Hydromechanical characterization of Château-Landon chalk behavior

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ABSTRACT: The paper deals with the effect of water saturation degree on the stress–strain response of a high-porosity and pure chalk, the Chateau-Landon chalk. A general experimental methodology is presented, including hydrostatic and triaxial compression tests performed under drained conditions with loading paths combining variations of stresses and water saturation degree to characterize the hydromechanical behavior of this porous material.

Keywords: Chalk, hydromechanical behavior, water saturation, porous.

1 INTRODUCTION

The French National Institute for Industrial Environment and Risks (Ineris) carried out numerous studies in the understanding and prediction of the consequences of climate change on the stability of abandoned subsurface cavities (Conil et al. 2022). According to climate changes, water level variations and changes in water saturation degree in the pillars of the mine should be observed because of the unpredictable modification of the rainfall regime. The specific case of a ground collapse of the chalk mine of Lorroy (Château-Landon, France) with consequences such as 7 deaths and 7 severely injured persons, during a major flood of the Seine River that affected the Paris Basin one century ago is a perfect illustration of the importance of water impacts on rock mass behavior. The existence of remaining accessible mine in the surroundings such as the "Royer" mine enable Ineris to carry out studies on the behavior of its chalk under unsaturated and saturated states. In this paper a study on the hydro-mechanical behavior of a partially saturated, porous, and pure chalk under low confining stress and the effect of changes in water saturation degree is presented, replicating the natural conditions of the Royer mine.

2 CHALK PROPERTIES, SAMPLING AND SPECIMEN PREPARATION

Test specimens were sampled at the Royer mine (Seine-et-Marne, France). It is a homogeneous and isotropic material at the sample scale and is rather pure (more than 97% $CaCO_3$) (Lafrance 2016).

The dry unit mass varies from 1,54 to 1,56 Mg/m^3, which corresponds to a porosity range of 42–45%. The specific gravity of solids (Gs) was found to be 2,76. 300 mm long and 50 to 100 mm in diameter cores were drilled horizontally from different pillars in the mine (Figure 1). Test specimens were prepared by coring 36 mm diameter cylinders from the 100mm plugs.

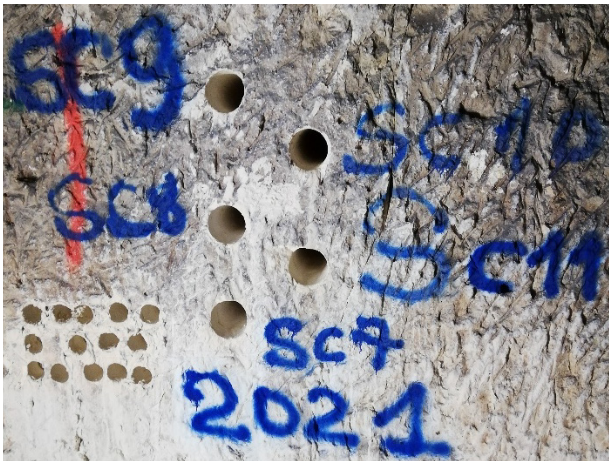

Figure 1. Plugs cored from pillars in the Royer mine.

3 APPARATUS, PROCEDURE, AND PROGRAMME

All tests are conducted using an auto-compensated triaxial testing system composed of a cylindrical cell and two 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. The measurement of deformation within specimens of chalk is not trivial. The task becomes significantly more difficult when testing specimens with greater water saturation degrees. Strain gauges cannot be used under such conditions because the bond between the gauge and the specimen becomes tenuous. Diametrically opposed pairs of vertically linear variable differential transducers (LVDTs) were then installed to measure axial deformations and a home-designed strain ring placed at the middle height of the sample for lateral strains (Figure 2).

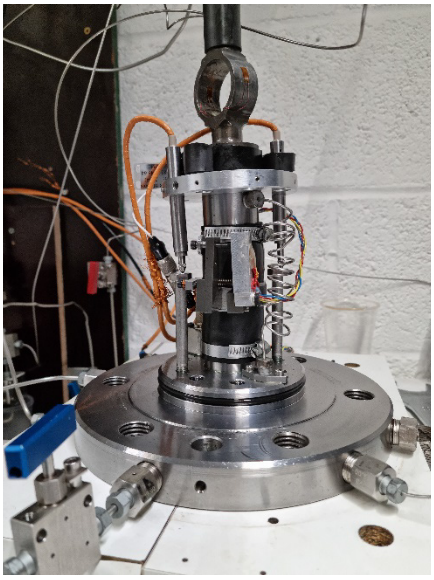

Figure 2. Local deformation measurement system.

