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Experimental investigation of the effect of temperature on the mechanical behavior of Tournemire shale

M. Masri [a], M. Sibai [a], J.F. Shao [a,*], M. Mainguy [b]

[a] *Laboratory of Mechanics of Lille, UMR8107 CNRS, University of Lille, 59655 Villeneuve d'Ascq, France*
[b] *TOTAL Scientific and Technical Center, Pau, France*

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ABSTRACT

This paper is devoted to the experimental investigation of the effect of temperature on the mechanical behavior of a typical anisotropic clayey rock, the Tournemire shale. Hydrostatic and conventional triaxial compression tests are first performed under room temperature for two principal loading orientations, respectively parallel and perpendicular to the bedding planes. The obtained results confirm an anisotropic mechanical behavior observed by the previous works. Further, hydrostatic and triaxial compression tests with different confining pressures are carried out under different temperatures up to 250 °C. With the increase of temperature, there is a significant decrease of Young's modulus and the compression failure strength but an increase of the overall deformability of material. The temperature change also affects the anisotropic response related to the deformation of bedding planes.

1. Introduction

Clayey rocks are recently extensively investigated in various engineering contexts: geological disposal of nuclear waste, heavy oil and shale gas exploitation, geothermal engineering, etc. In some situations clayey rocks act as a geological barrier or cover layer due to their low permeability. In other ones clayey rocks constitute reservoir formations such as in shale gas production. However, in all cases, the clayey rocks are subjected to combined mechanical loads, changes of fluid pressure and temperature. It is thus primordial to investigate the hydromechanical and thermo-mechanical behaviors of such rocks in order to evaluate the integrity and durability of structures in such complex contexts.

Due to their specific microstructure, mineralogical composition and geological evolution history, the clayey rocks manifest anisotropic mechanical, hydraulic and thermal behaviors. Due to the presence of parallel bedding planes, the clayey rocks can be considered as transversely isotropic materials. A number of previous experimental studies have been devoted to the characterization of elastic, plastic and failure behaviors of various clayey rocks. Without giving an exhaustive list of such works, some syntheses of representative experimental data can be found in [1–4]. Uniaxial and triaxial compression tests have generally been performed on rock samples drilled in different orientations with respect to the bedding planes. Both elastic moduli and failure stress are affected by the loading orientation, as well as the macroscopic failure mode. For instance, with the loading orientation perpendicular to the bedding planes, the material failure is related to the onset of localized shear band passing through bedding planes while a splitting failure mode is found when the applied stress is parallel to the bedding planes. The minimal failure strength is generally found when the loading orientation is around 45° and the material failure is inherently related to the sliding of bedding planes. Further, due to the presence of clay minerals such as smectite, the mechanical behavior of clayey rocks is also very sensitive to water content. A number of experimental investigations have been conducted in order to determine mechanical behaviors of clayey rocks under different saturations conditions for instance [5–7] just to mention some recent works. Due to the capillary force among other factors, the elastic modulus and failure stress generally increase with desaturation. However, due to material heterogeneity and low permeability leading to a strong hydric gradient, the drying process is also an important cause of micro-cracking. This desiccation damage can significantly modify the permeability and heat conductivity of rocks and then the integrity of geological barrier and cover layer. Concerning thermal effects on mechanical behavior, a series of experimental studies have been devoted to clay [8], soft clayey rocks [9,10] and only very few studies to hard clayey rocks [11,12,13]. Most of these works have focused at the hydromechanical characterization of engineered and geological barriers for geological disposal of nuclear waste. In general, the plastic consolidation stress is reduced by the increase of

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* Corresponding author.
E-mail address: jian-fu.shao@polytech-lille.fr (J.F. Shao).

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temperature and this leads to a thermal plastic collapse of material under constant stresses. The increase of temperature can also enhance the creep deformation of clayey rocks. However, in most previous studies, the value of temperature was often limited to 100 °C. For some engineering applications, for instance the heavy oil production by the steam assisted gravity drainage technique, there is a need to investigate the mechanical behavior of hard clayey rocks under higher temperature [14]. The objective of the present work is then to complete these existing investigations by carrying out new laboratory tests on a typical hard clayey rock with higher values of temperature up to 250 °C. The emphasis is given to the characterization of thermal effects on the deformation and compression strength behaviors in relation with its anisotropic structure. The experimental results expected will provide the background for further constitutive modeling and numerical analysis of engineering structures.

