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Authors:

Ju Wang, Yuemiao Liu, Liang Chen, Shengfei Cao

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中核集团核工业北京地质研究院
CNNC Beijing Research Institute of Uranium Geology



Beijing Research Institute of Uranium Geology, CNNC

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Abstract

In order to investigate the performance of GMZ-Na-bentonite under THMC coupled condition, a large-scale mock-up facility, named China-Mock-up was constructed in the laboratory of BRIUG. According to the preliminary concept of the high level radioactive waste (HLW) repository in China, a heater, which substitutes a container of radioactive waste, is placed inside the compacted GMZ-Na-bentonite blocks and pellets. Water inflow through the barrier from its outer surface is to simulate the intake of groundwater. The current experimental data of the facility is reported and analyzed in the report. It is revealed that the saturation process of the compacted bentonite is strongly influenced by the competitive mechanism between the drying effect induced by the high temperature and the wetting effect by the water penetration from outer boundary. For this reason, the desiccation phenomenon is observed in the zone close to the heater. The displacement of the heater and the stress evolution is also mentioned.

In the report, a constitutive model is proposed to tackle the principal THM coupling behavior of GMZ bentonite. With the proposed model, numerical simulations of the China-Mock-up test are carried out by using the code of LAGAMINE. A qualitative analysis of the predictive results is carried out, including the variation of temperature, saturation degree, suction and swelling pressure of the compacted bentonite. It is suggested that the proposed model is capable to reproduce the principal physico-mechanical behavior of GMZ bentonite.

KEYWORDS: High-level radioactive waste (HLW), geological repository, bentonite, lab testing, numerical modeling, thermo-hydro-mechanical-chemical (THMC)

1. Background

Deep geological disposal is internationally recognized as the most feasible and effective way to dispose of high-level radioactive waste (HLW). Repositories are generally designed on the basis of a multiple barrier system concept, which is mainly composed by engineered and natural barriers between the HLW and the biosphere. As the last line of defense between the waste container and host rock, the buffer/backfill is one of the most important components in the engineered barrier system. In the life cycle of the HLW disposal project, the buffer/backfill will be subjected to temperature increase due to heat emitted by the waste and hydration from water coming from the adjacent rocks (Gens et al, 2010). The buffer/backfill material is designed to stabilize the repository excavations and the coupled thermo-hydro-mechanical-chemical (THMC) conditions, and to provide low permeability and long-term retardation (Wang, 2010). A bentonite-based material is often proposed or considered as a possible buffer/backfill material for the isolation of the HLW. To guarantee the long-term safety of the engineered barrier, it is necessary to conduct research on coupled THMC behaviors of bentonite under simulative geological disposal conditions, and subsequently to reveal the property changes of the bentonite over a long period of time.

To understand the complex behaviors of the buffer/backfill material located in the coupled THMC environment, in recent years, there has been an increasing interest internationally in the construction of large-scale mock-up experimental facilities in the laboratory and in situ such as the Long Term Experiment of Buffer Material (LOT) series at the Äspö HRL in Sweden (Karlund et al, 2000), FEBEX experiment in Spain (Lloret & Villar, 2007), OPHELIE and PRACLAY heater experiments in Belgium (Li et al, 2006, 2010, Romero & Li, 2010) and Mock-Up-CZ experiment in Czech Republic (Pacovsky et al, 2007) etc. The experimental results and achievements obtained from these large-scale experiments provide important references on investigating the behaviors of bentonite under simulative nuclear radioactive waste repository conditions.

At the present stage, the Gaomiaozi (GMZ) bentonite is considered as the candidate buffer and backfill material for the Chinese repository. Lots of basic experimental studies have been conducted and favorable results have been achieved (Liu et al., 2003; Liu & Cai, 2007a; Ye et al. 2009a). In order to further study the behavior of the GMZ-Na-bentonite under relevant

repository conditions, a mock-up facility, named China-Mock-up, was proposed based on a preliminary concept of HLW repository in China. The experiment is intended to evaluate THMC processes taking place in the compacted bentonite-buffer during the early phase of HLW disposal and to provide a reliable database for numerical modeling and further investigations.

In order to predict the long-term behavior of GMZ-Na-bentonite under physico-mechanical coupling condition, an essential objective of the China-Mock-up test consists to establish a numerical approach. In this regard, a constitutive model is proposed to tackle the physical-mechanical behavior of GMZ-Na-bentonite. In the model, the following physical phenomena are taken into account: the transport of liquid (advection) and heat (convection and conduction), the vapor diffusion, the evaporation and condensation phenomena of water. The constitutive model of Alonso-Gens (1990) is used to reproduce the fundamental mechanical features of the GMZ bentonite in partially saturated condition. In order to validate the proposed model, a preliminary numerical simulation of the China-Mock-up test is carried out by the program LAGAMINE developed at Liege University (Charlier, 1987). The qualitative analysis of the predictive result is realized.

The overall approach is based on performing experiments according to the needs for additional studies on key processes during the early EBS evolution. The study will make use to the extent possible of on going experiments being conducted in the laboratory of Beijing Research Institute of Uranium Geology (BRIUG).

2. The T-H-M-C China-Mock-Up experiment

The China-Mock-up is mainly made up of eight components, namely compacted bentonite blocks, steel tank, heater and corresponding temperature control system, hydration system, sensors, gas measurement and collection system, real-time data acquisition and monitoring system (Fig. 1).

It is assumed that the duration of the China-Mock-up experiment will not be shorter than 4 years. Then, after a cooling period, the experiment will be dismantled and all the available results will be collected and evaluated.

The China-Mock-up experiment was assembled completely on 10th September 2010. The real-time data acquisition and monitoring system has recorded all the measurement data

from 1st April 2011. And the heater was switched on to reach a low temperature at 30°C from 1st April 2011 until 8th July 2011. The T-H-M-C experiment was commenced on 8th July 2011, then the power rises at 1°C/d to reach a maximum temperature at 90°C, and the hydration system injects at 0.5MPa with Beishan groundwater at the working time, and the injection rate is 400g/d, and later raises to 600g/d.

