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Long-term Performance of Engineered Barrier Systems

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China-Mock-up status Annual Report

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ABSTRACT

According to the preliminary concept of the high level radioactive waste (HLW) repository in China, a large-scale mock-up facility, named China-Mock-up was constructed in the laboratory of BRIUG, 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. The real-time data acquisition and monitoring system has recorded all the measurement data from 1st April 2011 to 8th November 2012. 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

Geological repositories are generally designed on the basis of a multiple barrier system concept, which is mainly composed by engineered and natural barriers. In the life cycle of the high-level radioactive waste (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 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 (Karnland 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 (Liu et al, 2011). 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 (Chen et al, 2012). 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 from1st 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 inject at 0.5MPa with Beishan groundwater at the working time, and the injection rate is 400g/d, and later raises to 600g/d. Recently, the injection rate has changed to 1500 g/d.

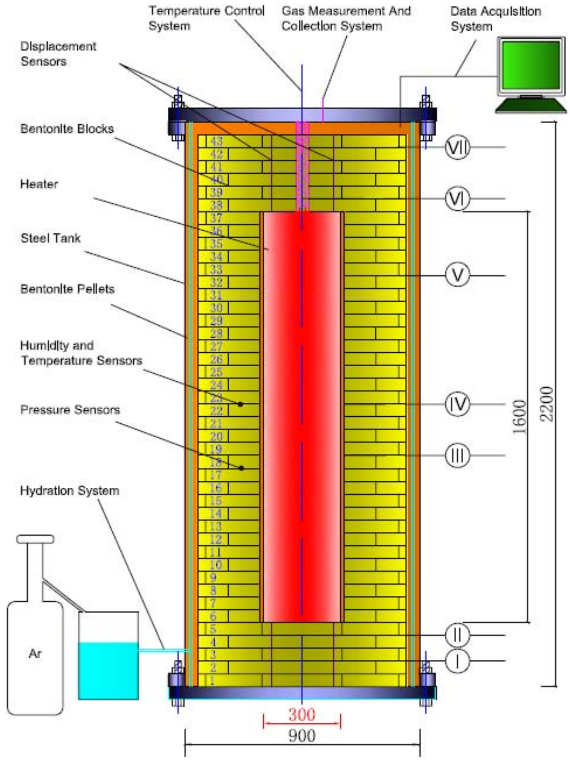


Figure 1 Sketch of the China-Mock-up facility (unit: mm).

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 8th November 2012.

3.1 Water consumption

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, and now the injection rate has changed to 1500 g/d. The water consuming with the time is illustrated in Fig. 2.

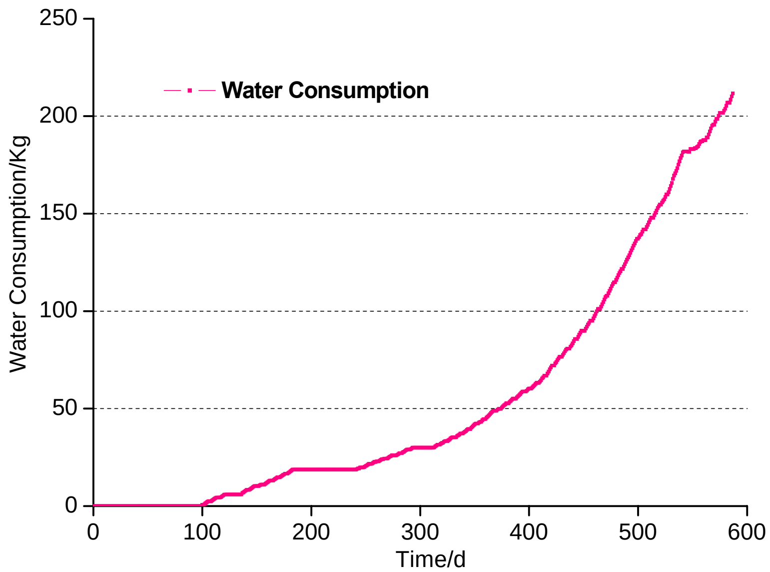


Figure 2 Water consumption with the time.

3.2 Relative humidity

Fig. 3 and Fig. 4 present the relative humidity variation with time at the bottom of the mock-up facility. As illustrated in the figures, the compacted bentonite is progressively saturated with time in section I and II, and the distance to the outer boundary has a significant influence on the saturation velocity. In the area close to the outer boundary, the compacted bentonite is almost totally saturated after 200 days. However, due to the extremely low permeability of compacted bentonite, the variation of relative humidity is limited in the central part of the facility.

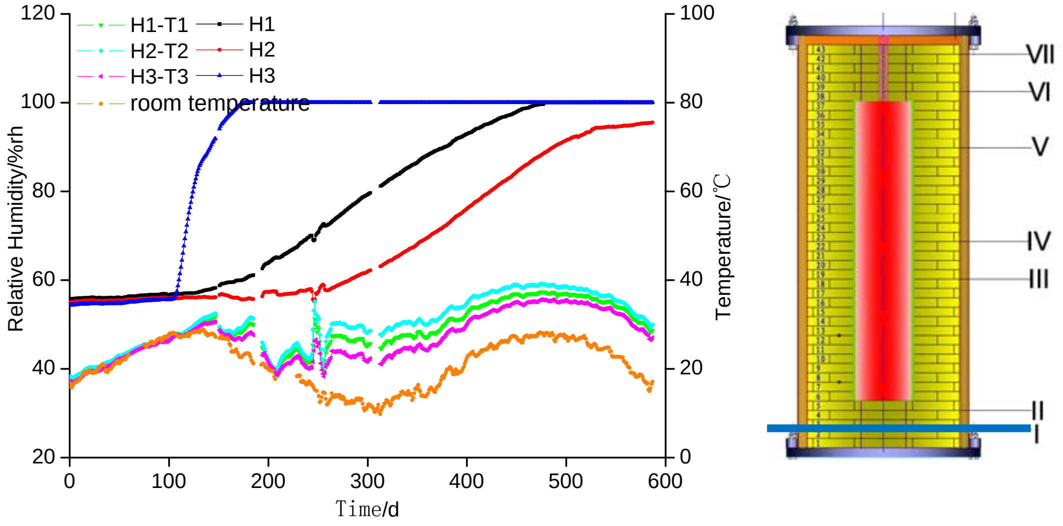


Figure 3 Relative humidity distribution at section I.