To obtain different water saturation levels, 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 (Delage et al, 1998). When the weight evolution of the specimen is stabilized, it is assumed to be in equilibrium with the controlled humidity atmosphere.

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 the dissolution phenomenon.

An experimental scheme presented in Table 1 was designed to study the influence of the water saturation degree on the mechanical behavior of the chalk. Short-term tests are performed under different saturation degrees. The calculated actual in situ stress obtained being 1 MPa, 5 different confining pressures were chosen between this value to perform triaxial tests at a saturated state of the material while the relative humidity measured inside the chalk mine is between to 97% and 100%, 4 water saturation degree where also chosen starting from a quasi-dry saturated state (35%) to a total saturated state.

Table 1. Experimental program for laboratory tests.

	Confining pressure (MPa)	Saturation degree (%)
Hydrostatic test	Up to 50 MPa	35, 60, 90, 100
Triaxial test	0,5; 1; 1,5; 2; 3	100

4 EXPERIMENTAL OBSERVATIONS ON THE CHATEAU LANDON CHALK BEHAVIOR

Figures 2 and 3 present stress–strain curves for hydrostatic and triaxial compression tests performed on cylindrical specimens. The curves illustrate the obvious reduction of compressive strength and axial stiffness as a function of increasing water saturation degree.

By looking at the results of the hydrostatic compression tests (Figure 2), the water sensitivity of chalk behavior is clearly shown. We can note two behaviors depending on the water saturation degree: under quasi-dry conditions (35% of water saturation degree), it behaves more like a rock and under higher saturated degrees (60% to 100% of water saturation degree), like a ‘soil’. Elastic and plastic compressibility are more important in the dry state (strong cohesion due to suction). For the quasi-dry state, it is possible to identify three phases and observe the beginning of the pore collapse. The first part of the curve shows a linear elastic behavior. When the effective hydrostatic stress reaches the limit value (11 MPa in this case), the plastic pore collapse occurs and produces important volumetric compaction. It results in an increase in contact surfaces between solid grains and enhances plastic hardening (Homand & Shao 2000). For higher saturated degrees, the first two phases cannot be observed but an increasing material hardening is observed, which is likely a consequence of void space reduction and rearrangement of grains (Collins et al. 2002). Additional hydrostatic tests will be carried out between 35% and 60% of water saturation degree to determine at which degree there is a change in behavior.

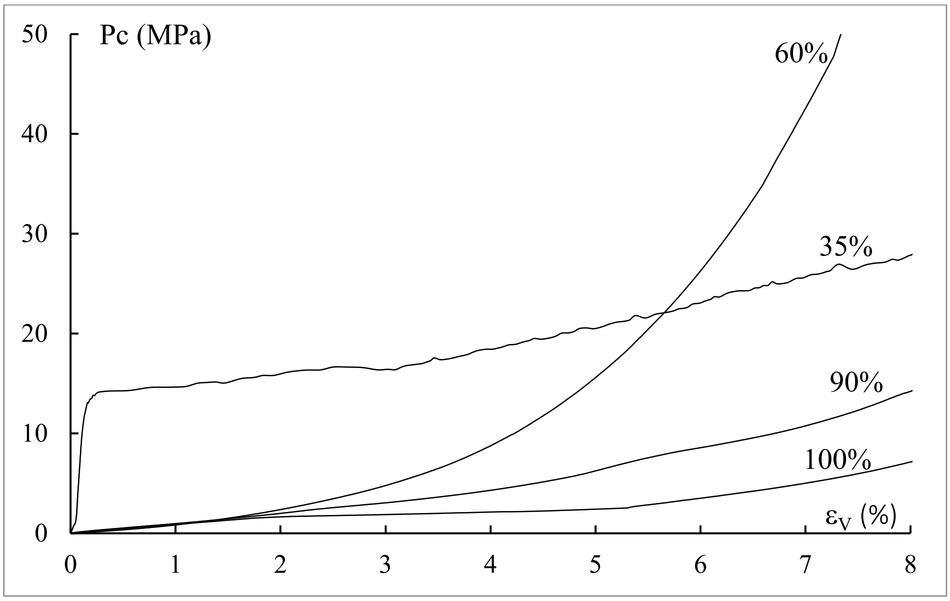

Figure 3. Stress-strain curves obtained from hydrostatic compression tests under different saturation states.