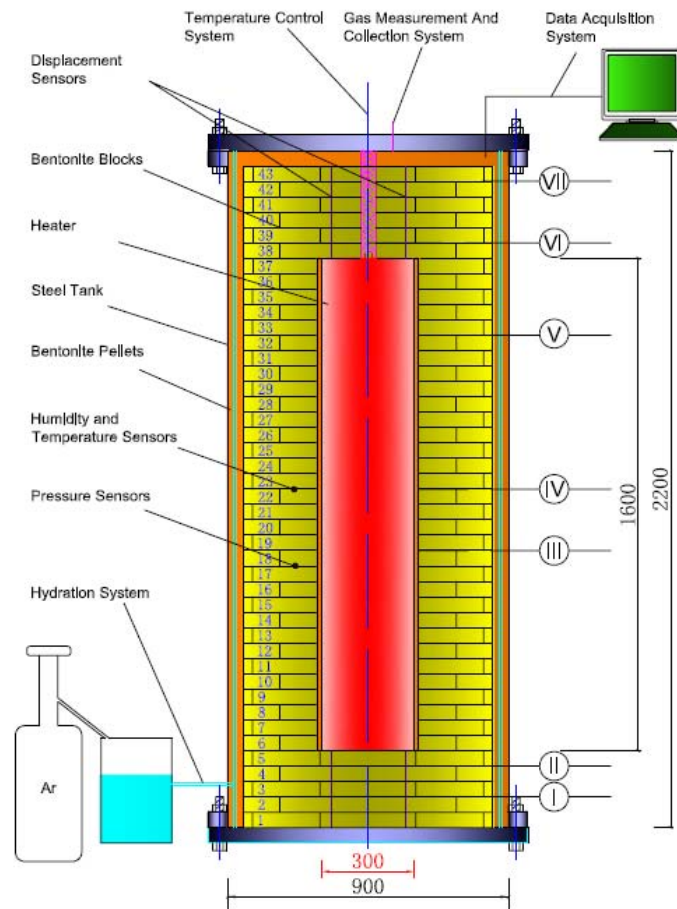


Fig. 1 Sketch of the China-Mock-up facility (unit: mm).

3. Experiment results of China-Mock-up

The China-Mock-up is equipped with 10 different types of sensors to monitor the comprehensive performances of GMZ Na-bentonite under coupled THMC conditions. The sensors placed in the bentonite have provided reasonable and consistent recordings, and continue to do so in the next operation phase of the experiment. The experimental results of

characterization performed concerning coupled T-H-M properties are reported and analyzed in this chapter. The time variation of the water consuming, relative humidity, temperature, and swelling pressured of the compacted bentonite are studied. The real-time data acquisition and monitoring system has recorded all the measurement data from 1st April 2011 to 18th April 2012.

3.1 Temperature

The temperature variation with time at the section III of the facility is illustrated in Fig. 2. As presented, the temperature is increased with time, especially for the sensors close to the heater. Due to the interrupt of electricity power, some fluctuations can be observed.

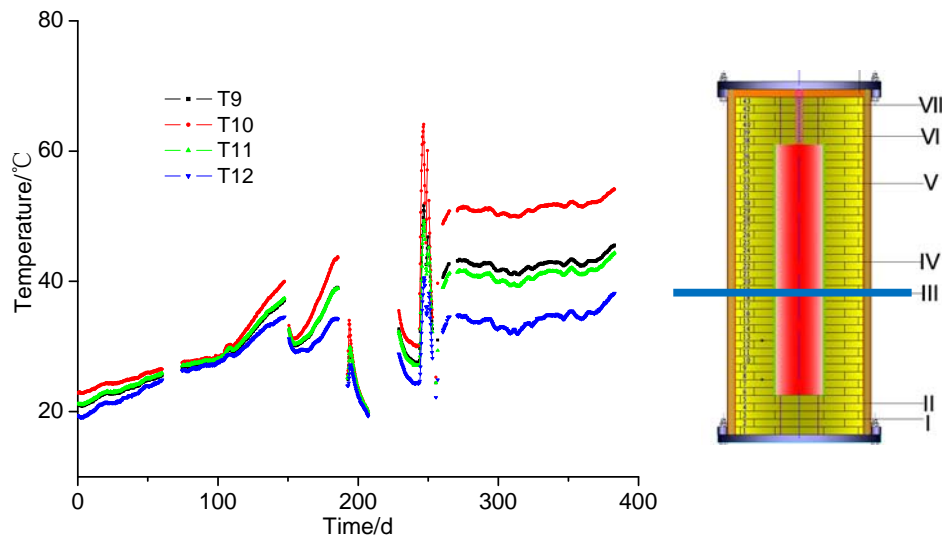


Fig. 2 Temperature variation with time at section III.

3.2 Relative humidity

The hydration process was carried out with Beishan groundwater. The initial injection pressure is 0.5MPa, with an injection rate is 400g/d. The injection rate is raised to 600g/d later after 300 days. The water consuming with the time is illustrated in Fig. 3.

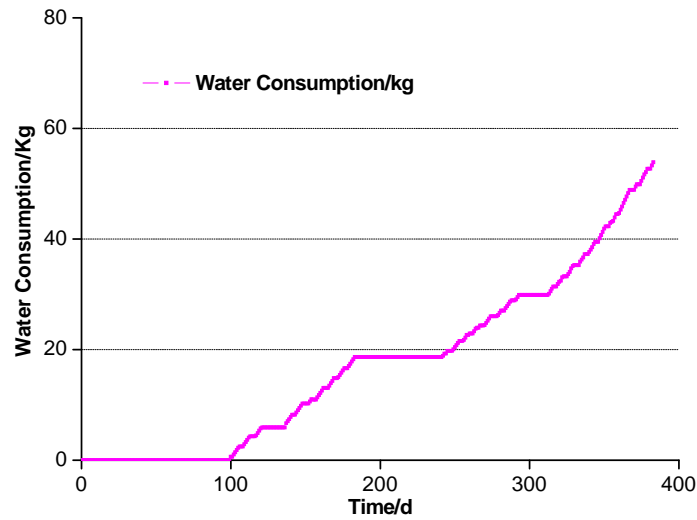


Fig. 3 Water consumption with the time.

Fig. 4 presents the variation of relative humidity with time at the sections III. It can be noticed that, the variation of relative humidity in this area is much more complex. In the zone close to the heater, the decrease of relative humidity can be observed. This phenomenon can be attributed to the competitive mechanism between the saturation process induced by the water penetration and the drying effect by the high temperature of the electrical heater. The desaturation phenomenon indicates that, due to the low permeability of the compacted bentonite, the drying effect is dominant at the beginning in the zone close to the heater.