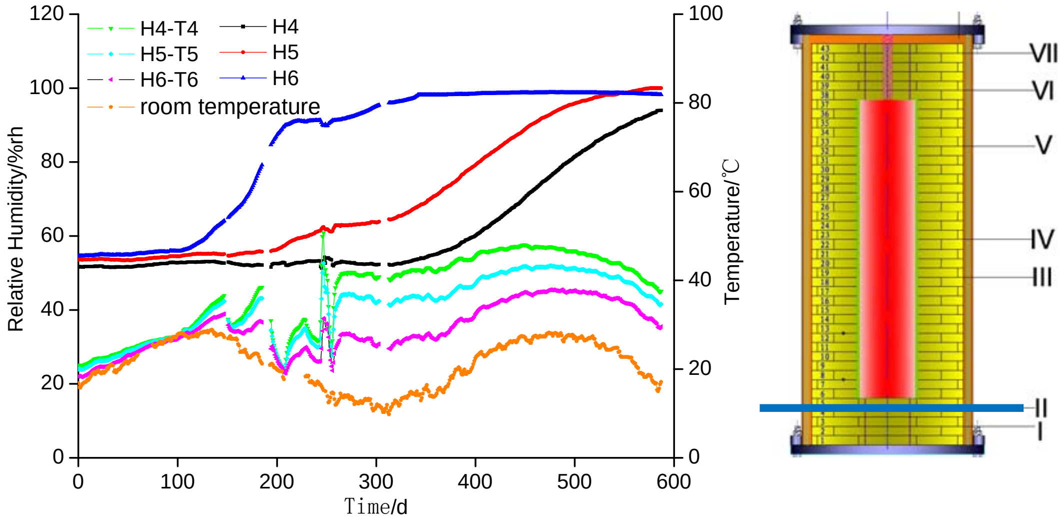


Figure 4 Relative humidity distribution at section II.

Fig. 5-7 present the variation of relative humidity with time in the sections III-V. It can be noticed that, the variation of relative humility 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. Then with the increase of the injection water, the saturation process is dominant after 500 days, and the humility is increased gradually.

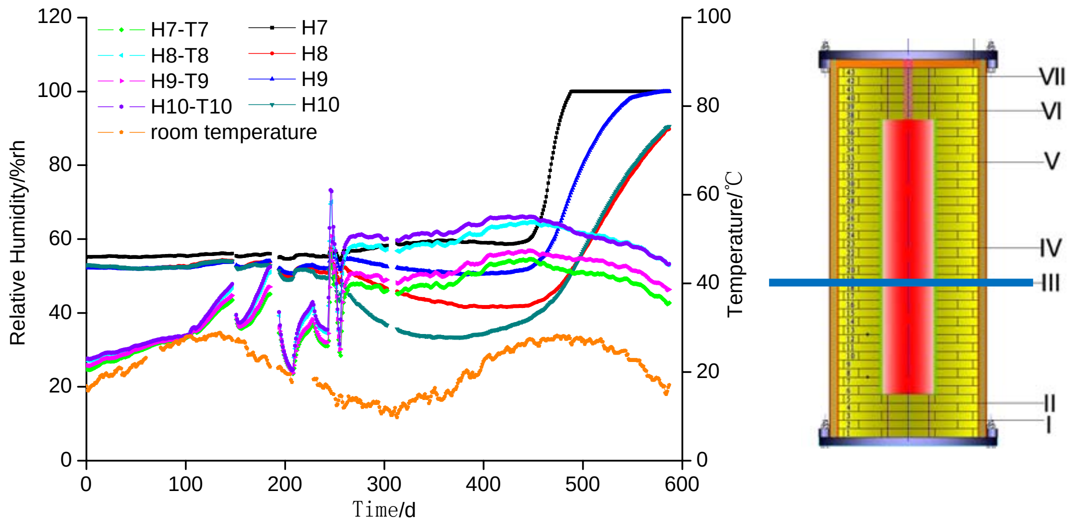


Figure 5 Relative humidity distribution at section III.

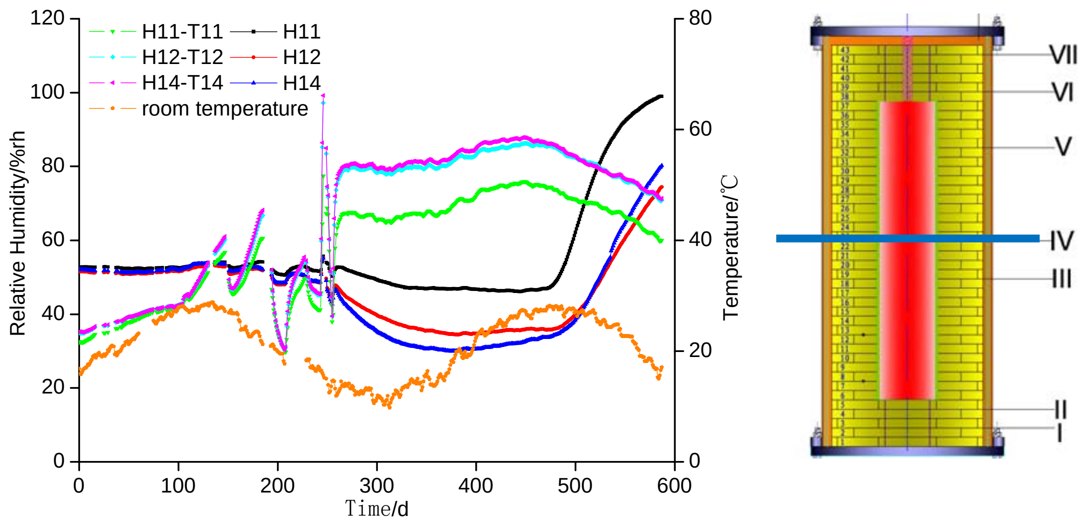


Figure 6 Relative humidity distribution at section IV.

