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Experimental investigation on the hydro-mechanical response of a shale subjected to gas invasion

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ABSTRACT

In the context of deep geological radioactive waste disposal, significant amount of generated gas is expected to migrate from the repositories into the surrounding host rock, affecting its hydro-mechanical state. In Switzerland, Opalinus Clay is the selected host geological formation and requires a comprehensive understanding of the relevant phenomena that characterize its behaviour associated with gas transport regarding the long-term safety assessment of the repository. In this context, water and gas injection tests were performed using a high pressure oedometer cell. The results suggest that gas-induced porewater displacement is a key feature during gas invasion processes in clay-rich host rock. Furthermore, water intrinsic permeability was not impacted by gas transport and consistently found in the order of 10^{-21} (m^2) before and after the gas invasion tests. The experimental outcome of the study provided unique observations of the hydro mechanical behaviour of Opalinus Clay when subjected to gas transport in the short-term and long-term.

KEYWORDS

Nuclear Waste Repository; Opalinus Clay; Hydro-Mechanical Behaviour; Gas Invasion

1. INTRODUCTION

Regardless of the national strategies concerning nuclear energy production, there is an urgent need to address the problem of disposing high-level nuclear waste produced by power plants. Switzerland foresees a deep geological repository which relies on a multi barrier system to isolate the waste from the biosphere for dozens of thousands of years. However, uncertainties still exist about the late stage of the repository when a significant amount of gas will be produced due to various processes. This gas production may cause gas pressure build-up with a potential propagation of the gas front into the host rock. Those circumstances can result in the loss of the mechanical integrity of the multi-barrier system and may impact the long-term safety of the repository (Levasseur et al., 2021).

In Switzerland, Opalinus Clay has been selected as the host geomaterial for the underground disposal of radioactive waste. More experimental evidence for a comprehensive understanding of the relevant phenomena that characterize the hydro mechanical (H-M) behaviour of Opalinus Clay (OPA) when subjected to gas invasion is thus required.

In this paper we are showing the results of an experimental campaign on OPA conducted with a high pressure oedometer apparatus allowing the performance of water and gas injection tests while assessing the vertical deformation of the tested material with the aim to better observe and understand the involved phenomena.

2. MATERIAL AND METHODS

2.1. Material

Opalinus Clay is a fine-grained sedimentary geomaterial with a mineral composition consisting mainly of silicates, carbonates and quartz. The tested material was retrieved from the deep borehole in Trüllikon in the Zürich Northeast siting region in Switzerland (Ammen and Palten, 2021) and was sourced at a depth of about 848 m. Complete geotechnical characterization has been performed and included: bulk density ρ = 2.50 g/cm^3, density of solid particles ρ_s = 2.78 g/cm^3, water content w = 0.05, void ratio e = 0.15, degree of saturation Sr = 0.63, initial total suction ψ = 66 MPa.

The pore structure of Opalinus Clay was studied by Mercury Intrusion Porosimetry (MIP), using the freeze-drying technique for sample preparation. To overcome the conformance effect and the compressibility of the sample below the entry pressure of mercury, a correction was applied to the MIP data according to (Comisky et al., 2011). As depicted in Figure 1, a unimodal pore size distribution was obtained in the range of 8 to 16 nm with a peak value at about 12 nm. The size of the detected porosity was from 4 to 60 nm; 4 nm being the smallest pore size detectable with the apparatus. The results are in good agreement with values from the literature on the same material (e.g., Crisci et al., 2019; Minardi et al., 2021). From the larger detected pores, air is expected to enter the pore space of the initially saturated porous medium at a capillary pressure of about 5 MPa according to Young-Laplace equation:

$$p_c = \frac{2\gamma \cos\theta}{r} \qquad (1)$$

where p_c is the capillary pressure and is related to the differential pressure between gas and water phase, γ is the water-air surface tension, θ the water-solid contact angle, and r the pore-throat radius.