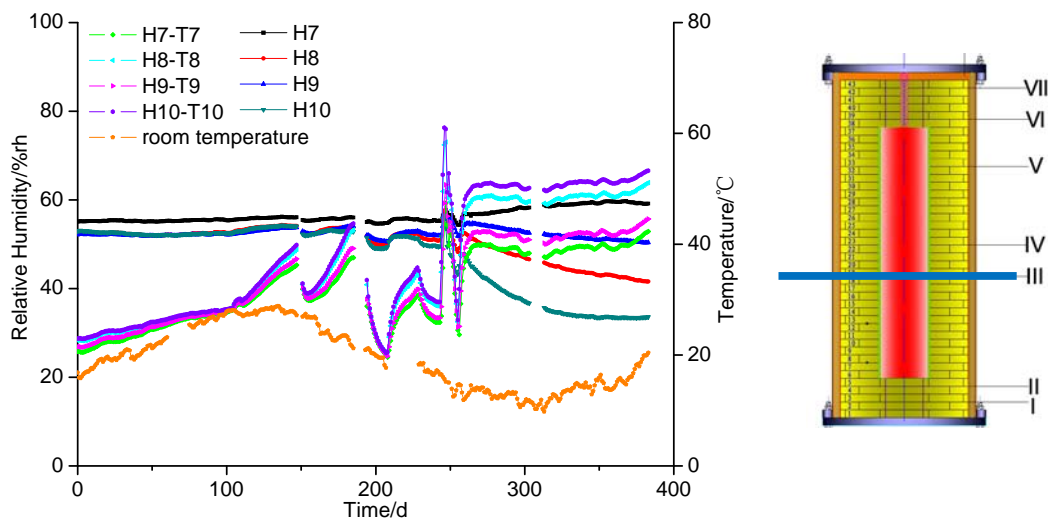


Fig. 4 Relative humidity distribution at section III.

3.3 Vertical displacement of the canister

In order to investigate the potential movement of canister in long-term, six LVDT sensors are installed in the China-Mock-up test to monitor the vertical displacement of the electrical heater. Three of them are installed at the bottom of the heater, and the others are installed in the upper part. The variation of the vertical displacement of the heater is presented in Fig. 5. It can be noticed that, the electrical heater moved upward after a stable phase. This phenomenon could be attributed to the thermal expansion of compacted bentonite, and the increased swelling of bentonite induced by the water penetration from outer boundary.

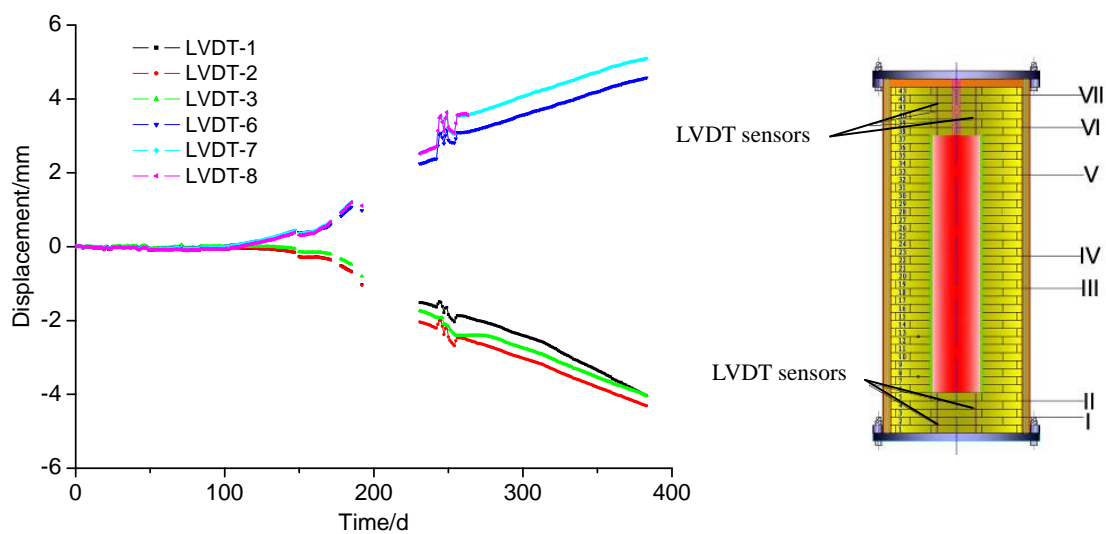


Fig. 5 Vertical displacement of the heater with time.

3.4 Stress evolution

In the China-Mock-up facility, the stress variation of the compacted bentonite is influenced by several mechanisms, including the thermal expansion induced by the high temperature, the swelling pressure generated by the water penetration, and etc. The stress evolution at the bottom and section II is presented in Fig. 6 and Fig7, respectively. As illustrated in the figures, a value around 0.8MPa is measured in this area. In other sections, almost no significant variation of stress in compacted bentonite is observed up to now. This could be attributed to two reasons: at first, as mentioned in section 3.2, the saturation process is relatively limited in other sections; and the second reason is the initial space between the sensors and the blocks of the compacted bentonite.

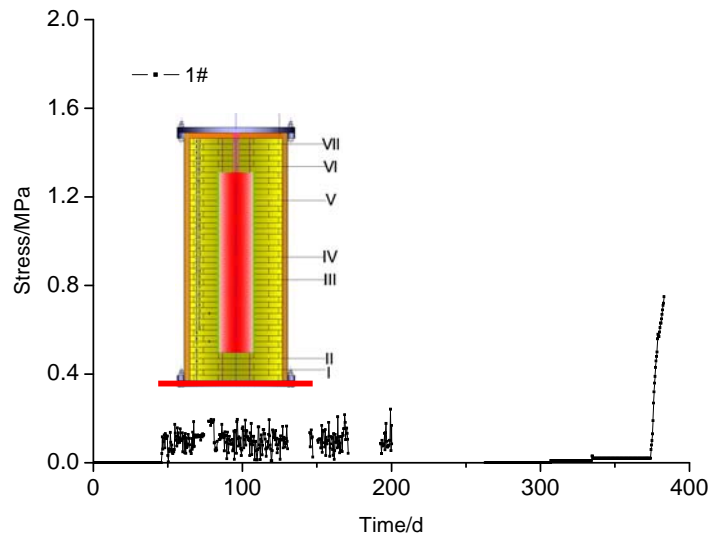


Fig. 6 Stress evolution at the bottom of China-Mock-up.

