Experimental study on hydro-mechanical coupling behaviours of highly compacted expansive clay

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Abstract: Highly compacted expansive clays have been usually considered as a possible material for sealing and backfill in deep geological disposal of radioactive waste. In this condition, the material is simultaneously subjected to water infiltration from the geological barrier and stresses generated by the swelling of engineered barriers in confined conditions. Its behaviour under hydro-mechanical loading is essential to the safe design of the whole storage system. In the present work, MX80 bentonite, a kind of expansive clay from Wyoming, USA, was studied. After compaction, its dry density was 1.8 Mg/m³ and its initial suction was 110 MPa. Firstly, the soil was humidified under controlled suction and free-swelling conditions. Significant swelling was observed. Secondly, four values of suction of 110, 39, 9 and 0 MPa were employed to perform isotropic compressive tests at constant suction conditions. That allowed studying the effect of suction on the yield pressure, elastic and plastic compressibility parameters. The results show that the elastic and plastic compressibility parameters increase when the suction decreases. The relationship between these parameters and the logarithm of suction can be linearly correlated. The yield stress drastically decreases upon wetting under free-swelling conditions, from 12 – 18 MPa (at an initial suction of 110 MPa) to 0.2 MPa at saturated state.

Key words: expansive clay; suction; compressibility; yield pressure; engineered barrier; radioactive waste disposal

1 Introduction

Highly compacted expansive clay is often proposed as a possible backfill or sealing material in high-level radioactive waste disposal. Once used in the field, the material is simultaneously subjected to water infiltration from the geological barrier and stresses generated by the swelling under confined conditions. A full understanding of hydro-mechanical coupling behavior of compacted expansive clay is essential to the safe design of the whole storage system.

In order to investigate the hydro-mechanical behavior of compacted expansive clays in laboratory, suction-controlled oedometer tests were usually performed [1, 2]. The works showed that the yield pressure \( p_\theta \) was higher at a higher suction. In addition, the elastic compressibility parameter \( \kappa \) and the plastic compressibility parameter \( \lambda(s) \) were also influenced by suction. As the time required to perform the suction-controlled oedometer tests on compacted expansive clay was usually important, these tests were not often replicated. As a consequence, the effect of suction was not able to be separated from other effects such as the initial state of compacted samples.

In the present work, suction-controlled compressive tests were performed using isotropic cell [3]. The tests were replicated allowing the separation of the suction effect and the repeatability of the test procedure.

2 Material and experimental methods

The MX80 bentonite, a kind of clay from Wyoming, USA, was investigated. It is one of the reference materials considered for the engineered barrier or sealing material in deep radioactive waste disposal. With its high content of montmorillonite (82%), its liquid limit \( w_L = 520\% \) and plastic limit \( w_P = 46\% \). Prior to utilization, the clay was sieved at 2 mm and dried at 44% of relative humidity, which corresponded to a suction of 110 MPa at 20 °C [4]. After reaching equilibrium, the soil water content was 10±2%. Then the soil was statically compacted under an isotropic pressure of 40 MPa. After compaction, the soil...
specimen was placed in a chamber at a relative humidity of 44% and a temperature of 20 °C. This procedure allowed obtaining compacted soil specimens with a dry density $\rho_d = (1.78 \pm 0.3) \text{ Mg/m}^3$ and a void ratio $e = 0.55 \pm 0.3$.

The isotropic cell used to perform compression tests at saturated state is shown in Fig. 1. The compacted soil sample (80 mm in diameter, 10 mm in height) was sandwiched between two porous stones which were embedded in two metallic plates. The two porous stones were connected to a controller of volume/pressure. The soil specimen and the metallic plates were covered by a 0.6 mm thick neoprene membrane. The isotropic pressure was applied to the soil sample through the membrane by another controller of volume/pressure filled with de-aired water. This controller was also used to monitor the volume change of the soil sample during tests. Calibration tests were performed on metallic specimen as described in the work of Tang et al. [3].