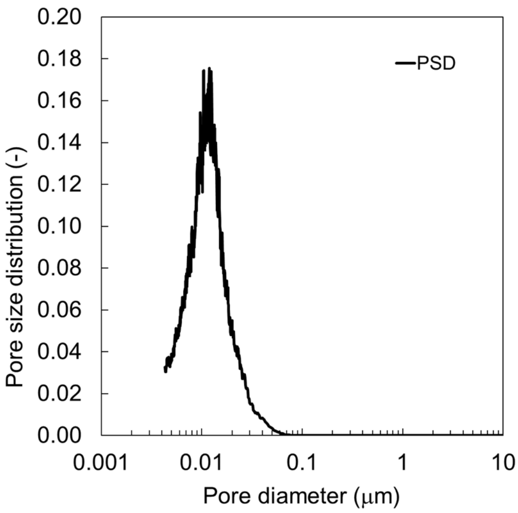

Figure 1. MIP test results of the OPA specimen

2.2. Experimental set-up and procedure

The experimental work used a high-pressure oedometer cell, as depicted in Figure 2 (left), that allowed to apply a vertical total stress up to 100 MPa with the possibility to perform water and gas injection from the bottom and top side of the specimen with a fluid pressure up to 16 MPa and 20 MPa, respectively (Minardi et al., 2021). The vertical deformation was assessed using three LVDTs with 0.2 μm resolution. The height and diameter of the specimen were 12 and 35 mm, respectively. The specimen was tested with the vertical load and fluid injection perpendicular to the bedding planes (S-sample).

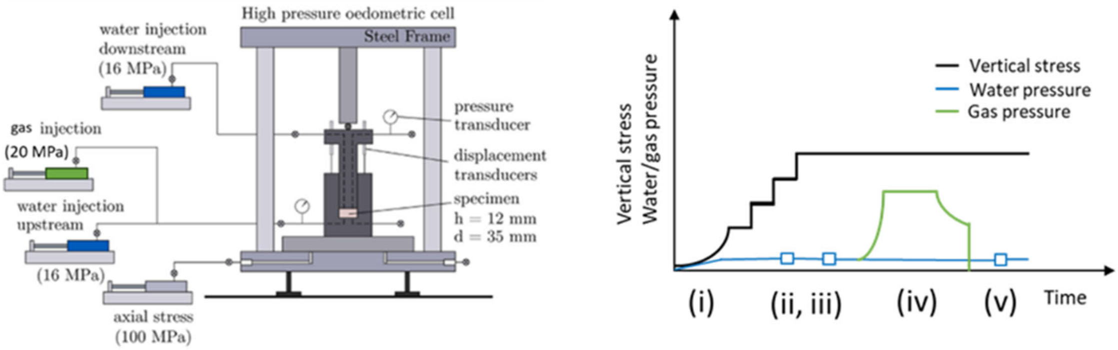

Figure 2. High-pressure oedometer test set-up (left); sequence of the water and gas injection tests (right)

The experimental procedure was composed of five test sequences (phases i to v) which are illustrated in Figure 2 (right) and described hereafter. As the preparation of the specimen from the core led to drying of the material, the experimental procedure started with (i) a water resaturation in isochoric conditions with synthetic water mimicking the in-situ porewater (Aschwanden et al., 2021). (ii) Mechanical loading up to the target vertical effective stress was performed to simulate in situ conditions. To do so, constant water pressure at the bottom ($u_{w,bot}$) and top ($u_{w,top}$) of the specimen was applied ($u_{w,bot} = u_{w,top}$ = 1 MPa) and the vertical total stress was increased in steps up to σ_v = 15 MPa. (iii) Constant head water permeability tests were performed at different vertical effective stresses by applying a differential pressure of 1 MPa between the top and bottom side of the specimen ($u_{w,bot}$ = 1.5 MPa and $u_{w,top}$ = 0.5 MPa). (iv) Then, in order to perform the first gas injection test, the water pump connected at the bottom side of the specimen was replaced by the gas pump, and gas pressure (nitrogen, N_2) was increased at a fast constant flow (0.2 ml/min for an initial gas volume of 500 ml in the reservoir) until the target gas pressure ($u_{g,bot}$ = 10 MPa) was reached; gas pressure was then kept constant until steady state conditions were observed for both gas flow and volumetric response of the tested specimen. Finally, the gas pump was stopped, ensuring constant gas volume at the inlet, and gas pressure decay was monitored (so called shut in). Water back-pressure at the top side of the specimen was kept constant during the entire phase at $u_{w,top}$ = 1 MPa. (v) After the gas injection phase, water resaturation was performed under constant vertical total stress, followed by a second water permeability test in order to assess the evolution of the intrinsic permeability due to gas transport.