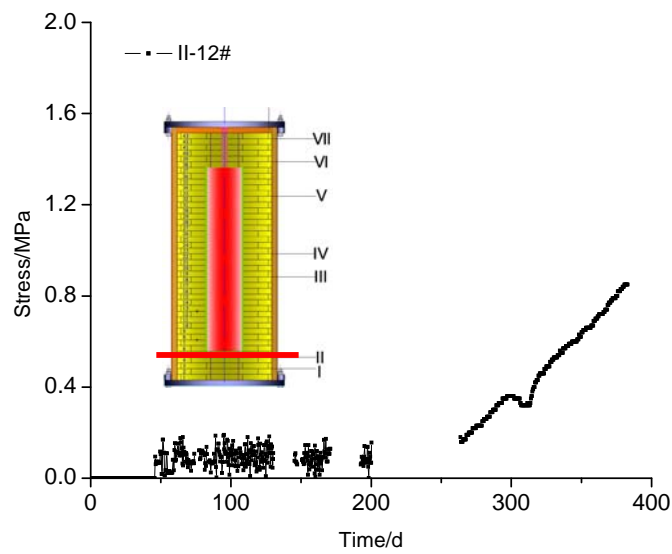


Fig. 7 Stress evolution at section II.

4. Numerical study of the China-Mock-up

4.1 constitutive model

In order to reproduce the physico-mechanical behavior of the GMZ bentonite aforementioned, a coupled THM model is proposed. In the model, various THM coupling phenomena are taken into account, including the transport of heat (conduction and convection), motion of

liquid water, vapor diffusion, and their couplings with mechanical behaviors. The main formulations of the proposed model are presented in this part.

4.1.1 diffusion model

In general, the compacted bentonite is composed of three phases, namely the solid, liquid water and gas (air and water vapor). In the simulations, the conservation mass of each phase (water or gas) is assumed. The phase exchange term thus will not be considered in the balance equations. The variables chosen for the description of the flow problem are liquid water pressure, gas pressure and temperature.

(1) water species

For the water species, the mass conservation equation is obtained by summing the balance equation of liquid water and water vapor. The equation includes the variation of water storage and the divergence of water flows in each phase. Considering water vapor is a component of gaseous phase, it thus has two contributions: the advective flux of gaseous phase and the non-advective flux of the water vapor related to vapor diffusion inside the gaseous phase, which can be written as (Collin et al., 1999):

$$\frac{\partial \rho_w n S_{r,w}}{\partial t} + \text{div}(\rho_w \underline{f}_w) + \frac{\partial \rho_v n S_{r,g}}{\partial t} + \text{div}(\underline{i}_v \rho_v \underline{f}_g) = 0 \quad (1)$$

where ρ_w is liquid water density; n is the medium porosity; $S_{r,w}$ is water saturation degree, \underline{f}_α ($\alpha=w,g$) represents macroscopic velocity of the phase α ; \underline{i}_v is the non-advective flux of water vapour; ρ_v is water density; $S_{r,g}$ is the gas degree of saturation in volume and t is the time. The first two items in Eq. (1) are related to liquid water, and the latter two are associated with water vapour; ρ_v is water density; $S_{r,g}$ is the gas degree of saturation in volume and t is the time. The first two items in Eq. (1) are related to liquid water, and the latter two are associated with water vapour.

The generalized Darcy's law for multiphase porous medium is adopted to simulate the motion of liquid water:

$$\underline{f}_w = -\frac{k_{\text{int}} k_{r,w}}{\mu_w} [\nabla p_w + g \rho_w \underline{y}] \quad (2)$$

where p_w is the liquid water pressure; y is the vertical upward directed co-ordinate; g is the gravity acceleration; μ_w is the dynamic viscosity of the liquid water, and k_{int} is the intrinsic

permeability.

For the pores partially filled by air, it will be more difficult to constitute pathways for water flow, the permeability is consequently decreased. The variation of permeability with the saturation degree is taken into account by introducing the variable of water relative permeability $k_{r,w}$.

The water vapor flow is assumed to follow Fick's diffusion law in a tortuous medium. In the study, the formulation proposed by the model of Philip and Vries (1957) is adopted:

$$\underline{i}_v = -D_{\text{atm}} \tau_v n S_{r,g} \nabla \rho_v \quad (3)$$

where D_{atm} is the molecular diffusion coefficient and τ_v is the tortuosity.

(2) Heat diffusion

In the context, one unique temperature variable is adopted. It means that the temperature is assumed to be homogenous in all phases. The heat transport is related to three effects: conduction, convection and vaporization, as presented in the following equation:

$$q' = -I \nabla T + [c_{p,w} \rho_w \underline{f}_w + c_{p,a} (\underline{i}_a + \rho_a \underline{f}_g)] + c_{p,v} (\underline{i}_v + \rho_v \underline{f}_g) (T - T_0) + (\underline{i}_v + \rho_v \underline{f}_g) L \quad (4)$$

where I is the medium conductivity; $c_{p,\alpha}$ ($\alpha=w, v, a$) represents the specific heat of phase α .

In general, the thermal conductivity is dependent on the temperature and saturation degree. For simplicity, the influence of temperature on thermal conductivity is not considered therein.

4.1.2 Mechanical model

The significant influence of saturation degree on the mechanical behavior of soil has been verified by numerous experimental studies, which should be taken into account in the mechanical modeling. Based on the experimental investigations, some constitutive models are proposed (Alonso, 1990; Alonso, 1999; Tang, 2009). The BBM model is widely used because of its capacity of representing the main fundamental features of partially saturated soils in a consistent and unified manner. It should be noted that the expensive behavior of compacted bentonite is better represented with the modified BBM model (Alonso et al., 1999) by taking into account of the microstructural variation during wetting process. However, the formulation of the model is much more complicated, and some parameters are difficult to identify. As a preliminary study, the BBM model is adopted. A brief introduction to this model is given.

(1) Yield surface

The BBM model is based on the classic Cam-clay model. In consideration of the influence of saturation degree on the mechanical behavior, suction is adopted as an independent variable in this model. The plastic yield surface is thus written in three-dimensional stress space (p , q , s). For the BBM model, the yield surfaces are composed of three parts. In the (p , q) space, for a given suction, the yield surface can be written as:

$$q^2 - M^2(p + p_s)(p_0 - p) = 0 \quad (5)$$

where p is the mean stress; q refers to the deviatoric stress; M is the slope of the critical line, and p_s represents the soil strength in extension.