The cell used to perform the isotropic compression tests at suction-controlled state was similar to that described by Tang et al. [3]. The schematic view of the cell is shown in Fig. 2. The system for loading and monitoring the volumetric strain of the soil specimen is similar to the cell shown in Fig. 1. The suction in the soil specimen was controlled by the saturated saline solution embedded below the lower plate. Several holes (2 mm in diameter) were perforated on the lower plate allowing the moisture exchange between the soil specimen and the chamber containing the saline solution.

To perform the compression test at saturated state, the compacted soil sample was first installed in the cell described in Fig. 1. A very low confining pressure (100 kPa) was then applied to the soil sample. After that, distilled water was injected in the back-pressure outlets to saturate the soil. The volume change of the soil sample during wetting was monitored by the controller of volume/pressure used to apply the confining pressure. The soil was considered saturated when the swelling reached stabilization and the volume of water injected into the soil was larger than the pore volume in the soil. After the saturation phase, loading and unloading paths were applied in steps. The time required for each loading step for the stabilization of volume change varied from 200 hours to 2 000 hours.

For the compression tests under constant suctions, the compacted soil specimens (having an initial suction of 110 MPa) were first humidified at two suctions: 39 and 9 MPa. After reaching equilibrium, the specimens were installed in the cell described in Fig. 2 having a saturated saline solution corresponding to the suction imposed. After that, the loading/unloading tests were performed incrementally until a pressure of 50 MPa.

### 3 Experimental results

The results obtained during the wetting phase are shown in Fig. 3. From the initial value of 110 MPa, the soil suction was decreased to 39 MPa first and then 9 MPa, and finally to zero. The results show a significant swelling during the wetting phase; the volume of the soil increased 28% when the suction decreased from 110 to 39 MPa, 50% when the suction decreased to 9 MPa, and 75%–80% after full saturation. The axial
and radial strains were similar because of the isotropic microstructure of soil obtained from isotropic compaction.

The results obtained by compressive test performed at saturated state are shown in Fig.4. After the saturation phase, the void ratio increased from 0.55 to 1.70. After that, the isotropic pressure was increased in steps from 0.1 to 0.2, 0.5, 1, 2 and 5 MPa prior to being unloaded to 2 and 0.2 MPa. The following parameters can be determined from the curves: yield pressure $p_0 = 0.20$ MPa; elastic compressibility parameter $\kappa = 0.139$; plastic compressibility parameter $\lambda(s) = 0.252$. Note that $\kappa$ corresponds to the elastic rebound part at low stresses, $\lambda(s)$ corresponds to the linear virgin compressive part, and $p_0$ is determined from the intersection of these two slopes (see Ref.[5] for more details).

Several compression tests were performed at a suction of 39 MPa. The results are shown in Fig.6. After the wetting path (suction decreased from 110 to 39 MPa), the void ratio increased from 0.55 to 0.90–0.94. For the tests Iso08, Iso10 and Iso13, the loading path was stopped at 5 MPa. The test Iso02 was stopped at a pressure of 10 MPa. For the test Iso01, the soil was loaded until 50 MPa and then unloaded to 1 MPa. The results show that the curves are similar. The small difference between the curves can be attributed to the scattering of the initial void ratio obtained after wetting. From the test Iso01, the compressibility parameters determined are: yield pressure $p_0 = 1.03$ MPa; elastic compressibility parameter $\kappa = 0.017$; plastic compressibility parameter $\lambda(s) = 0.087$. The elastic compressibility parameter determined from all the tests varies from 0.014 to 0.029. As the tests Iso02, Iso08, Iso10, and Iso13 were stopped at stresses lower than 10 MPa, the plastic compressibility parameter can not be determined. Nevertheless, if the result obtained from the test Iso01 is used, $\lambda(s) = 0.087$, the yield pressure can be determined from these tests, which varies in the range of 1.0–2.0 MPa.

