

Effect of anisotropy on thermally-induced strains of kaolin clay

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ABSTRACT: The thermomechanical behaviour of clayey soils is critical for various geotechnical and geoenvironmental applications, yet the underlying particle-scale mechanisms remain debated. This study investigates the effect of varying temperatures and inherent anisotropy on the volumetric response of kaolin clay under isotropic compression conditions. In order to investigate the effect of initial anisotropy on the volumetric response during thermal loading, the specimens were obtained by cutting these cakes parallel to the compression direction and the axial and radial deformations were measured separately. A recently designed temperature-controlled isotropic cell was employed to investigate the isotropic and deviatoric strain response of the specimens during thermo-mechanical loading. The cylindrical specimens were first saturated and then normally consolidated to 250 kPa effective stress. A thermal cycle was applied to the specimens consisting of i) heating from room temperature of 20 °C to 90 °C at a heating rate of 0.05 °C/min, followed by ii) cooling to room temperature. The testing results showed a significant effect of the anisotropy on the thermo-mechanical response of the kaolin clay. The findings of this study contribute to a deeper understanding of the effect of fabric anisotropy on the behaviour of kaolin clays under changing temperature.

KEYWORDS: Kaolin, anisotropy, thermo-mechanical behaviour, isotropic compression, temperature variations.

1 INTRODUCTION

The impact of temperature on mechanical behaviour of geomaterials is of increasing concern in geoenvironmental engineering. Over the past decades, considerable attention has been devoted to studying the response of fine-grained soils to the combined effects of stress and temperature, particularly in the context of nuclear waste geological disposal (Hueckel and Baldi, 1990; Sultan et al., 2002; Romero et al., 2005). This research has predominantly focused on high-swelling clay subjected to elevated temperatures and pressures resulting from the confinement of the engineered barrier system.

The investigation into the effects of temperature changes on mechanical behaviour of non-active or moderately active clay has been relatively limited despite their relevance to various applications such as shallow geothermal plants (Murphy and McCartney, 2015), energy geostructures (Laloui and Di Donna, 2013), and heating in rapid shear deformation (Sulem et al., 2007).

It is commonly accepted that clay exhibits irreversible contraction in normally consolidated (NC) states and reversible expansion in highly overconsolidated (OC) states upon heating and subsequent cooling (Hueckel and Baldi, 1990; Cekerevac and Laloui, 2004; Abuel-Naga et al., 2007; Di Donna et al., 2015).

Despite this clay complex thermo-mechanical behaviour is widely reported in the literature, its origin is still unknown. Recent studies explore the particle-scale origin of clay thermo-mechanical behavior (Di Donna et al., 2024). Clay particle interactions include non-contact forces, which are electrochemical in nature and prevail in face-to-face configuration and contact forces, which are mechanical forces transferred from one particle to another through a contact surface, typical of edge-to-face configuration. Noncontact forces include electrostatic Coulombic forces and van der Waals attractive forces. Di Donna et al., (2024) concluded that the electrochemical interactions governing the face-to-face particle configuration can only explain the elastic volumetric response of overconsolidated clays subjected to heating. The

thermo-plastic behaviour associated with the reduction of the pre-consolidation pressure with temperature and the volumetric plastic compressive strain in response to heating in normally-consolidated clays is attributed to the edge-to-face particle configurations.

It is argued that the thermal collapse is associated with the macro pores closure, as a consequence of slippage at edge-to-edge contact, as it was demonstrated to be the case for plastic deformation occurring under mechanical loading (Pedrotti and Tarantino, 2018). According to this approach, it is expected that the volumetric response of an anisotropic clay sample (with a preferential clay particle orientation) to isotropic loading, either mechanical or thermal, would be different along the two directions parallel and perpendicular to the preferential clay particles orientation plane.

Limited information is available to the effect of initial samples anisotropy on the volumetric response of clay under temperature changes. This aspect is investigated in this work through the analysis of two isotropic compression tests run on anisotropic clay samples under thermal loading.

2 EXPERIMENTAL CAMPAIGN

2.1 Material

Commercially available Speswhite kaolin clay (IMERYS, France) with plastic limit $w_p = 0.32$ and liquid limit $w_L = 0.64$ was chosen for the tests presented in this paper. The grain size distribution reveals 80 % clay fraction (<0.002 mm), 20 % silt fraction (<0.05 mm), and a median particle diameter of $D_{50} = 1.3\mu\text{m}$.