The pre-consolidation pressure p_0 varies with the suction. The following equation is proposed which is well known as the LC curve:

$$p_0 = p_c \left(\frac{P_0^*}{p_c} \right)^{\frac{\lambda(0)-k}{\lambda(s)-k}} \quad (6)$$

where P_0^* is the pre-consolidation pressure in saturated condition; p_c is a reference pressure; k is the elastic slope of the compressibility curve against the net mean stress; $\lambda(0)$ is the plastic slope for the saturated condition, and $\lambda(s)$ refers to the plastic slope of the compressibility curve against the net mean stress (Fig. 8).

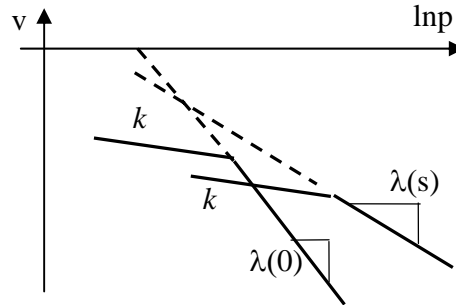


Fig. 8 Compression curve for saturated and unsaturated soil.

Under unsaturated condition, the suction contributes to stiffening the soil against the external load. Hence, the plastic slope of the compressibility curve varies with the suction. The following equation is proposed to represent this phenomenon:

$$\lambda(s) = \lambda(0)[(1-r)\exp(-\beta s) + r] \quad (7)$$

where γ and β are the parameters describing the changes in soil stiffness with suction. The

LC curve defines another part of the yield surface used for modeling the collapse behavior under wetting.

Numerous studies confirmed that irreversible volumetric deformation may be induced by variations in suction. Therefore, the SI yield surface, which defines the maximum previously attained value of the suction, is employed to take into account this phenomenon:

$$F_2 = s - s_0 = 0 \quad (8)$$

where s_0 represents the maximum historic suction submitted to the soil.

(2) Hardening law

The evolution of yield surfaces is assumed to be controlled by the total plastic volumetric strain ε_v^p . Two hardening laws define the evolution of state variables p_0 and s_0 with the irreversible strain:

$$dp_0^* = \frac{(1+e)p_0^*}{\lambda(0) - \kappa} d\varepsilon_v^p \quad (9)$$

$$ds_0 = \frac{(1+e)(s_0 + P_{at})}{\lambda_s - k_s} d\varepsilon_v^p \quad (10)$$

where e is the porosity of the soil; P_{at} is the atmospheric pressure; λ_s and k_s are the plastic and elastic stiffness parameters for suction variation, respectively.

4.2 Numerical simulations

In order to validate the proposed, the numerical simulation of the China-Mock-up test is carried out in this part.

4.2.1 Geometry and Boundary Conditions

A 2D-axisymmetric finite element simulation is realized with the help of the software LAGAMINE. The geometry and boundary conditions are illustrated in Fig. 9.

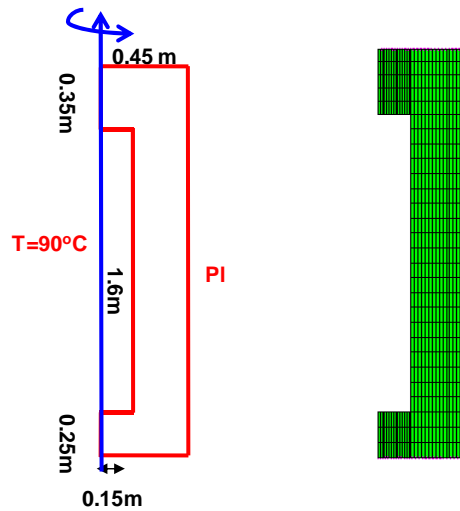


Fig. 9 Boundary conditions and mesh.

For simplicity, the steel tank is neglected to address the problem in the numerical test. The fixed horizontal/vertical displacement is imposed on the nodes in contact with the steel and the heating is simulated by imposing the temperature on the nodes in contact with the heater. The hydration influence is modeled by increasing water pressure on the nodes of outer boundary. The convection transfer between the GMZ bentonite and atmosphere is simulated thanks to frontier thermal elements. In the simulations, air flow is not considered, whereas the vapor diffusion is assumed.

The system is initially at temperature of 20 °C. The gas pressure is assumed to be constant in order to have a better numerical convergence. The compacted GMZ bentonite has an initial water saturation of 48% and a void ratio of 0.57. According to the water retention curve determined, a suction of 80MPa is initially employed. As aforementioned, the dissolved air will not be taken into account.

Following the experimental procedure, the numerical simulation is divided into two phases: firstly, the temperature on the boundary connected to the heater and the water pressure on the outer boundary are increased respectively to 90 °C and 2MPa in 10 hours. In the following, the boundary conditions applied previously are kept constant in 3 years.

4.2.2 Determination of THM parameters

(1) Hydro-thermal properties

Among the hydro-thermal properties, the water retention curve and permeability are considered as the key factors on the water intake volume and the final saturation degree. Measured data of water content in function of suction is available (Chen et al., 2006). The relation between suction and water saturation is adopted in the study:

$$S_{r,w} = S_{r,res} + a_3 \frac{S_{r,u} - S_{r,res}}{a_3 + (a_1 s)^{a_2}} \quad (11)$$

where $S_{r,u}$ is the maximum saturation degree in the soil and $S_{r,res}$ is the residual saturation degree for a very high value of suction.

Values of $S_{r,u}$ and $S_{r,res}$ determined in test are 1.0 and 0.1, respectively. Calibration of this function on measured data gives the values of the following parameters: $a_1=3.5 \times 10^{-6} \text{ Pa}^{-1}$, $a_2=0.8$, $a_3=90$. Water retention curve of GMZ bentonite is illustrated in Fig. 10.

Relative permeability curves are determined based on the experimental investigation (Ye et al., 2009b), as shown in Fig. 11. The intrinsic permeability $k_{int}= 2.0 \times 10^{-21} \text{ m}^2$ is chosen according to the experimental data. Thus, we have

$$k_{r,w} = \frac{(S_{r,w} - S_{r,res})^4}{(S_{r,u} - S_{r,res})^4} \quad (12)$$

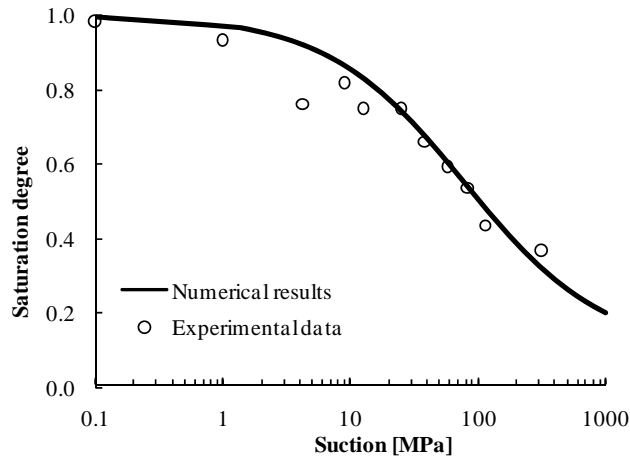


Fig. 10 Water retention curve of GMZ bentonite.

