E3S Web of Conferences **382**, 04008 (2023) https://doi.org/10.1051/e3sconf/202338204008
UNSAT 2023

Experimental investigation on the hydromechanical behaviour of a porous chalk

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Abstract. This paper deals with the impact of climate change on stability of abandoned subsurface cavities in chalk due to its indirect effect on ground water levels. It is the first part of a general work on the hydromechanical behaviour of a partially saturated soft rock (a porous chalk) and the effect of changes in water saturation degree. An experimental investigation including a laboratory-testing program is presented. Different degrees of saturation are imposed by controlled relative humidity conditions. Conventional hydrostatic and triaxial compression tests are performed under drained conditions for saturation degree up to 100% under low confining pressures. The obtained results have allowed to show up fundamental aspects of the chalk behaviour. The high sensitivity of the extracted material to water is described and a water induced plastic deformation is observed.

1 Introduction

Numerous shallow underground cavities, natural or manmade, well known or totally unlocated, undermining the France's territory. A large majority of those mine workings appears to be very sensitive to the variations of their environmental parameters. Due to the seasonal environmental changes (water table, hygrometry) the pillars of mines in chalk are often submitted to variations of the degree of water saturation. These changes could affect the short- and long-term stability of pillars in the underground quarries [2].

Among others, the specific case of a ground collapse (with consequences as: 7 deaths and 7 severe injured persons, major landside taking away several houses) that affected the Paris Basin during a major flood of the Seine River one century ago is an illustration of the importance of water variation impacts on rock mass behaviour. The chalk mine known as Beaulieu (Fig. 1.) located in the commune of Château-Landon, collapsed in January 1910, in direct connection with the flood of the Seine River. The lowest parts were then invaded and gradually the whole structure weakened and collapsed.

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 Beaulieu mine (Fig. 1). This mine also showed signs of instability evolving in 2016 following exceptional climatic events in the region. It was then studied and monitored.

Various investigations have been carried out on the collapse phenomena for mineworking [1, 11, 12, 13]. [5] showed that the mechanics of unsaturated soils could be used to investigate the behaviour multiphase chalks.

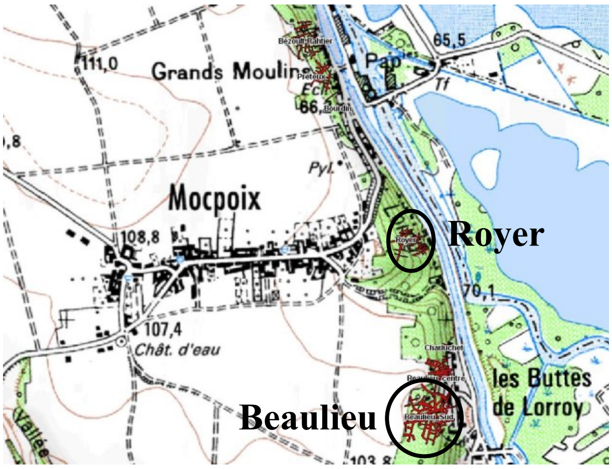

Fig. 1. Localization of Beaulieu and Royer mines

The objective of this paper is to describe the response of a specific chalk over the entire realm of water content from dry to saturated conditions and under low confining stresses, replicating the natural conditions of a chalk mine. The effect of water content on the stress–strain response of the chalk has been investigated. These aspects have been considered through a series of tests performed on chalk specimens. Each series of tests involved the application of different water saturations (from dry to saturated atmospheres), chalk samples were put in equilibrium with atmospheres whose relative humidity was controlled.

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2 Testing procedure

2.1 Material

2.1.1 Preparation of specimens (Chalk origin and sample preparation)

All the tests have been performed on an outcrop chalk from Campanian age called Chateau-Landon's chalk sampled in the Royer mine (Seine-et-Marne, France). It is relatively homogeneous and an isotropic material at the sample scale. It is rather pure (more than 97% $CaCO_3$). Its porosity ranges from 42% to 45% with an average of about 44%. Its permeability is about 2 mD ($2 \times 10^{-15}\ m^2$).

