porous rocks (Homand and Shao. 2000; Han and al. 2016), a typical stress strain curve of a porous rock is generally composed of three phases, which are confirmed by this present study of the chalk.

For the dry state (35% of water saturation), the first concave shows a linear elastic behaviour. When the effective hydrostatic stress reaches the limit value (11 MPa in this case), the plastic pore collapse occurs and produce an important volumetric compaction. It results in an increase in contact surfaces between solid grains and enhances plastic hardening.

For higher saturated degree, after the pore collapse phase there is an increasing material hardening observed which is a consequence of void space reduction and rearrangement of grains.

In this present work, the effective hydrostatic stress is increased up to 50 MPa. It is possible to identify three phases and observe the beginning of the pore collapse. Elastic and plastic compressibility are more important in the dry state (strong cohesion due to suction).

Because of its high porosity, this rock has a very particular behaviour: under a dry state (35% of water saturation), it behaves like a fragile rock and under high saturated degree, like a soil. This means that the water saturation degree strongly affects the mechanical behaviour of the chalk under hydrostatic compression, it shows a strong increase of the deformability of the chalk with the increase of the saturation.

5.2. Plastic deformation under triaxial compression

The plastic deformation process under triaxial compression is complex and strongly influenced by the confining pressure, especially for a saturated state of the sample.

Under a very low confining pressure (for instance 0.5 MPa), the chalk exhibits an elastoplastic brittle behaviour (Fig. 6). The sample failure is marked by a strain softening phase. This is generally generated by the coalescence of micro-cracks. When the mean stress is under a certain limit value, we can argue that the plastic deformation of chalk is essentially due to matrix shearing (dislocation type mechanism) activated by the applied deviatoric stress.

For the tests under higher confining pressures (between 1 MPa and 3 MPa which are considered high since the in-situ stress is 1 MPa), no peak stress can be identified until a large value of axial strain (Fig. 5). The chalk presented an elastic-plastic ductile behaviour. It is not easy to identify the initial elastic limit which obviously increases with the confining pressure. A brittle to ductile transition is noted in the behaviour when the confining pressure increases.

With the increase of the confining pressure, the peak stress progressively becomes less pronounced and even disappears. After the elastic limit, there is a transition from the volumetric compressibility to dilatancy during the deviatoric loading. The dilatancy referred to the development of an incremental volumetric dilatation during plastic deformation (Wong et al. 1997).

5.3. Bases for a constitutive modelling of this chalk

The experimental results presented before have shown that the Chateau Landon chalk has two plastic deformation processes: the pore collapse, and the matrix shearing. These two should be considered in the constitutive modelling. A plastic model based on the Gurson's criterion has been proposed for porous chalk (Shen and Shao. 2018). Recent developments in nonlinear homogenization techniques have provided a way to develop plastic models for porous rocks. Therefore, some micro-mechanics based elastoplastic models have been proposed for porous rocks (Shen et al. 2013). The ongoing development consists in considering the influence of the saturation degree on the studied chalk behaviour previously discussed with these constitutive bases.

6. Conclusions

This paper presents an original experimental investigation to study the hydromechanical behaviour, thus water sensitivity, of a porous chalk.

Two series of experiments have been performed. With the hydrostatic tests, the basic mechanical behaviour of the chalk was investigated in different water saturated conditions. According to the results, it seems to exist a critical water saturation degree at which a sudden transition from "fragile rock" to "soil" behaviour takes place (one additional hydrostatic test will be done at a water saturation degree chosen between 35% and 60%). Partially physical explanations can be issued in connection with the microscopic structure of the chalk. The triaxial tests performed on initially water saturated samples have been carried out under different confining pressures. The results show the brittle to ductile transition behaviour with the increasing confining pressure. 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. Additional triaxial tests will be carried out under different water saturation conditions and a very low confining pressure (0.5 MPa) to complete this experimental investigation.

The experimental data will provide valuable information for the formulation and validation of a constitutive model for porous rocks. This will be considered in future work.

This case study analysis (Chateau-Landon) is interesting for knowledge and research initiatives regarding interaction between climate change and rock mechanics, not only dealing with underground cavities but also landslides and rockfalls.

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