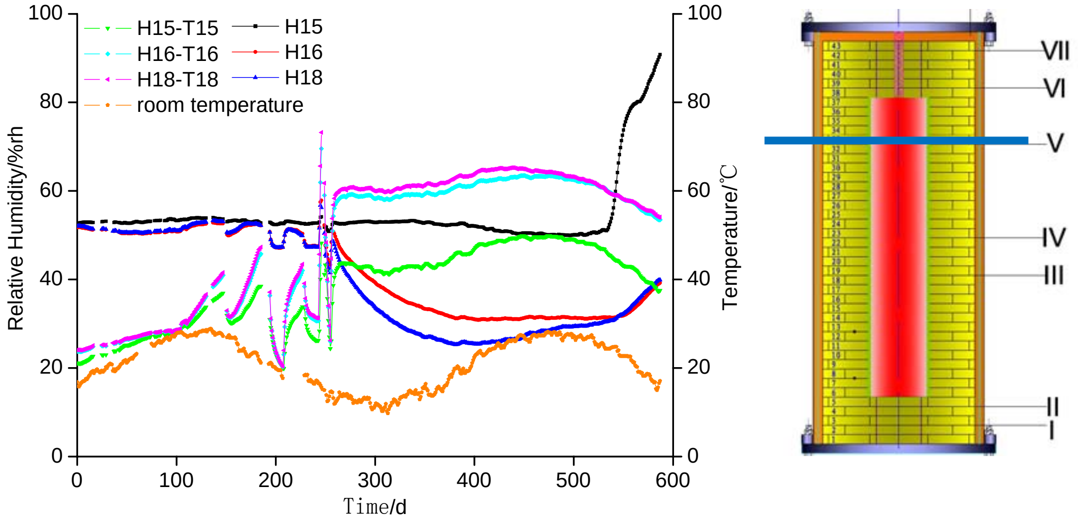


Figure 7 Variation of relative humidity at section V.

The variation of relative humidity with time on the top of the China-mock-up facility is illustrated in Fig. 8-9. Thanks to the longer distance to the heater, it can be noticed that the desiccation induced by the high temperature is less evident in this area. However, the desaturation phenomenon is still noticed in the central part of the section with the increase of temperature in this area. In addition, the relative humidity is sensitive to the fluctuation of the temperature.

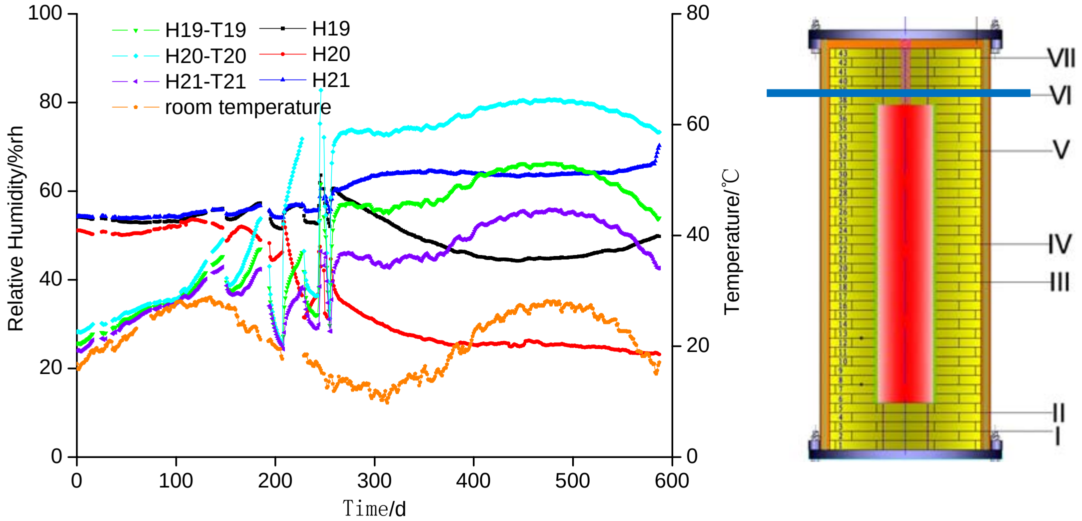


Figure 8 Variation of relative humidity with time at section VI.