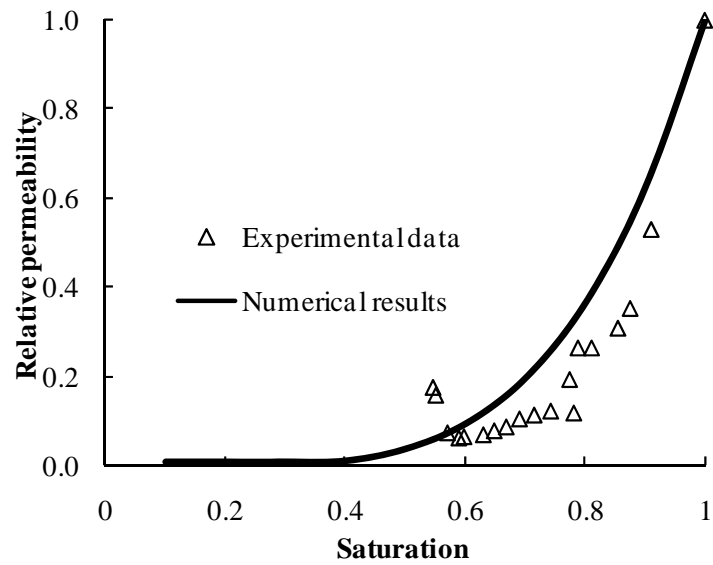


Fig. 11 Variation of relative permeability in function of saturation degree.

A linear relation is adopted to describe the variation in thermal conductivity with saturation degree, as shown in Fig. 12. Table 1 summarized the other parameters of the hydraulic and thermal properties:

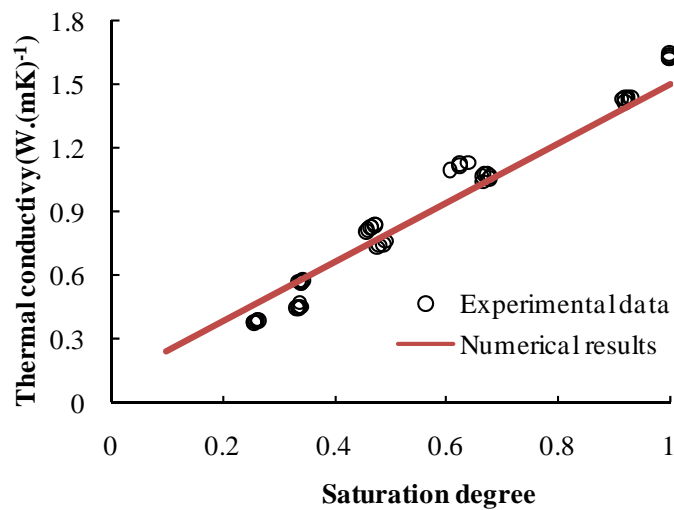


Fig. 12 Variation of thermal conductivity with saturation degree.

Table 1 Parameters of the flow model.

Grain density ρ_s (kg.m ⁻³)	Grain specific heat $c_{p,s}$ (J.kg ⁻¹ K ⁻¹)	Water density ρ_w (kg.m ⁻³)	Water dynamic viscosity μ_w (Pa.s)	Water specific heat $c_{p,w}$ (J.kg ⁻¹ K ⁻¹)	Air density ρ_a (kg.m ⁻³)
1.6×10^3	2.6	1.0×10^3	1.009×10^{-3}	4.18×10^3	1.205
Air dynamic viscosity μ_a (Pa.s)	Air specific heat $c_{p,a}$ (J.kg ⁻¹ K ⁻¹)	Water vapour specific heat $c_{p,v}$ (J.kg ⁻¹ K ⁻¹)	Latent heat of vaporization L (J.kg ⁻¹)	Tortuosity, τ	
1.80×10^{-5}	1.0×10^3	1.90×10^3	2.50×10^6	0.1	

(2) Mechanical parameters

The mechanical loading test at constant suction and temperature (Cui et al. 2011) revealed that elastic stiffness parameters k and plastic stiffness parameters $\lambda(s)$ of the GMZ bentonite increase with decrease of suction but are independent of the temperature changes. The effect of temperature on the yield stress p_0 of the GMZ bentonite is found to be insignificant. For simplicity, a constant value of the elastic stiffness parameter k is adopted. The parameters γ and β which define the variation of $\lambda(s)$ with suction, are determined based on experimental data (Fig. 13).

The LC curve describes the evolution of p_0 with suction, which depends on k , $\lambda(s)$ and p_c . The reference pressure p_c cannot be directly determined, thus a calibration procedure is adopted. The stiffness parameters k_s and λ_s define the volumetric strain changes induced by suction. According to the experimental study, a volumetric strain of 32.4% is obtained when the suction is decreased from 110 to 9 MPa. Considering that the volumetric strain is induced in a wetting procedure (inferior to the maximum historic suction), it can be considered as elastic volumetric strain. Therefore, a value of 0.07 is determined for k_s . Due to the lack of experimental data, an average value of λ_s obtained from other types of Bentonite (0.25) is taken in the simulation (Collin et al., 1999). Based on the water retention curve, s_0 can be fixed from the initial saturation degree.

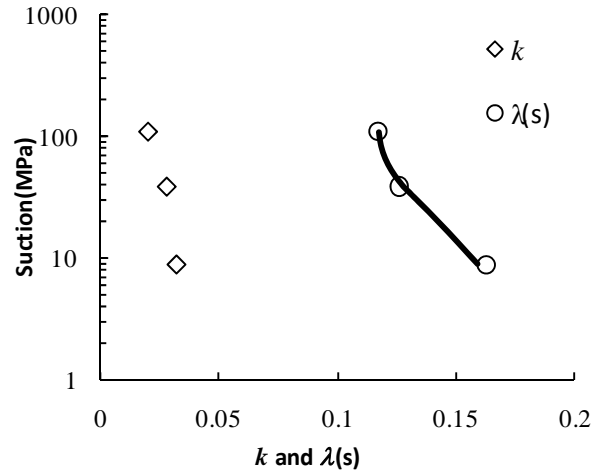


Fig. 13 Variation of k and $\lambda(s)$ with suction.