The results of the triaxial compression tests presented in figure 3 show the influence of the confining pressure on the mechanical behavior of saturated chalk.

For a very low confining pressure (0,5 MPa), the chalk behavior shows a peak strength at 1,3% axial strain and a small volumetric compaction is obtained. The sample failure is marked by a strain softening phase (net peak deviatoric stress at 0,9 MPa). This is generally generated by micro-cracks coalescence. For higher confining pressures (between 1 MPa and 3 MPa, the estimated vertical in-situ stress in the pillar being 1 MPa), the chalk behavior becomes clearly different, and no peak stress can be identified until a large value of axial strain. An important plastic hardening zone is obtained, and no apparent macroscopic failure of the sample is observed (visual inspections of the tested samples do not reveal any signs of strain localizations).

This chalk presented an elastic-plastic ductile behavior under saturated conditions. It is not easy to identify the initial elastic limit which obviously increases with the confining pressure. Additional triaxial tests were also carried out at 0,5 MPa and the different water saturation degrees (35%,60%,90%,100%) to complete the experimental investigation.

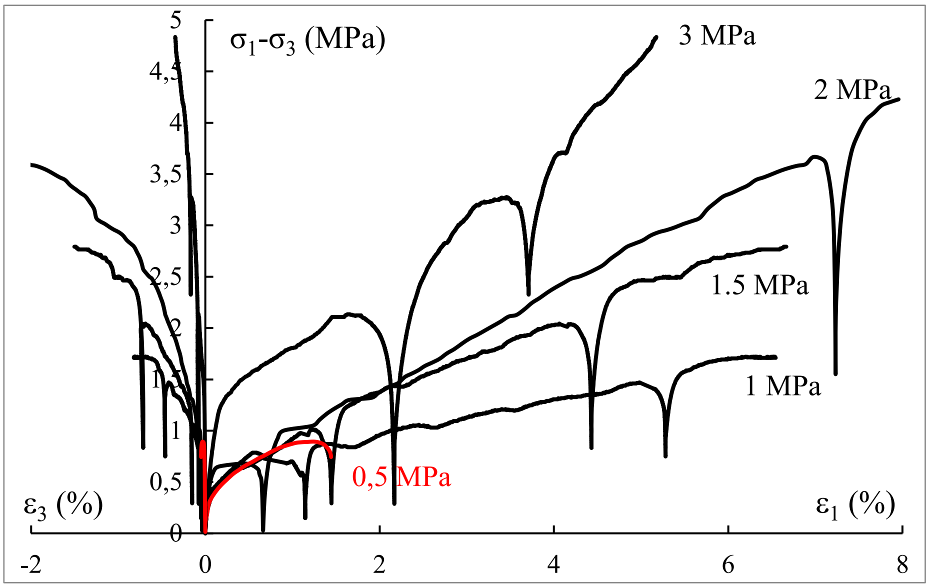

Figure 4. Deviatoric stress versus axial and lateral strains during triaxial compression tests.

5 BASES FOR A CONSTITUTIVE MODELING OF THIS CHALK

The experimental results have shown that this 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 behavior previously discussed with these constitutive bases.

6 CONCLUSION

An extensive set of mechanical tests has been carried out on a porous and pure chalk. The objective was to consider the effect of water saturation degree and confining pressure on the hydromechanical response of the material. Different testing configurations were used, each aimed at considering a different aspect of the material response. Performance of the different testing procedures required the development of a system for reliable and accurate measurement of deformations where the use of conventional techniques is not reliable. The study has led to separate conclusions in regards the response of the chalk. The stress–strain response of the chalk transforms from linear to nonlinear as a function of confining pressure and water content. The triaxial tests results show mainly ductile behaviour with the increasing confining pressure except for the one at 0,5 MPa confining pressure where the peak strength is reached after 1,3% of deformation, while in the hydrostatic tests, it seems to exist a critical water saturation degree at which a sudden transition from "soft rock" to "soil" behaviour takes place (hydrostatic tests). Additional tests were also carried out to complete this experimental investigation, they confirmed the results. In future work, the efficiency of the model will be assessed by comparing the numerical results and experimental data for hydrostatic and triaxial tests with different confining pressures and different water saturation degrees. The last step will consist of simulating a flooded pillar and studying its stability.

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