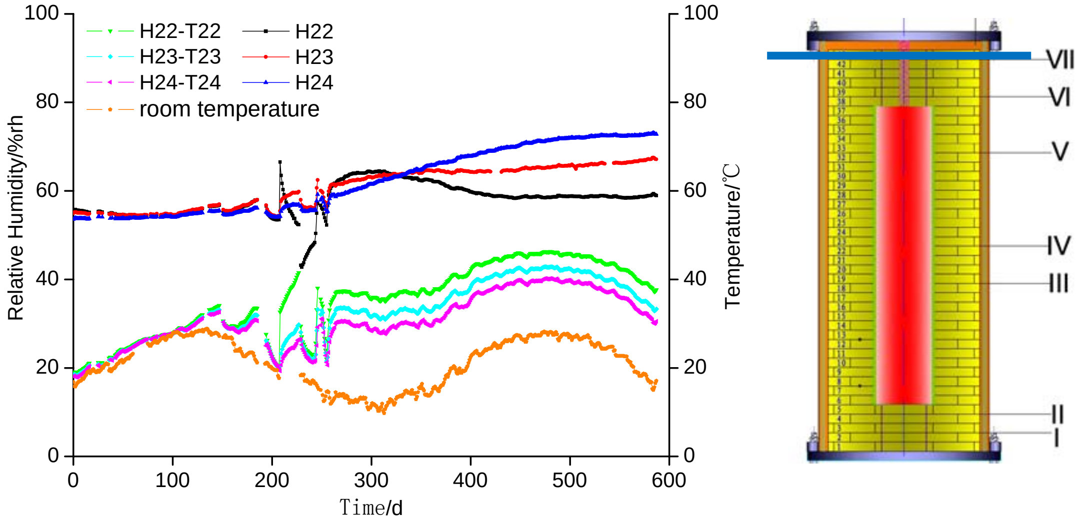


Figure 9 Variation of relative humidity with time at section VII.

3.3 Temperature

The temperature variation with time in different sections of the facility is illustrated in Fig. 10-16. As the beginning of the test, the temperature is increased globally with time, especially for the sensors close to the heater, the temperature has decreased distance from the heater. Due to the interrupt of electricity power, some fluctuation can be observed. It is noticed that the temperature has decreased after 500 days with the development of the seasons, but unfortunately some of the sensors are out of work.

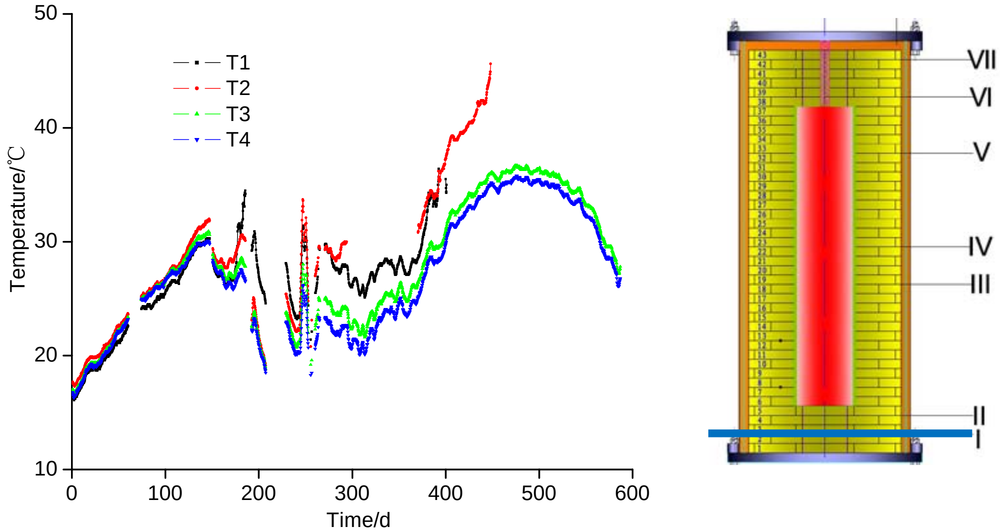


Figure 10 Temperature variation with time at section I.