3. RESULTS AND DISCUSSION

3.1. Hydro-mechanical results (phases I to iii)

During resaturation, the tested specimen was put in contact with water at low pressure, and as water was sucked in, contributing to induce swelling of the material, vertical total stress was progressively increased to ensure isochoric conditions and minimize damage due to swelling. To further enhance saturation, the water pressure was increased up to 1 MPa and a differential water pressure was applied between the bottom and the top of the specimen so that water could flow across the specimen and flush the trapped gas within the pore space. The swelling pressure developed during this phase was S_p = 3 MPa and is shown in Figure 3.

The mechanical compression up to the target vertical effective stress allowed an assessment of the relationship between void ratio and the applied stress. The deformation of the oedometer system was accounted for every loading step (Ferrari et al., 2016). Figure 3 shows the compression of the specimen with increasing vertical effective stress. The water intrinsic permeability was computed from the constant head tests performed at different vertical effective stresses. The water intrinsic permeability was obtained in the range of $2\ 3 \cdot 10^{-21}$ m^2 and is in good agreement with values reported in the literature for the same material (Crisci et al., 2019; Minardi et al., 2021).

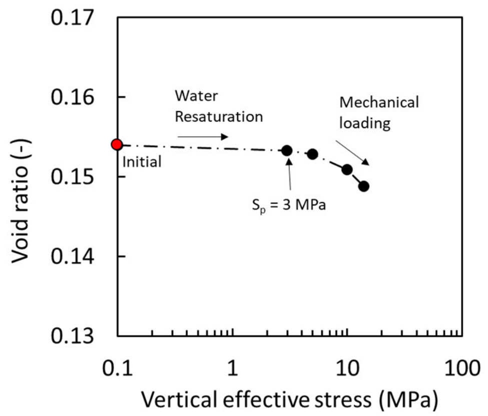

Figure 3. Oedometer curve for the tested specimen

3.2. Gas injection (phase iv)

The gas injection test was performed at fast gas pressure build-up rate with the intention to favour an undrained response of the material. The applied boundary conditions, such as vertical stress and fluids pressures are shown in Figure 4 (top).

The global axial strain of the specimen computed from the measurement of the vertical deformation, shown in Figure 4 (middle), indicates that almost no deformation was observed at the early phase as gas pressure was likely below the entry pressure and had not yet invaded the pore space. Once gas reached a pressure of about 5 MPa at t = 17 h, expansion of the specimen was observed, indicating the start of gas invasion, which was associated with porewater displacement and development of capillary pressure. The air entry value was consistent with the estimation from the MIP test. Expansion continued as gas pressure increased further. Once gas pressure was kept constant at 10 MPa from t = 30.5 h, expansion continued to slightly increase and reached a strain of 0.14% and was followed by a slow reduction and stabilization at about -0.07% until t = 193 h. As gas pressure decreased during the shut-in phase, t > 193 h, the specimen experienced compression. Gas pressure after shut-in was measured at 5.7 MPa.

The observed mechanical response was consistent with the measured outflow from the specimen. Gas breakthrough was observed only after the maximum gas pressure was reached (t = 50 h). This suggests that gas movement was impaired by the low permeability of the specimen. With time, as gas further invaded the pore space, the measured outflow increased until steady state conditions were observed at about t = 193 h. The gas outflow at standard temperature and pressure (STP) conditions was about 2 mm^3/s. During the shut-in, gas outflow decreased until almost no flow was observed anymore.