The in-situ extraction procedure of the chalk is a major concern since the materials are subjected to coring, deconfinement, transport, conditioning, and laboratory preparation effects, which often lead to desaturation and damage. It is recommended wrapping cores directly after extraction to avoid prolonged exposure to air [3-6]. In this study, cylindrical specimens with diameters of 50 to 100 mm are drilled, wrapped in plastic film, and stored in airtight bags. Water-content measurements are then carried out once in the laboratory. The aim of this procedure is to avoid changes in water content and limit the desaturation of the samples.

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. Based on the average mineral grain size, this specimen size appears to be large enough to be a representative volume element of the chalk.

2.1.2 Saturating procedures

To obtain a fixed and homogeneous (or uniform) water saturation level, chalk samples are placed in hermetic chambers each above a different salt-saturated water solution, which enables to obtain a fixed relative humidity (RH) in the chamber atmosphere. Depending on the nature of salt, and on temperature, different RH are obtained (Table 1). When the weight evolution is stabilized, the specimen is assumed to be in equilibrium with the controlled humidity atmosphere.

Meanwhile, the fluid used for complete water saturation is distilled water mixed with crushed chalk and then filtered for it to be in chemical equilibrium with chalk to avoid dissolution phenomenon.

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

2.2 Experimental methods

2.2.1 Experimental scheme

The pure mineral composition of this chalk allows us to capture the sensitivity of chalk behaviour more easily to water content. To complete the existing experimental data on the behaviour of the Royer chalk, an experimental scheme 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 considered under different saturation degree (ranging from a dry state corresponding to 35% to a saturated state of the material).

There are a few numbers of previous experimental results available on this chalk [2-8] so the new results obtained in this work will complete and compare with the previous ones to give a more extensive database.

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

2.2.2 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. For the saturated samples the injection of water is operated after the application of the confining pressure.

All tests are conducted by using an auto-compensated triaxial testing system (Fig. 2.) 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 deviatoric stress loading, the second one for the confining pressure.

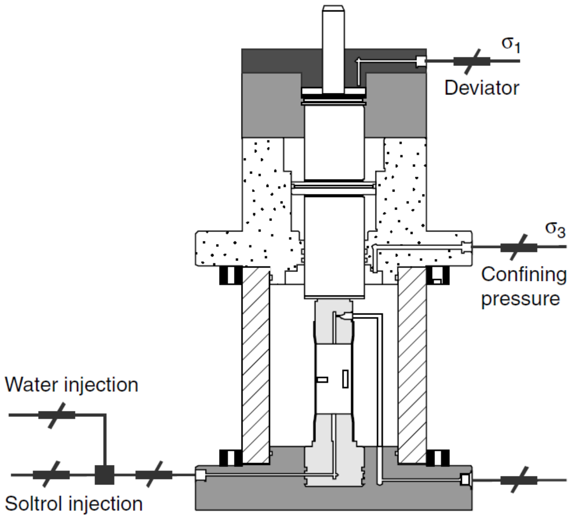

Fig. 2. Schematic presentation of the auto compensated triaxial cell

3 Experimental results and discussion

3.1 Drained hydrostatic compression tests

The drained hydrostatic tests are realized with different saturation degrees. The loading rate of the hydrostatic rate is 4×10^{-4} MPa/s. The obtained stress-strain curves are shown in Fig. 3.

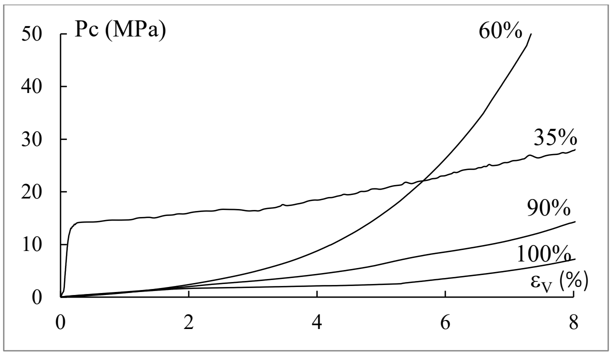

Fig. 3. Stress-strain curves of Chateau-Landon chalk obtained in hydrostatic compression tests under different saturation degrees

These curves illustrate the sensitivity of the mechanical response of the chalk to change in water saturation degree (thus suction). They are in good agreement with the water weakening effects described by [4-11]. The increase of the resistance with the decrease of the degree of saturation is related to the variation of the suction, due here to the phenomenon of capillarity.