2. Material studied and experimental procedure

The anisotropic material studied in this work is upper Toarcian massive shale taken from the Tournemire site in the Massif Central region of France. This is a typical clayey sedimentary rock located between two aquifer limestone layers and affected by faults and fractures of tectonic origin. The average mineralogical compositions of the shale are: 27.5% kaolinite, 16.5% illite, 19% quartz, 15% calcite, 2.7% chlorite, 8.3% I/S (interstratifier) and 11% others (pyrite, siderite, feldspars, etc.). The typical values of porosity and density at different temperatures are presented in Table 1 [2]. The initial permeability of the shale is very low and ranges from$10^{-19}m^2$ to $10^{-21}m^2$. The natural water content in the shale varies from 4.5% to 8% [6]. Cubic blocks of about 40 cm were cut from the experimental gallery of the Tournemire underground research laboratory. In order to avoid the modification of the water content and keep the shale in the state as close as possible to that in situ, the shale blocks from the site were covered by a waterproof coating (Rubson) until preparation of samples in the laboratory.

All the tests presented in this paper were performed on cylindrical samples with 37 mm in diameter and 74 mm in height. The samples were bored with air pressure from the cubic blocks and prepared with caution to reduce the disturbance of the material. The emphasis of this work is put on the temperature effects on the mechanical behavior of shale; only two groups of samples are considered and they are respectively bored in the perpendicular and parallel directions to the bedding planes of the shale.

The mechanical tests were carried out in a home-designed high pressure autonomous triaxial cell with a self-compensated axial piston. This cell is composed of three independent pressure chambers. A lower chamber is used to apply the confining pressure. The axial stress or displacement is generated with the help of an independent upper pressure chamber. A third pressure chamber is designed to compensate the effect of confining pressure on the axial stress. This cell was designed to perform hydrostatic, uniaxial and triaxial tests under different temperatures. For this purpose, the cell is equipped with a temperature-controlled heating collar which can provide a maximal temperature of 300 °C. An acquisition system and a microcomputer were used to register the experimental data. The axial displacement was measured by a pair of LVDTs which were placed locally between the bottom and upper surfaces of sample. Concerning the lateral strain in transversely isotropic materials, two lateral strains should generally be measured, respectively in the parallel and perpendicular directions to the bedding planes. However, for the sake of simplicity and putting the emphasis on the temperature effects, only the global radial strain of sample is measured using a specifically designed ring. It is a circumferential (circular) metal ring on which a complete strain gage bridge is glued. This ring is able to measure radial compaction and dilation of the sample but not able to distinguish two lateral strains in anisotropic materials.

Table 1
Porosity and density of shale at different temperatures [6].

Temperature (°C)	Porosity (%)	Density (g/cm^3)
65	8.35	2.72
80	8.53	2.73
150	13.7	2.76

In the present work, hydrostatic tests, uniaxial compression tests and triaxial compression tests were performed on the samples of shale cored in two principal orientations. Three confining pressures (5, 10 and 20 MPa) and five values of temperature (20, 100, 150, 200 and 250 °C) were considered. For each test, the sample was first heated until the desired value of temperature. The confining pressure or hydrostatic stress was then increased with a constant rate of 0.573 MPa/min before the loading of axial stress. Uniaxial and triaxial compression tests were performed under the axial strain-controlled condition with an axial strain rate of 10^{-6}/s. As mentioned above, the shale has a very low permeability. It is very difficult to obtain a fully saturated state. For the sake of simplicity, all the tests in this work were performed on the samples with the natural saturation state without resaturation phase. Further, all the tests were realized under pseudo drained condition but without controlling the evolution of pore pressure. Moreover, under high temperature levels, there could be a change in the physical state of pore water such as vaporization and related impacts on the mechanical behavior of the shale. These aspects are not studied in the present work which is limited to the analysis of global behavior of the shale under different values of temperature.

3. Main results and discussions

3.1. Hydrostatic compression tests

Hydrostatic compression tests are generally used to identify the anisotropic behavior of Tournemire shale. Such tests are ideally conducted on cubic sample allowing the determination of three principal strains regarding the structural framework of rock. However, for the sake of simplicity, only cylindrical samples drilled in the perpendicular orientation were tested. Therefore, the axial strain indicates the deformation in the direction perpendicular to the bedding planes. The evolutions of axial and radial strains versus confining stress are shown in Fig. 1 for five values of temperature. It clearly observed that the axial strain is much greater than the radial strain. Considering that the axial strain is in the perpendicular direction to bedding planes while the radial one in the parallel direction. This result confirms that the shale presents a transversely isotropic property of deformation. The axial strain is clearly nonlinear due to the progressive closure of bedding planes. Concerning the thermal effects, the deformation of shale in both orientations is enhanced by the temperature increase. This heating-induced volumetric compaction has also been observed on clays and other clayey rocks [8–10]. It seems that there is a reduction of plastic consolidation stress threshold by the increase of temperature. Further, we compared the axial strain obtained in the present work under room temperature with that reported in [2] on a cubic sample and found a good concordance between two series of tests.