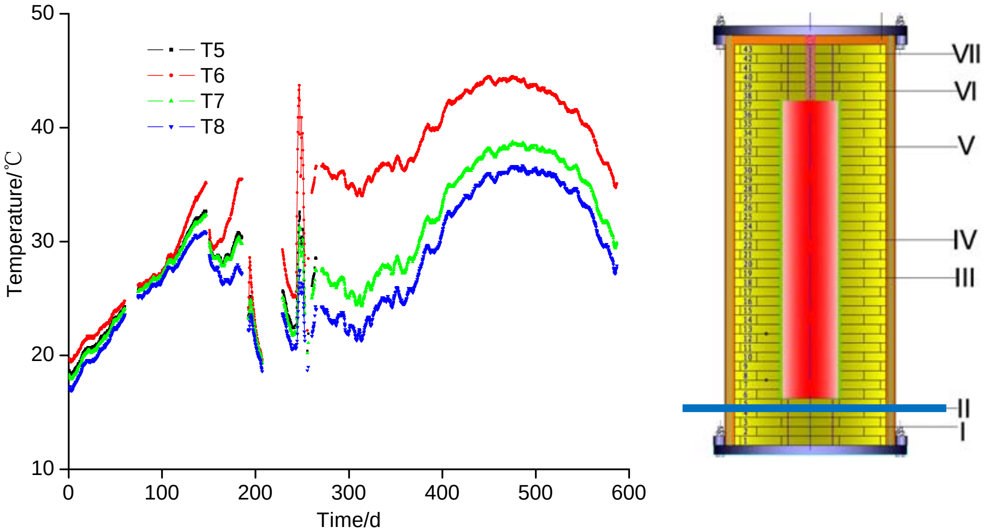


Figure 11 Temperature variation with time at section II

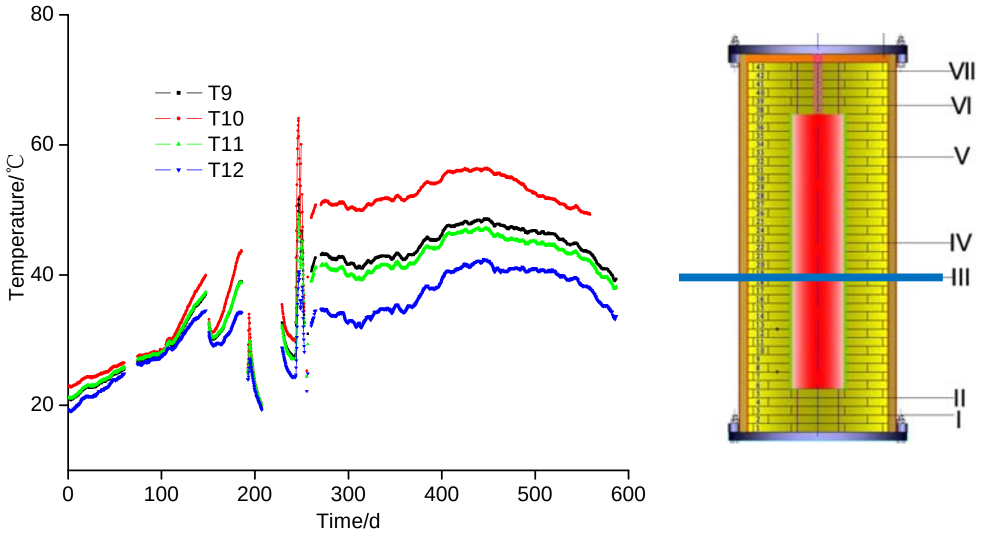


Figure 12 Temperature variation with time at section III.

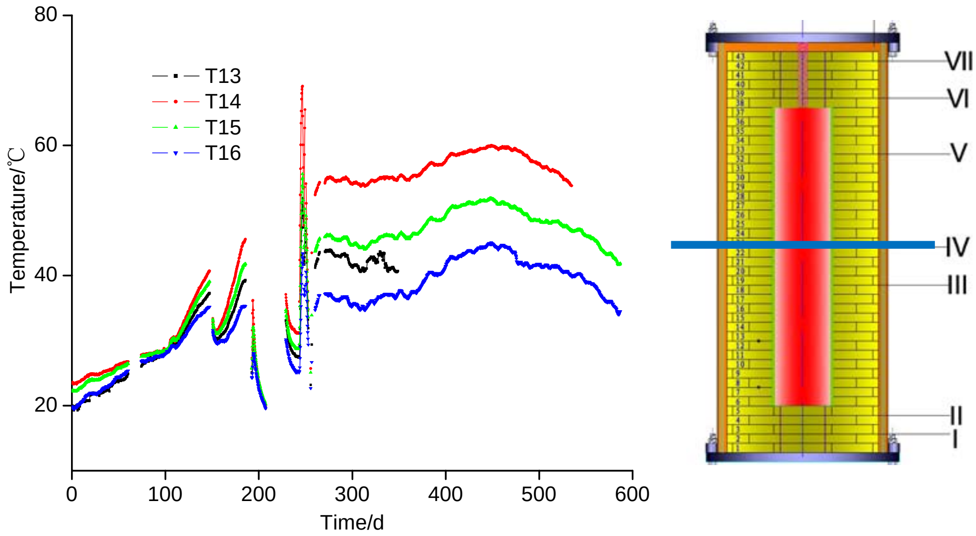


Figure 13 Temperature variation with time at section IV.

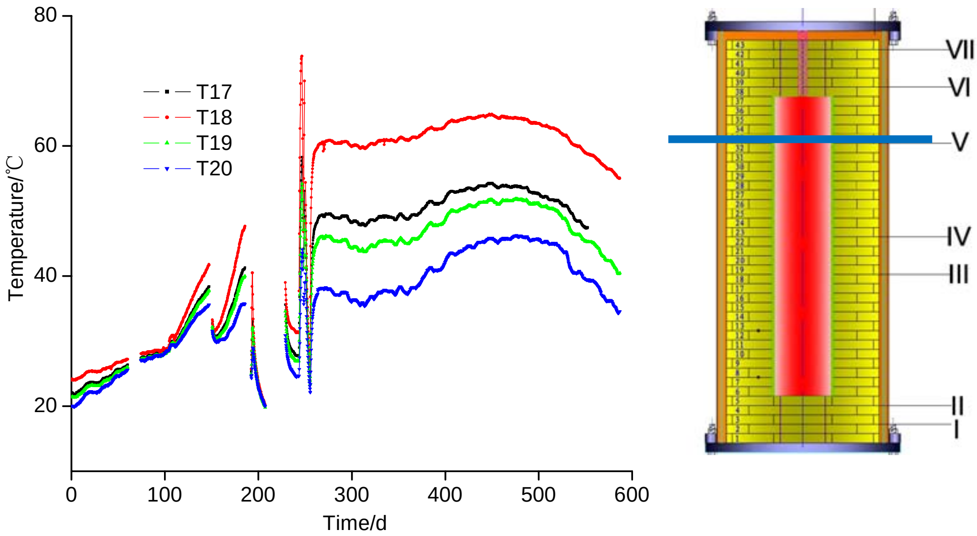


Figure 14 Temperature variation with time at section V.

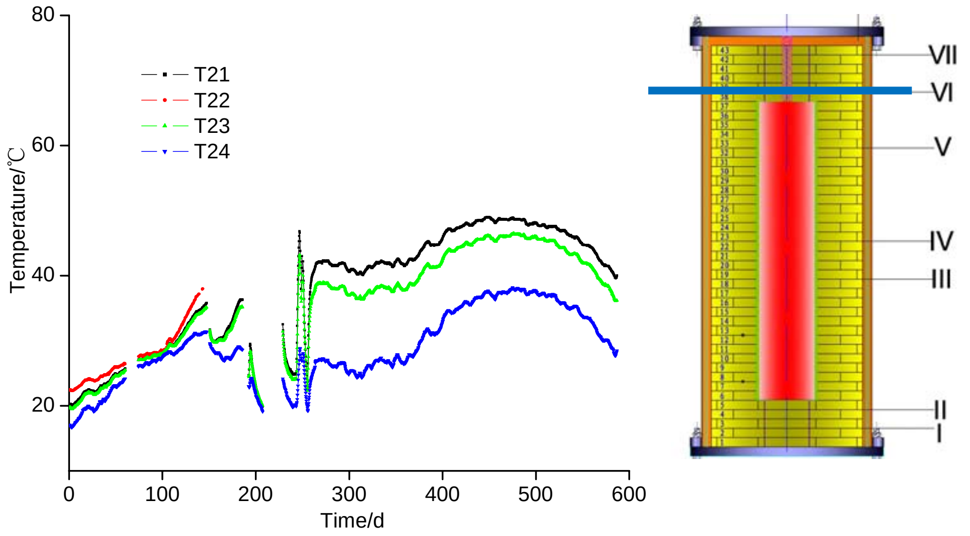


Figure 15 Temperature variation with time at section VI.