To prepare the samples, Speswhite Kaolin clay powder was mixed with acidic de-ionised de-aired water with an electrical conductivity of $20\mu\text{S/cm}$ at 25°C and $\text{pH} = 4.0 \pm 0.2$ as explained below. The suspension was left to settle for 72 hours before the supernatant liquid conductivity was first measured. The clay was considered 'monoionic with no excess salts' (concentration of salt $<10\text{--}5\text{mol/L}$) when the supernatant liquid conductivity was $<100\mu\text{S/cm}$.

The pH was adjusted using HNO₃ 2%. The acidic pore fluid was aimed at generating a card-house structure before heating (Pedrotti and Tarantino, 2017).

2.2 Samples preparation

A slurry was obtained by sedimentation of pluviated (passing through a 0.5 mm sieve) oven-dried kaolinite powder into the 170 mm diameter and 120 cm high consolidometer filled with the acidic de-ionised de-aired water (clay concentration of the suspension equal to 320 g/L which corresponds to suspension = 5_{wL} = 320%).

Kaolinite particles were left to settle until a clear supernatant liquid was visible on the sediment. Once the sediment height reached equilibrium, the supernatant water was removed from the cylinder by siphoning.

The effective stress was initially increased up to 20 kPa by imposing suction with a negative water column. The sediment was finally consolidated to 200 kPa vertical stress.

Clay specimens 38 mm diameter and 76 mm high were trimmed from the 170 mm diameter clay cakes. In order to investigate the effect of initial anisotropy on the volumetric response during thermal loading, the specimens were obtained by cutting these cakes parallel to the compression direction and the axial and radial deformations were separately measured. The homogeneity of the samples prepared according to three different procedures was analysed by X-ray Computed Tomography (XCT) at Laboratoire 3SR in Grenoble, France.

2.3 Experimental setup

The newly developed isotropic cell was designed to test saturated clay specimens of 38 mm diameter and 76 mm height subjected to isotropic total stress and temperature to be increased or decreased independently at controlled rate (Figure 1).

The vertical and radial displacements are locally measured with Hall effect transducers glued on the neoprene membrane, while diaphragm pressure transducers measure pore water pressure on the sample's top and bottom. This was considered of primary importance to ensure drained conditions during heating by continuously checking that the thermal induced pore water pressure remained under acceptable limits.

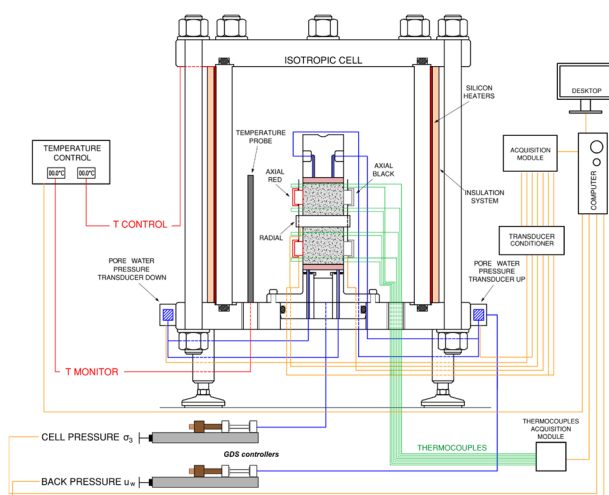


Figure 1. Temperature-controlled isotropic compression cell setup (Casarella et al., under rev).

The heating system comprises four flexible silicon rubber electrical heaters and a temperature probe installed in the cell, which gives a feedback signal to control the power input

supplied to the heaters and required to maintain a target cell's water temperature (overall precision $\pm 0.1^\circ\text{C}$). More information about the experimental equipment and its mechanical and thermal calibration can be found in Casarella et al. (under rev).

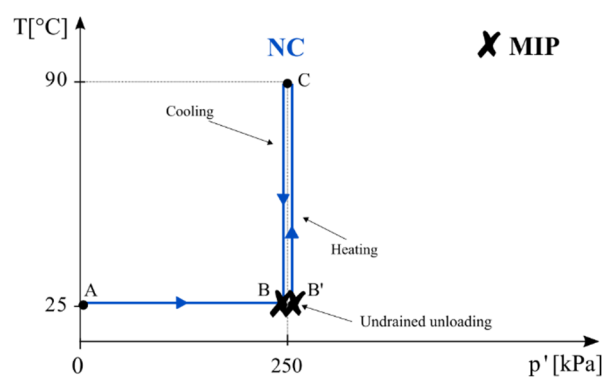
2.4 Experimental program

In the results presented hereafter, two thermomechanical paths were considered.