The results of the compressive tests at the initial suction, $s = 110$ MPa, are shown in Fig.7. For the test
Iso06, the soil was loaded in steps until 50 MPa and then unloaded to 0.2 MPa. For the test Iso14, loading was stopped at 5 MPa. For the test Iso15, loading was stopped at 20 MPa. In the case of test Iso16, the maximum pressure was 60 MPa. The results show that the curves obtained from all the tests are quite similar. The elastic compressibility parameter varies from 0.006 to 0.010; the plastic compressibility parameters were 0.057 (Iso06) and 0.074 (Iso16). The yield pressure obtained is in the range of 12–18 MPa.

To analyze the effect of suction on the compressibility parameters (elastic and plastic), the obtained parameters are plotted versus the corresponding suction for all the tests in Fig. 8. In spite of the scattering of the results, a clear trend can be observed: $\lambda(s)$ and $\kappa$ increase when the suction decreases. The relationship between the compressibility parameters and the logarithm of suction can be correlated with linear functions:

$$s = 135e^{-52\kappa}$$

$$s = 1114e^{-37\lambda(r)}$$

In Fig. 9, the yield stress is plotted versus the corresponding suction. The results of Lloret et al. [2] on Febex bentonite are also presented. It can be noted that the decrease of suction (wetting) drastically decreases the yield stress from 12–18 MPa (at $s = 110$ MPa) to 0.2 MPa (at saturated state). The effect of suction on the decrease of yield stress is more pronounced for MX80 bentonite compared with Febex bentonite.

4 Discussions

The thermo-mechanical behavior of compacted MX80 bentonite has been investigated by Tang et al. [6], and a constitutive model was developed to simulate the observed behavior [7]. In the present work, only the hydro-mechanical behavior of the compacted MX80 bentonite was investigated. The results presented by Tang et al. [5] were completed by the tests at saturated state and by replicating the tests at constant suctions. The increase of the elastic and plastic compressibility parameters during wetting has been observed by Lloret et al. [2] on Febex bentonite and by Tang et al. [6] on MX80 bentonite. This effect has been explained by the swelling of clay aggregates upon wetting giving rise to the mechanical softening. The results confirmed this effect and showed that this relationship can be correlated with a linear function between $\kappa$ (or $\lambda(s)$) and the logarithm of suction for the wide range of suction from 0 to 110 MPa.

The decrease of yield pressure upon wetting is a well-known phenomenon in the mechanics of unsaturated soils. In the case of compacted expansive soil, this phenomenon is more significant because of the swelling of clay aggregates which induces important swelling of soil (more than 75% of swelling volumetric strain during saturation phase in the present study). In the case of Febex bentonite [2], the swelling...
volumetric strain obtained when decreasing the suction from 110 MPa to zero was 30% under free-swelling conditions. This swelling is less significant than that obtained on the compacted MX80 bentonite. That can explain the results shown in Fig. 9, the effect of suction decrease on the yield stress was more significant on the MX80 bentonite than that on the Febex bentonite.

Replicated tests were performed allowing the estimation of scattering related to the experimental procedure. The results show that the scattering of the results obtained was small enough for a satisfactory analysis of the suction effect on the compressibility parameters and the yield pressure. Moreover, it is in the same order of magnitude of the temperature effect that was observed previously by Tang et al. [6]. Actually, the engineered clay barrier for geological disposal repository of high-level radioactive waste will be subjected to thermo-hydro-mechanical coupling processes. Thus, the replicated tests are recommended when the coupled thermo-hydro-mechanical behavior of this material is investigated.

5 Conclusions

Suction-controlled compression tests were performed on compacted MX80 bentonite. Firstly, wetting the soil under free-swelling conditions showed a significant swelling (up to 75% when suction decreased from 110 MPa to 0). In addition, this swelling was isotropic, consistent with the sample preparation by isotropic compaction. The subsequent loading under constant suction conditions allowed studying the effect of suction on the compressibility parameters. The results showed a linear relationship between the elastic (or plastic) compressibility parameter and the logarithm of suction ranging from 110 MPa to 0. The yield stress decreased drastically from 12–18 MPa (at the initial suction of 110 MPa) to 0.2 MPa (at saturated state). Comparison with Febex bentonite showed that the effect of suction on the decrease of yield stress was more pronounced for MX80 bentonite. This shows the importance of the free-swelling effect on the mechanical behavior.

References