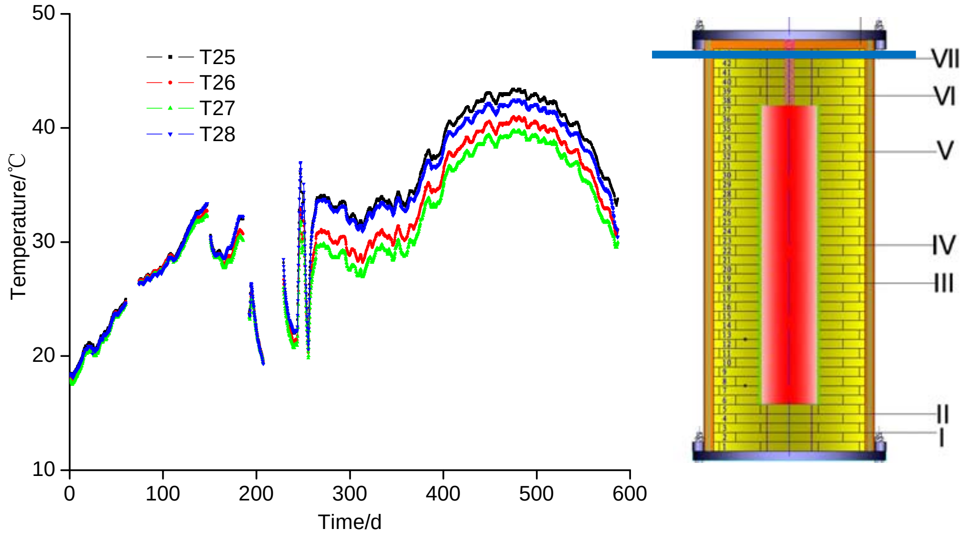


Figure 16 Temperature variation with time at section VII.

3.4 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. 17. 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. In the proceeding of the test, the displacement became more and more flat.

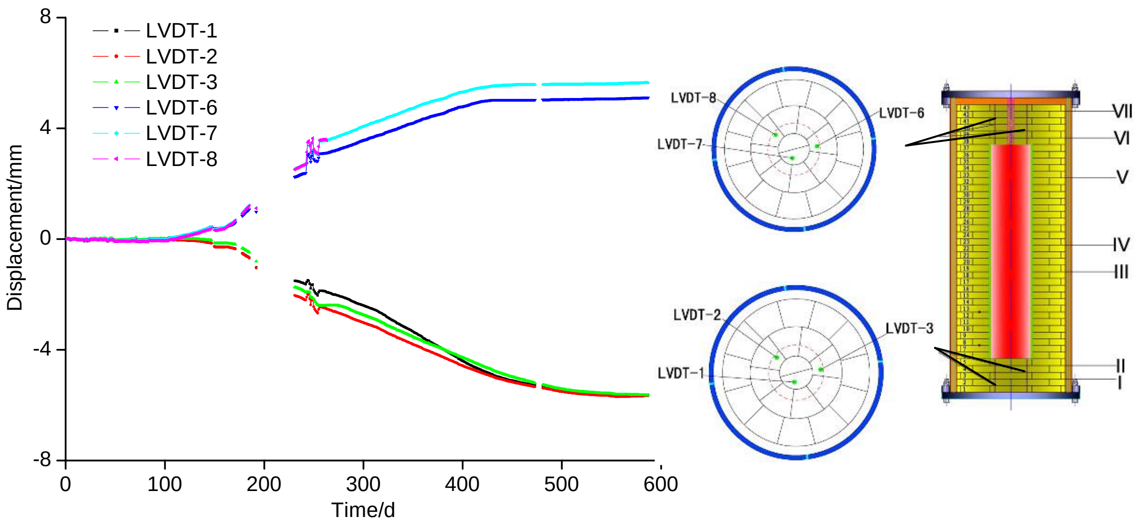


Figure 17 Vertical displacement of the heater with time.

3.5 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 section I-III is presented in Fig. 18-20. As illustrated in the figures, with the increase of the injection water, the saturation process is dominant, and the stress in this area is increased gradually. 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.

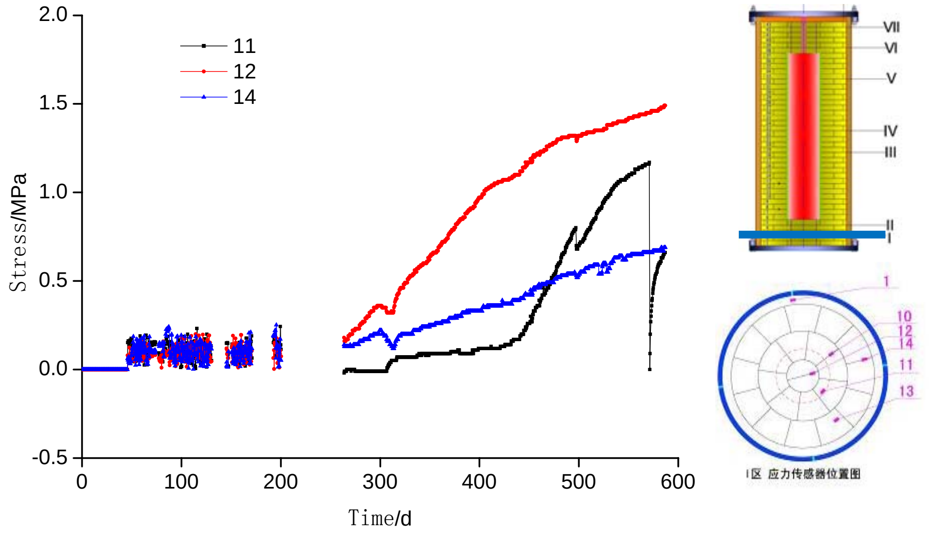


Figure 18 Stress evolution at section I of China-Mock-up.