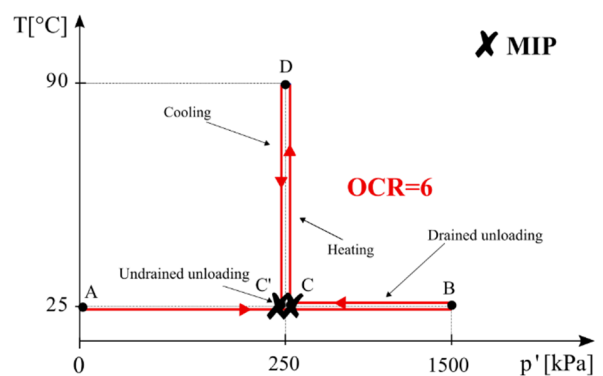
In the first test (K1-SW-I250), the sample was isotropically consolidated in the cell up to a mean effective stress $p' = 250$ kPa, and then subjected to a thermal cycle $25^\circ\text{C} \rightarrow 90^\circ\text{C} \rightarrow 25^\circ\text{C}$ (constant heating/cooling rate of $3^\circ\text{C}/\text{h}$) at a constant mean effective stress, as illustrated in Figure 2a.

In the second test (K6-SW-I250), the sample was isotropically consolidated up to a mean effective stress $p' = 1500$ kPa and then unloaded to $p' = 250$ kPa (OCR=6), before being subjected to the same thermal cycles as the first test (Figure 2b).

Mercuric Intrusion Porosimetry measurements were realized where indicated in the figure, but are not discussed here. A deep analysis can be found in Casarella et al., (under rev.).



(a)



(b)

Figure 2. Thermomechanical paths imposed to thermally test the material under (a) NC and (b) OC conditions (Casarella et al., under rev).

3 RESULTS

As expected and in accordance with literature, irreversible thermal compaction is observed in the first test, as the sample is heated under normally consolidated conditions. During heating, the NC sample settles with a non-linear volume variation. During cooling, the soil does not recover the deformation accumulated upon heating. In contrast to the NC state, heating produces mainly reversible dilation in the highly overconsolidated (OC) sample. All these results are discussed

in Casarella et al., (under rev.) and not reported here as out of the scope of this paper.

Figure 3 shows the displacement recorded by axial and radial transducers over an iso-thermal (at 20 °C) consolidation step of around 250 kPa. In Figure 3a, the data are for consolidation at low stress, from 15 to 250 kPa (from the NC test, but comparable for the same step of the other one), while in Figure 3b the data are for consolidation at high stress, from 1250 to 1500 kPa (from the loading phase of the OC sample).

A discrepancy between the measured axial strain and the measured radial strain is observed for both tests. At lower mean effective stress, the axial strain (average measurement between the two local axial transducers installed on the sample) is 2.5 times higher than the radial strain (Figure 3a). When the isotropic load is increased, this disparity tends to narrow, and it is almost wholly recovered at a mean effective stress of 1500 kPa (Figure 3b). This might imply that the layered fabric created during pre-consolidation in one-dimensional conditions (consolidometer) enhances particle realignment along the vertical direction upon isotropic loading, resulting in a more significant recorded axial strain of the sample.