The dependence of these parameters on the stress state generated in the soil sample is not taken into account. The values of parameters used in the simulations are summarized in Table 2.

Table 2 Parameters employed in mechanical model.

Saturated virgin compression index $\lambda(0)$	Elastic compression index k	Saturated pre-consolidation pressure p^*_0 (MPa)	Elastic stiffness index upon suction k_s	Plastic stiffness index upon suction λ_s	Maximum value of the suction s_0 (MPa)
0.18	0.027	0.6	0.08	0.25	80
Reference stress p_c (MPa)	Ratio $\lambda(s)/\lambda(0)$ for high suction γ	Parameters to control the increase of stiffness with suction β (MPa ⁻¹)			
0.45	0.65	0.045			

4.2.3 Predictive results and analysis

With the given parameters, the simulations of experimental process are carried out. The evolution of temperature vs. time in the lateral direction (along the red line) is illustrated in Fig. 14. As defined in boundary conditions, the temperature is kept at 90 °C on the nodes connected to the electric heater. At the beginning, the temperature of compacted bentonite increases rapidly, especially in the first month. Thanks to the frontier thermal elements, the temperature on the exterior boundary also increases with time.

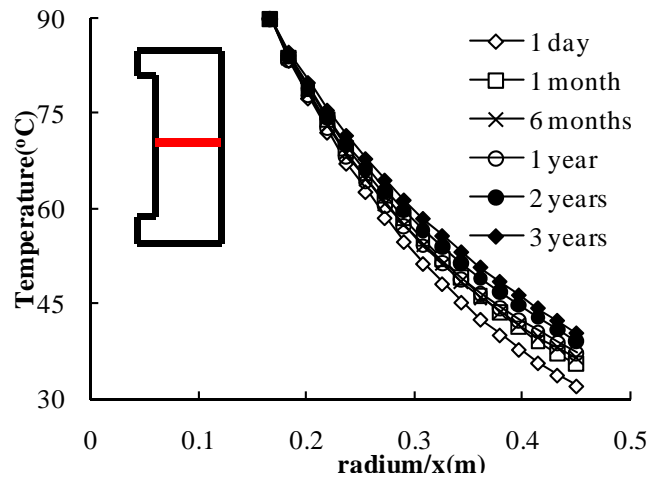


Fig. 14 Evolutions of temperature vs. time (along the red line).

The compacted bentonite is progressively saturated by the water inflow (Fig. 15), which is in an opposite direction to heat flow. However, due to the extremely low permeability and evaporation, the compacted bentonite close to the heater still stays partially saturated after 3 years (Fig. 16).



Fig. 15 Water flow at the end of simulation (3 years).

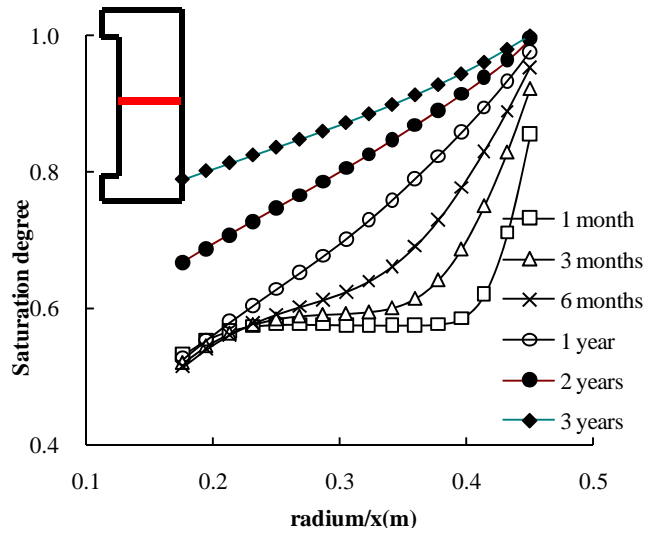


Fig. 16 Distribution of saturation degree with time.

In terms of suction, due to the saturation process by water penetration, the suction is decreased globally (Fig. 17). It is interesting that a more significant suction (100 MPa) than the initial value (80 MPa) can be noticed at the beginning. It indicates that the bentonite is desaturated in this period of time.

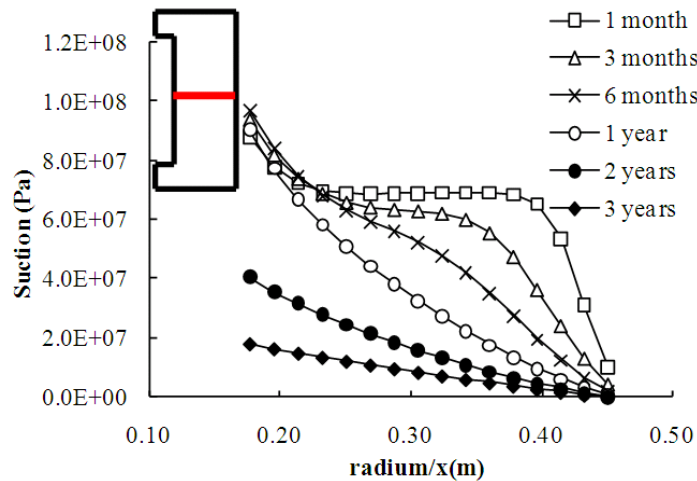


Fig. 17 Suction-time evolution in lateral direction.

This phenomenon is well presented in Fig. 18, in which the suction responses of the three points (A, B, C) in lateral direction are illustrated. It is noticed that at point A, the suction

increases at first, and then decreases. This desaturation-saturation process can be attributed to the evaporation phenomenon generated by high temperature of the electrical heater. In Fig. 19, water vapor is generated and transported towards outer boundary in the field exposed to high temperature. The desaturation process indicates that at the beginning, the evaporation phenomenon is dominant compared to the saturation effect induced by the water inflow. This phenomenon is also observed in other experimental tests, like the Canister Retrieval Test (CRT) carried out by SKB (Akesson et al., 2010).