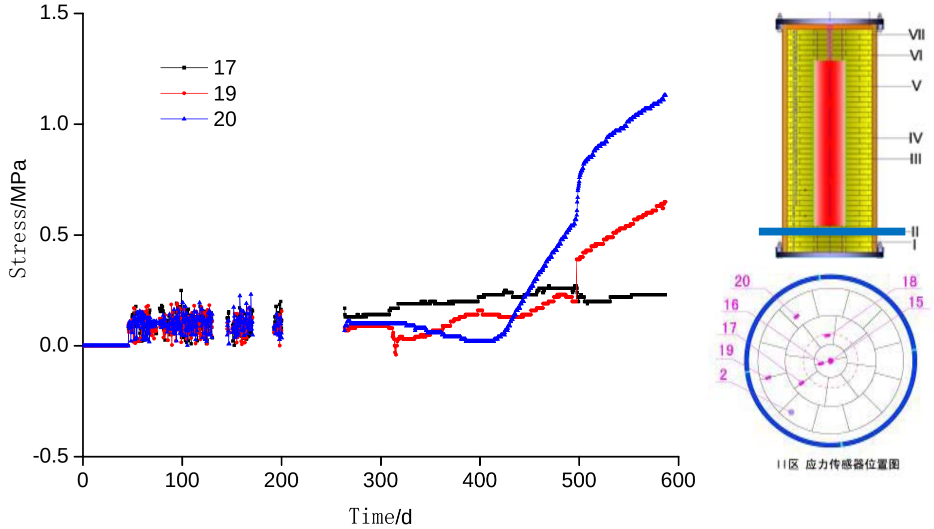


Figure 19 Stress evolution at section II.

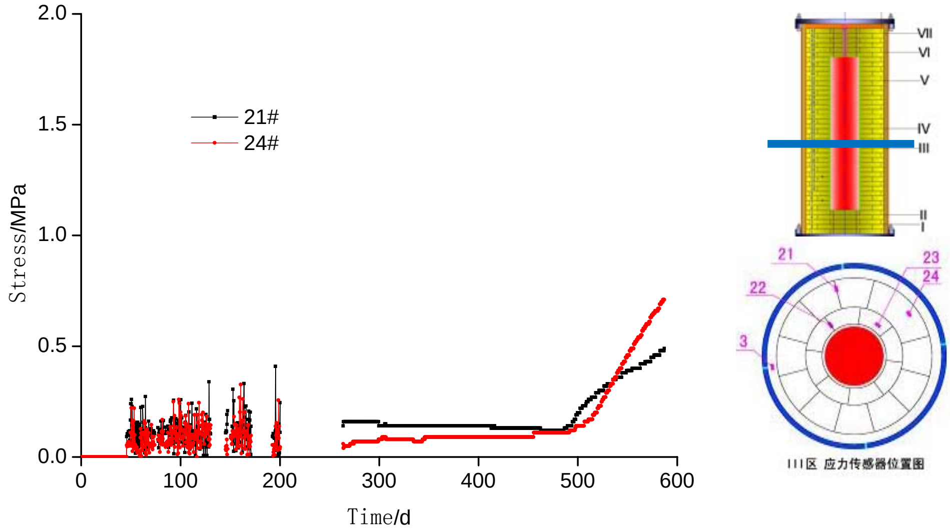


Figure 20 Stress evolution at section III.

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. A 2D-axisymetric finite element simulation is realized with the help of the software LAGAMINE.

4.2 Temperature field evolution

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. 21. 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.

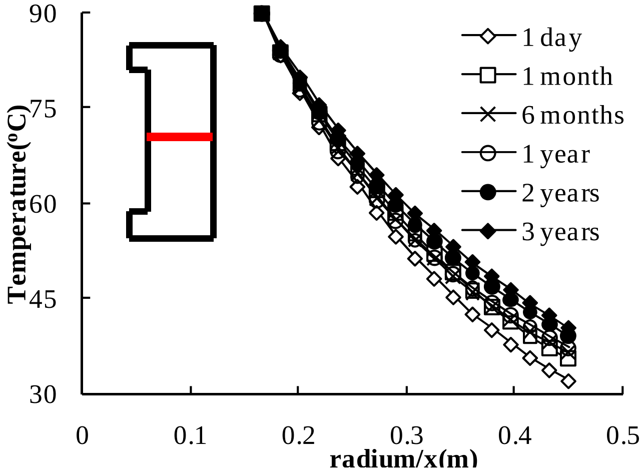


Figure 21 Evolutions of temperature vs. time (along the red line).

4.3 Humidity field evolution

The compacted bentonite is progressively saturated by the water inflow (Fig. 22), 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. 23).

Figure 22 Water flow at the end of simulation (3 years).