The volumetric strain curve is usually composed of three different phases: a nonlinear concave phase with a decreasing compaction due to progressive closure of microcracks, a quasi-linear phase corresponding to elastic compaction of pores and a nonlinear phase with increasing compaction indicating the onset of the plastic collapse [7].

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 likely a consequence of void space reduction and rearrangement of grains [7-8].

3.2 Drained triaxial tests

The degree of saturation going from 90% at the surface of the pillar to 98% towards the core as indicated by [2], the surface area created by the desaturation of the chalk probably ensures a confinement that allows it to be maintained thanks to the suction generated. A total resaturation without confinement of the sample would lead to its collapse [10]. Therefore, we have intentionally chosen to test the sample under a pressure (0,5 MPa) lower than the in-situ pressure (1 MPa).

All triaxial tests were performed under drained conditions at constant loading rate (5×10^{-6}/s). The stress path was the following: at 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.

The obtained stress-strains responses are shown in Fig. 4 and 5.

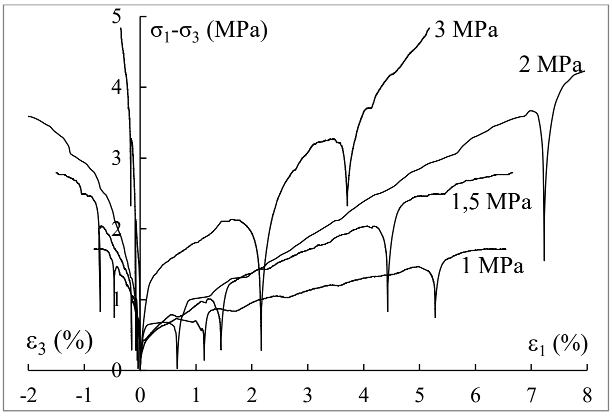

Fig. 4. Stress-strain curves of saturated Chateau-Landon chalk obtained in triaxial compression tests under different confining pressures

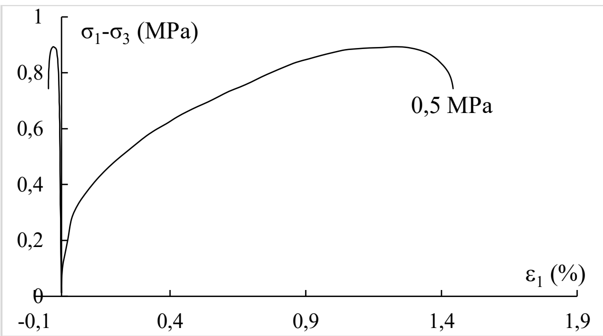

Fig. 5. Stress-strain curves of saturated Chateau-Landon chalk obtained in triaxial compression tests for a confining pressure of 0,5 MPa

https://doi.org/10.1051/e3sconf/202338204008

For a very low confining pressure (0,5 MPa), the chalk behaviour is rather brittle, and a small volume compaction is obtained (Fig. 5). The sample failure is marked by a strain softening phase (net peak deviatoric stress at 0,9 MPa). This is generally generated by the coalescence of micro-cracks [7]. We could argue that when the mean stress is under a certain limit value, the plastic deformation of chalk is essentially due to matrix shearing activated by the applied deviatoric stress [8].

For higher confining pressures (between 1 MPa and 3 MPa, the in-situ stress being 1 MPa), the chalk behaviour becomes clearly different, and no peak stress can be identified until a large value of axial strain (Fig. 5). An important plastic hardening zone is obtained, and no apparent macroscopic failure of the sample is observed (visual inspections of the tested samples does not reveal any signs of strains localizations).

This chalk presented an elastic-plastic ductile behaviour under saturated conditions. 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. These results show a strong influence of an effective confining pressure on the mechanical behaviour of a saturated chalk.

