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Thermo-mechanical volume change behaviour of Opalinus Clay

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ABSTRACT

The paper examines the thermo-mechanical volume change behaviour of Opalinus Clay in relation to different stress conditions and overconsolidation ratio (OCR) values and evaluates the impact of temperature on some hydro-mechanical properties of this material. To this aim, a focused experimental campaign consisting in high-temperature/high-pressure oedometric tests has been carried out. The results show that the thermo-mechanical volume change behaviour of Opalinus Clay is heavily affected by the OCR: thermal expansion is found when the heating is carried out at high OCR, whereas irreversible thermal compaction is observed when heat is applied at a vertical effective stress that is sufficiently close to the vertical effective yield stress. The study of the thermal cyclic behaviour shows that expansive irreversible strains can occur upon first heating at high OCR and that a reversible behaviour follows during subsequent thermal cycles. The experimental results reveal an impact of temperature on yielding: a decrease in the yield threshold is detected when compression is applied at high temperature with respect to the yield threshold found at low temperature. Compressibility and swelling indexes are not significantly influenced by thermal changes, as well as the oedometric modulus and the secondary compression coefficient, whereas consolidation processes are found to occur faster at high temperature. The obtained results are presented in this paper together with a description of the testing device and experimental procedure employed.

1. Introduction

In recent years, several shale formations have been involved in geo-energy related engineering fields that foresee the presence of high thermal loads or significant temperature variations. Such thermal conditions are related to a need to reach great depths (several hundred of metres), as in the case of CO_2 sequestration and Enhanced Geothermal System (EGS) technologies, or to the presence of thermal sources, as in the context of nuclear waste geological disposal. In addition, thermal changes can occur in shale formations through the injection of drilling and fracturing fluids at great depths, where a higher temperature with respect to the one of the injected fluid is encountered as a result of the geothermal gradient. Therefore questions are raised on the impact of temperature variations on the hydro-mechanical properties of shale formations and on the thermal response of the material at different stress conditions. The Opalinus Clay shale formation is considered as host-material for the construction of a deep geological repository for radioactive waste in Switzerland. The formation is expected to be exposed to higher temperatures relative to those found in-situ due to the disposal of the canister containing radioactive waste[1,2]; as a consequence, the thermo-mechanical behaviour of Opalinus Clay shale must be thoroughly analysed.

The thermo-mechanical behaviour of clays has been widely studied in the past, and extensive knowledge in this area has been acquired. The elastic domain has been found to reduce with an increase in temperature[3–7], and negligible thermal effects on the elastic and plastic compressibility of clays have been found by several authors[3,5,7–10]. The volumetric behaviour due to temperature changes has been found to be strongly dependent on the degree of overconsolidation,[3,6–11] as heating a normally consolidated clay results in volumetric contraction, slightly overconsolidated samples show initial expansion followed by thermal contraction, and highly overconsolidated samples undergo thermal expansion. Uncertainties remain with respect to basic mechanisms involved in the thermal compaction phenomenon, which is generally attributed to physico-chemical interactions between clay and water where a change of temperature produces a variation in the thickness of the double layer. In particular, thermal perturbations caused by an increase in temperature would result in the removal of bound water molecules and thus in an irreversible decrease in double layer thickness[12,13]. On the other hand, an increase in temperature causes also a rearrangement of particles[10] and generates structural disturbance together with mineral and adsorbed water thermal expansion.[14] The

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combination of such phenomena may lead to either thermal expansion or thermal compaction based on the predominant mechanism: both irreversible compaction[3,5–11] and irreversible expansive behaviour[14] have been experimentally observed. The effects of temperature on the coefficient of consolidation of clays have also been addressed in the past: in general an increase in temperature appears to generate an increase in the coefficient of consolidation, mainly due to a decrease in water viscosity at high temperatures.[9]

In recent years, attention has been paid to the study of the thermo-mechanical behaviour of argillites and shales given their involvement in the development of energy-related geo-engineering applications. Most studies on argillites have focused on the impacts of temperature on strength properties of these materials and have found a slight decrease in strength with an increase in temperature up to 100 °C.[15–17] A thermoplastic response similar to that found on clays, has been observed in an argillite[18]. While shales are heavily involved in energy-related fields, their thermo-mechanical behaviour has been poorly studied. Irreversible thermal compaction has been observed in Pierre shale[19] and for a Canadian shale[20]; a thermo-elasto-plastic response under temperature variations similar to that observed in clays has been reported for Opalinus Clay[21] together with a decrease of the failure strength at high temperatures.[22] On the other hand, the evolution of hydro-mechanical properties of shales with temperature at different stress levels has not been extensively examined thus far; this is of relevance when predictions of the response of the material are sought via the use of numerical tools.