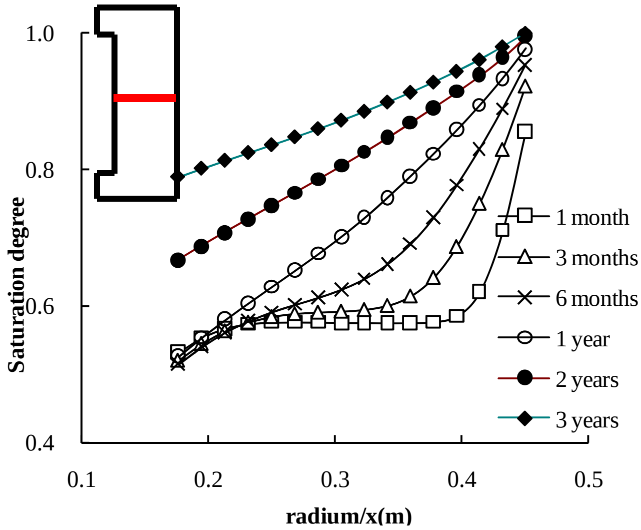


Figure 23 Distribution of saturation degree with time.

In terms of suction, due to the saturation process by water penetration, the suction is decreased globally (Fig. 24). 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.

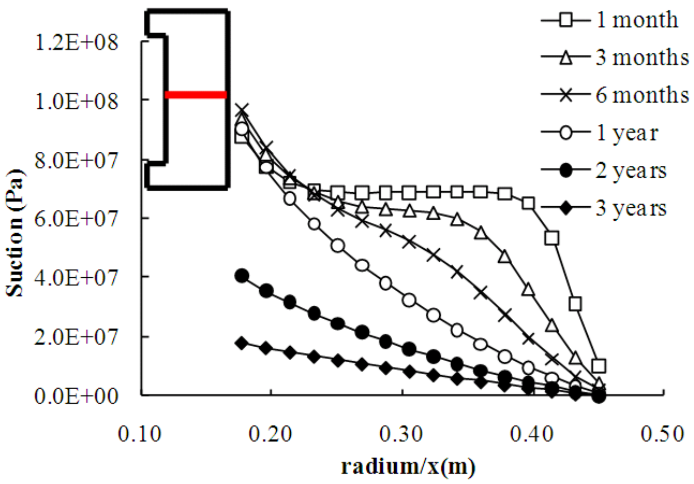


Figure 24 Suction-time evolution in lateral direction.

This phenomenon is well presented in Fig. 25, 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. 32, 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).

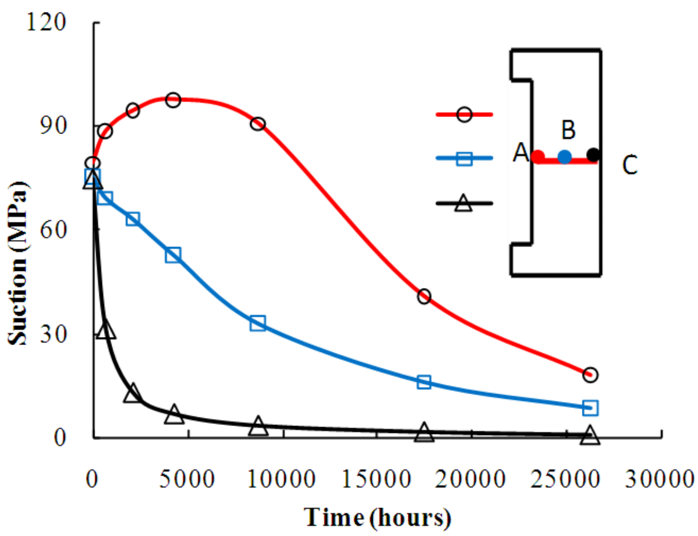


Figure 25 Suction responses of the three points in lateral direction.

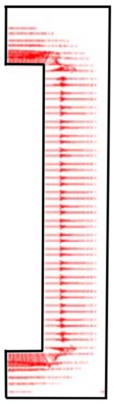
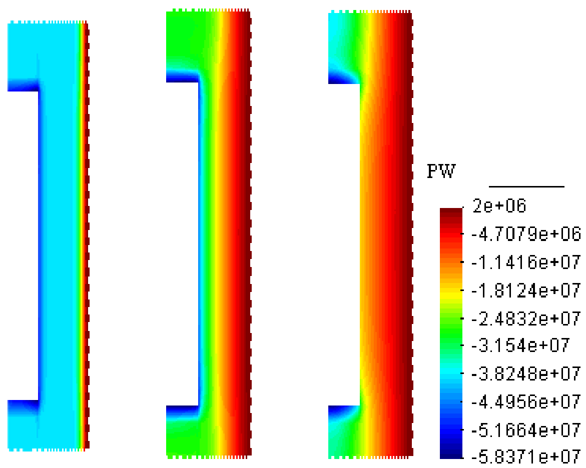


Figure 26 Vapor flows at the end of simulations (3 years).

The predicted water pressure with time is illustrated in Fig. 27. 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.



(a) 1 months. (b) 1 year. (c) 3 years.

Figure 27 Distribution of water pressure.

4.4 Swelling pressure evolution

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. 28.

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.

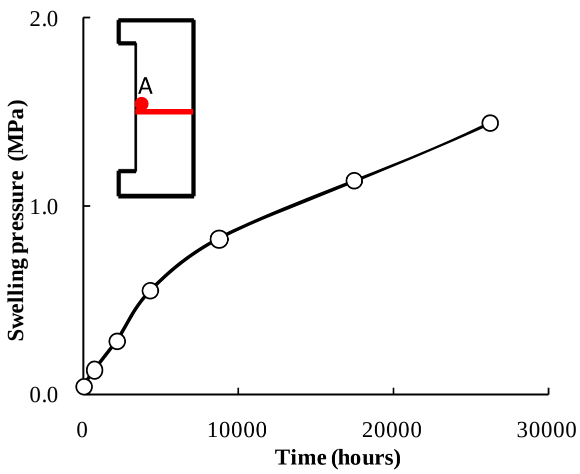


Figure 28 Swelling pressure evolution at point A.

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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