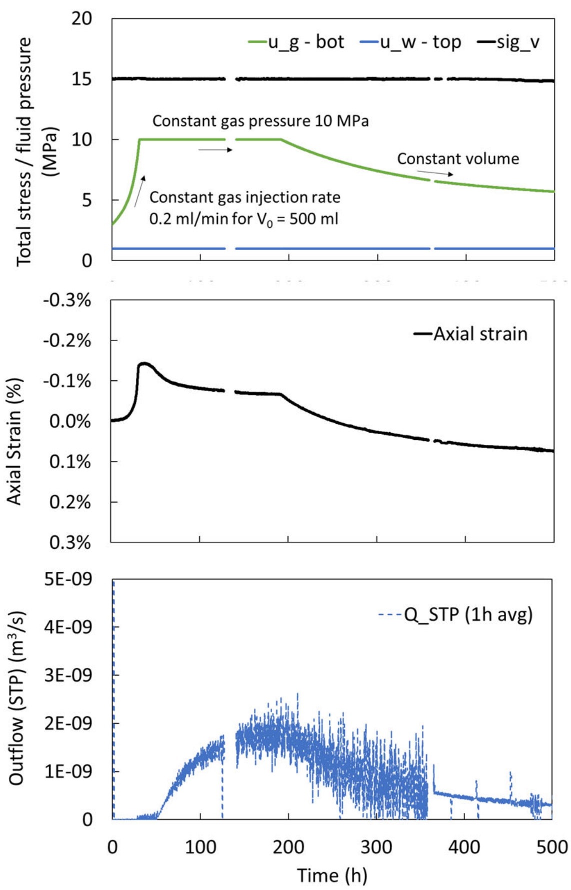

Figure 4. Gas injection test results

3.3. Hydro-mechanical results (phase v)

No significant strain (less than 0.01%) due to water uptake was observed during resaturation at constant vertical stress. The water intrinsic permeability after resaturation was found very similar to prior to the gas injection, $2\text{-}3\cdot10^{-21}$ m^2, suggesting that gas transport did not impair the intrinsic permeability of the tested material.

4. CONCLUDING REMARKS

In this study, the hydro-mechanical response of Opalinus Clay associated with gas transport was investigated. Water and gas injection tests have been performed using a high pressure oedometer cell to replicate the in-situ stress conditions. In particular, the short- and long-term responses to gas invasion were assessed during fast gas pressure build-up.

The interpretation of the results in terms of drained/undrained behaviour is consistent with the general deformation behaviour of clayey geomaterials. If the tested material is subjected to fast gas pressure build-up, it is more likely that gas transfer is initially associated with larger deformation due to generation of excess porewater pressure during the transient phase. The results suggested that gas-induced porewater displacement is a key feature during gas invasion processes in clay-rich host rock. Furthermore, the consistent water permeability values obtained before and after the gas injection test suggest that the involved gas transport processes are unlikely to impact the long-term barrier function of the host rock.

The experimental outcome of the study provided additional observations of the hydro-mechanical behaviour of Opalinus Clay associated with gas transport in the short-term and the long-term. Further experimental investigation, as well as numerical analysis, are required to better understand the involved processes, such as the development of non-uniform and localized strains associated with gas invasion.

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REFERENCES

Ammen, M., and Palten, P.J. 2021. TBO Trüllikon-1-1: Drilling. NAB 20-09, Nagra, Wettingen, Switzerland.

Aschwanden, L., Camesi, L., Gimmi, T., Jenni, A., Kiczka, M., Mäder, U., Mazurek, M., Rufer, D., Waber, H.N., Wersin, P., Zwahlen, C., and Traber, D. 2021. TBO Trüllikon-1-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles. NAB 20-09, Nagra, Wettingen, Switzerland.

Comisky, J.T., Santiago, M., McCollom, B., Buddhala, A., & Newsham, K.E. 2011. Sample Size Effects on the Application of Mercury Injection Capillary Pressure for Determining the Storage Capacity of Tight Gas and Oil Shales. *Unconventional Resources Conference, SPE*.

Crisci, E., Ferrari, A., Giger, S.B., & Laloui, L. 2019. Hydro-mechanical behaviour of shallow Opalinus Clay shale. *Engineering Geology*, 251, 214–227.

Ferrari, A., Favero, V., & Laloui, L. 2016. One-dimensional compression and consolidation of shales. *International Journal of Rock Mechanics and Mining Sciences*, 88, 286–300.

Levasseur, S., Collin, F., Daniels, K., Dymitrowska, M., Harrington, J., Jacops, E., Kolditz, O., Marschall, P., Norris, S., Sillen, X., Talandier, J., Truche, L., & Wendling, J. 2021. Deliverable D6.1 of the project EURAD, Work Package Gas.

Minardi, A., Stavropoulou, E., Kim, T., Ferrari, A., & Laloui, L. 2021. Experimental assessment of the hydro-mechanical behaviour of a shale caprock during CO_2 injection. *International Journal of Greenhouse Gas Control*, 106, 103225.

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