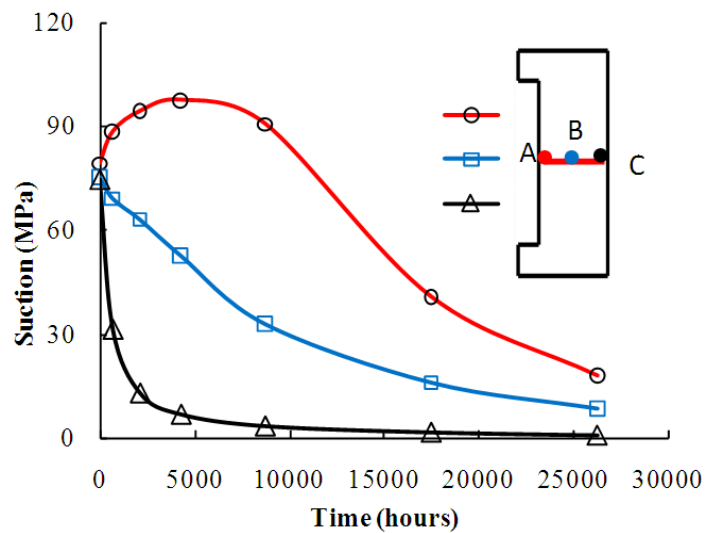


Fig. 18 Suction responses of the three points in lateral direction.

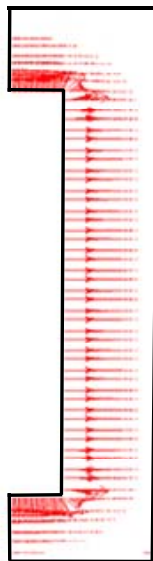


Fig. 19 Vapor flows at the end of simulations (3 years).

The predicted water pressure with time is illustrated in Fig. 20. It is noticed that in the field exposed to high temperature, the suction is more significant, especially for the area close to the upper surface and the bottom of the electrical heater. At the end of the simulations (3 years), a suction of around 59 MPa is reached in this field. This result seems reasonable considering that the field is far from the outer boundary. Moreover, the evaporation generated by high temperature is also more significant.

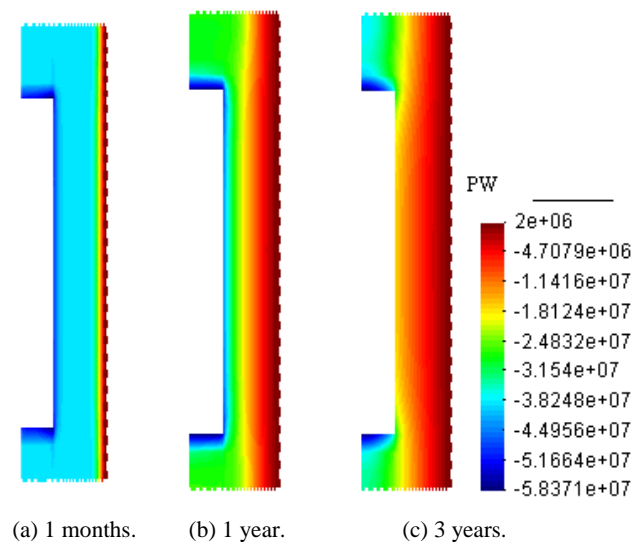


Fig. 20 Distribution of water pressure.

The swelling pressure variation with time at point A with co-ordinates $r=0.15$ m and $z=0.123$ m is illustrated in Fig. 21.

It can be noticed that the swelling pressure increases rapidly at the beginning, and a value of 1.5 MPa is obtained after 3 years, which seems relatively limited. It can be attributed to two reasons: first, considering the saturation process is not completed, the maximum value is not yet reached; on the other hand, the expansion strain induced by the variation in microstructure of bentonite during wetting process is not considered in the BBM model.

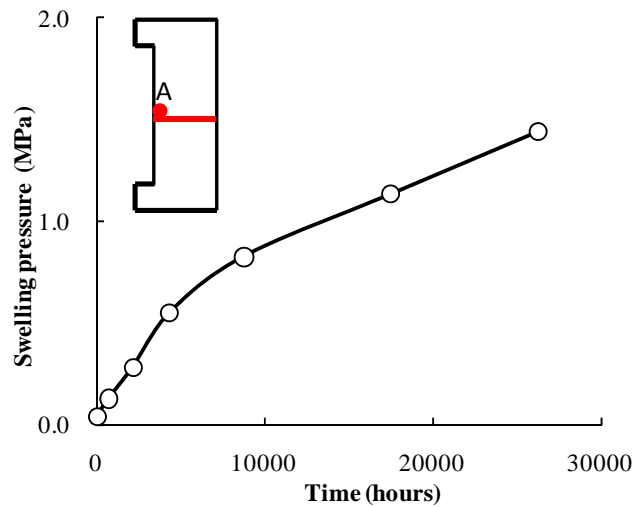


Fig. 21 Swelling pressure evolution at point A.

5. Conclusion

The buffer material is one of the main engineered barriers for the HLW repository. In order to study the behavior of the compacted GMZ-Na-bentonite under coupled THMC conditions, a large-scale mock-up facility, China-Mock-up based on a preliminary concept of HLW repository in China, has been designed and constructed in the laboratory of BRIUG.

The current experimental data is presented in the report, including the variation of temperature, relative humidity, stress and displacement etc. A thermo-hydro-mechanical model is proposed to reproduce the complex coupling behavior of the compacted GMZ bentonite. With the proposed model, numerical simulation of the China-mock-up test is realized. According to the analysis of the experimental and numerical results, some conclusions are obtained and summarized as follows:

(1) The experimental data indicates that the saturation process of the compacted bentonite is strongly influenced by the competitive mechanism between the drying effect induced by the high temperature and the wetting effect by the water penetration from the outer boundary. For this reason, the desiccation phenomenon is observed in the zone close to the heater.

(2) Due to the THM coupling phenomena and its influence to the mechanical behavior of the compacted bentonite, the heater is not stationary in the facility. At present, an upward movement of the heater is observed.

(3) Based on the qualitative analysis of the predictive results, it is suggested that the proposed model is capable to reproduce the principal coupled THM behavior of the compacted GMZ bentonite. As a qualitative analysis of the predictive results, the numerical study realized only can be considered as a preliminary verification of the proposed model. With the progress of the experimental test, further study is needed.

The China-Mock-Up experiment is an important milestone of the buffer material study for HLW disposal in China. The observed THMC processes taking place in the compacted bentonite-buffer during the early phase of HLW disposal can provide a reliable database for numerical modeling and further investigations of EBS, and the design of HLW repository.

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