4 Conclusion

This paper presented the description of the general context of the study and the effects of water saturation on the hydromechanical behaviour of chalk, the methodology developed for its experimental study in the laboratory, the description of the tests performed, and the first results obtained. The results confirmed the great susceptibility of the Chateau-Landon's chalk to changes in the water saturation degree.

Two series of experiments have been performed. In the first series (hydrostatic tests), the basic mechanical behaviour of the chalk is investigated in different water saturated conditions. In the second series (triaxial tests), tests in initially water saturated samples have been carried out under different confining pressures.

It was observed that the saturated sample (under zero suction) and low confinement had a low resistance which shows the high sensitivity of this chalk to water saturation degree. In the Royer mine, the state of the pillars is stable even with a very high saturation degree (around 95%) [2]. Those better characteristics are related to the quasi-saturated state under suction in which the pillars are, due to surface evaporation. Their stability is thus conditioned by their hydrostatic state, which is itself dependent on the water inflow by capillary infiltration and surface evaporation by the ventilation of the gallery. Following the laboratory results, quick saturation due to flooding remains the main danger for the stability of chalk mines.

To complete the experimental investigation and validate these observations, additional triaxial tests will be carried out under different water saturation conditions and a very low confining pressure (0,5 MPa).

References

1. F.G. Bell, M.G. Culshaw, J.C. Cripps, *A review of selected engineering geological characteristics of English chalk*, Eng. Geol. **54**, 3-4 (1999)
2. N. Conil, P. Gombert, M. Al-Heib, N. Spitzenteder, R. Muller, D. Pajiep, *An underground research laboratory at Château-Landon (France) to study the impact of climate change on the stability of abandoned mine*s, Bull Eng Geol Environ **82**, 11 (2023)
3. N. Conil, J. Talandier, H. Djizanne, R. de La Vaissière, C. Righini-Waz, C. Auvray, C. Morlot, G. Armand, *How rock samples can be representative of in situ condition: A case study of Callovo-Oxfordian claystones,* J. of Rock Mech. & Geol. Eng. **10**, 4 (2018)
4. V. De Gennaro, P. Delage, G. Priol, F. Collin, Y.J. Cui, *On the collapse behaviour of oil reservoir chalk*. Géotechnique. **54**, 6 (2004)
5. P. Delage, C. Schroeder, Y.J. Cui, *Subsidence and capillary effects in chalks*, EUROCK '96, Prediction and performance on rock mechanics and rock engineering 2, Turin, Italy (1996)
6. R.T. Ewy, *Shale/claystone response to air and liquid exposure, and implications for handling, sampling and testing*, Int. J. of Rock Mech. & Min. Sci. **80** (2015)
7. B. Han, S. Y. Xie, J. F. Shao, *Experimental investigation on mechanical behaviour and permeability evolution of a porous limestone under compression*, Rock Mech. Rock Eng **49** (2016)
8. S. Homand, J.F. Shao, *Mechanical Behaviour of a Porous Chalk and Water/Chalk interaction. Part 1: Experimental Study*, Oil Gas Sci Technol **55,** 6 (2000)
9. N. Lafrance, C. Auvray, M. Souley, V. Labiouse, *Impact of weathering on macro-mechanical properties of chalk: Local pillar-scale study of two underground quarries in the Paris Basin,* Eng. Geol. **213** (2016)
10. J. Munoz-Castelblanco, J.M. Pereira, A. Minh Tang, P. Delage, *Comportement de la craie du site de Lorroy*, Research report, ENPC, Navier/CERMES Laboratory, 15 p (2011)
11. G. Priol, *Comportement mécanique différé et mouillabilité d'une craie pétrolifère,* ENPC, PhD thesis, 217 pp (2005)
12. C. Sorgi, *Contribution méthodologique et expérimentale à l'étude de la diminution de la résistance des massifs rocheux par vieillissement*. BCRD Final report, INERIS-DRS : 132 pp (2004)
13. M.L. Talesnick, Y.H. Hatzor, M. Tsesarsky, *The elastic deformability and strength of a high porosity, anisotropic chalk*, Int. J. of Rock Mech. & Min. Sci. **38**, 4 (2001)