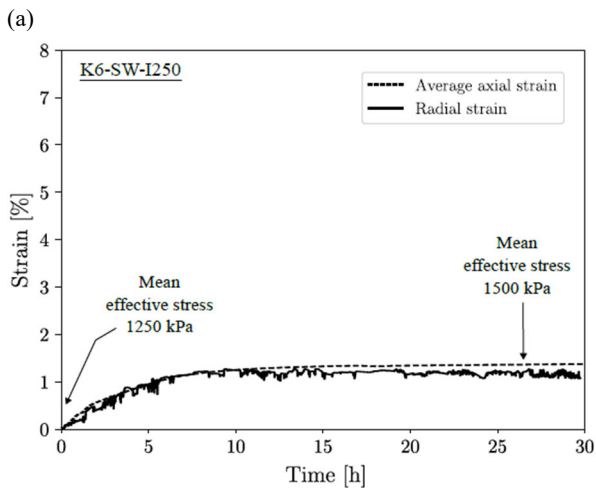
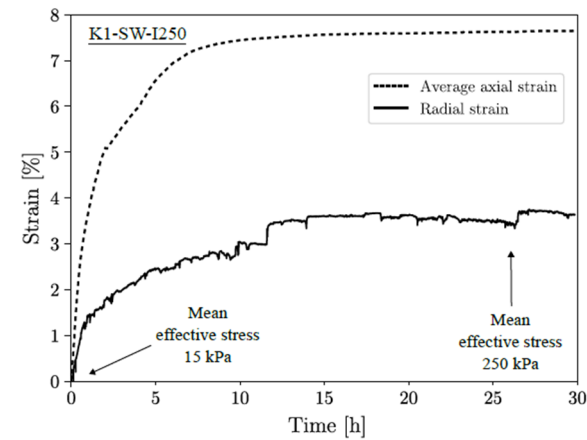


Figure 3. Evaluation of samples anisotropy at ambient temperature: comparison of axial and radial strains over an iso-thermal consolidation step (20 °C) of around 250 kPa for (a) low stress loading and (b) high stress loading.

The memory of the initial one-dimensional compression is almost entirely erased when the mean effective stress is increased.

An analogous phenomenon is observed under thermal loading on the NC sample (Figure 4).

The axial thermal contraction recorded over temperature increase is 1.8 times larger than the radial one (Figure 4). The same preferential direction noticed during mechanical compression emerges upon thermal loading. However, it is interesting that the disparity decreases over cooling, where the radial strain is 1.4 times smaller than the average axial strain.

A positive temperature variation in NC clays seems to induce changes in the fabric in the same fashion as an increase in mean effective stress.

This let thing to an irreversible rearrangement of particles to explain the plastic contraction upon heating, a rearrangement analogous to the one proposed by Pedrotti and Tarantino (2018a) to describe the plastic contraction of clays upon vertical compression.

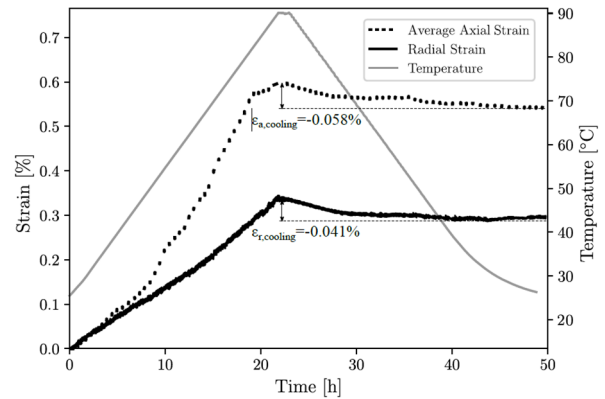


Figure 4. Evaluation of samples anisotropy upon thermal loading in the NC test: comparison of axial and radial strains over a heating cooling cycle (25 °C → 90 °C → 25 °C).

4 CONCLUSIONS

Recent studies argued that the plastic deformation of NC clay is associated with the macro pores closure, as a consequence of slippage at edge-to-edge contact. This was demonstrated to be the case for plastic deformation occurring under mechanical loading (Pedrotti and Tarantino, 2018), but also for the thermal collapse induced by heating under NC conditions (Di Donna et al., 2024).

The motivation driving this work was to corroborate these conclusions by verifying that the volumetric response of an anisotropic clay sample (with a preferential clay particle orientation) to isotropic loading, either mechanical or thermal, would be different along the two directions parallel and perpendicular to the preferential clay particles orientation plane.

The results presented in this work seem to confirm this hypothesis. In the tested samples, the clay particles are expected to have a sub-horizontal initial distribution resulting from the samples preparation procedure, and the experimental results clearly show a larger deformation along the axial direction than along the radial one, during thermal loading in NC conditions (plastic thermal deformation). According to previous studies, the plastic deformation would be associated with closure of macropores which would occur mainly axially. The elastic deformation associated with cooling is significantly less anisotropic.

Limited information on anisotropy before and after thermal loading and at different mean effective stress was collected in this experimental campaign. Further investigations on the preferential direction of compaction upon mechanical and thermal loading might be investigated by observing the

thermomechanical response of samples with different artificially induced fabrics.

5 ACKNOWLEDGEMENTS

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