The impact of the degree of overconsolidation and the effect on the yield stress and on the position of the compression line, are critical aspects in the analysis of the thermo-mechanical behaviour of clays; it is thus important to clarify these concepts in the context of the analysis of the thermo-mechanical behaviour of shales. Several studies on argillites and shales have highlighted the elasto-plastic response of these materials where both reversible and irreversible deformations can be produced upon mechanical loading and where a yield threshold defines the limit of the elastic domain.[6,23,24] Significant efforts have been made to develop elasto-plasticity based models for argillites and shales[25,26] which can also take into account the presence of some degree of plasticity before the main yield surface is reached.[27–29] The ratio of the maximum stress level ever experienced by a material (preconsolidation pressure) to the actual effective stress is commonly expressed as "overconsolidation ratio" (OCR).[30] This quantity refers to a pure mechanical compaction process. The overburden, which have occurred throughout the geologic history of shales, is among the factors that determine the value of the yield stress, but it is not the only one: particles and water-cations system rearrangement,[31] cementation processes[32,33] that occur during diagenesis and degradation phenomena, may induce a variation in the yield stress which becomes an apparent preconsolidation pressure. When the actual stress state has to be compared to the yield stress in the case of a material which have been subjected to chemical processes during its burial history, the term "yield stress ratio" (YSR) is to be used, which is the ratio of the effective yield stress of the material to the actual or imposed effective stress.[34] When dealing with shales, the need to distinguish between the two concepts of OCR and YSR is encountered, due to the relevance of the geologic history for these geomaterials. In this paper, both the concept of YSR and OCR should be adopted in order to distinguish between the yield stress exhibited by the material and the yield stress induced by mechanical loading in the laboratory. However, the term "OCR" is used here to identify the ratio of the vertical effective yield stress to the actual vertical effective stress, regardless of the way in which the yield stress is induced in the material.

In the context of this study, evidences are sought regarding the impact of temperature on the yield stress for shales, and the effect of the OCR on their thermal volume change behaviour. The thermal cyclic behaviour and thus the dependency of the thermal volumetric response on the temperature history have not been widely studied, and the temperature induced variation in porosity in shales has never been widely discussed. An investigation on the thermo-mechanical volume change behaviour of Opalinus Clay is carried out and presented in this paper. More specifically, this comprehensive experimental campaign aims (i) at analysing the thermal behaviour of Opalinus Clay in relation to different stress conditions and (ii) at examining the impact of temperature on hydro-mechanical properties of the shale formation. The first task involves examining the phase in which the radioactive waste is emplaced in the repository tunnels with the consequent heating of surrounding materials. The second task involves clarifying how the mechanical response of the material is altered by thermal perturbations. To address these issues, the experimental programme foresees mechanical loading and unloading paths under different constant temperatures and heating-cooling phases under varying levels of constant vertical effective stress. A high-pressure/high-temperature oedometer cell was developed, set up and calibrated to allow for the analysis of the volume change behaviour of shales under high temperatures (up to 100 °C) and under high stress levels (up to 100 MPa). Temperatures exceeding 100 °C are not expected for the host geomaterial in the Swiss concept for the construction of geological repositories for nuclear waste disposal,[1,2] while testing under high-pressure conditions allows to observe the transition from the pre-yield phase to the post-yield phase of the material and to cover a broad range of possible depths and vertical stresses for the repository. The testing tools used, the experimental procedure employed and the studied shale are first described; the results of the experimental campaign are then presented and discussed in the second part of the paper.

2. Experimental testing

2.1. Testing equipment

Shale testing requires the application of high pressures in order to observe the transition from the pre-yield to the post-yield phase. In addition, a broad range of vertical stress levels must be explored in order to capture potential effects of an additional variable (e.g., effects of temperature on the yield stress and on mechanical properties of the material). To examine the thermo-mechanical behaviour of shales, a high-pressure oedometer cell was used[35]; the cell is equipped with a temperature control system: the layout of the testing apparatus is presented in Fig. 1. The cell is heated by a silicon heater mat: heating is achieved through an electrical resistance placed between two layers of woven fibreglass impregnated with a silicon elastomer. Heater mats allow one to easily modify testing devices when introducing temperature control.[37] The heater mat is approximately 3 mm thick, and the permissible surface temperature ranges from −60 °C to +200 °C. The

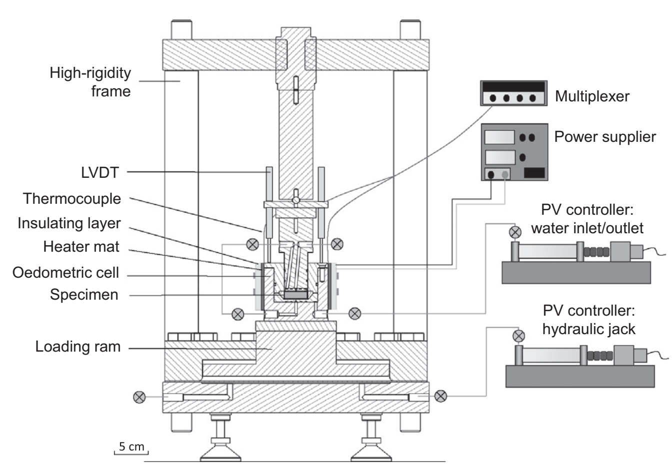

Fig. 1. The high-pressure oedometric cell modifierd for controlled-temperature testing (modified from[36]).