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ABSTRACT

A large-scale mock-up facility, China-Mock-up based on a preliminary concept of high level radioactive waste (HLW) repository in China, which is used to study the THMC properties of compacted GMZ-Na-bentonite, was constructed in the laboratory of BRIUG. A heater, which substitutes a container with radioactive waste, is placed inside the compacted GMZ-Na-bentonite blocks and pellets with total dry density 1600 kg/m^3. Water inflow through the barrier from its outer surface is to simulate the intake of groundwater. In order to design the power of the heater and the parameter of the heat insulation layer, as well as the evolution of the heat, water flow and stress in the buffer material, numerical modeling was conducted. 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 of EBS, and the design of HLW repository.

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 mainly composed by engineered and natural barriers between the HLW and the biosphere. The buffer/backfill material as one of the most important components in the engineered barrier system is the last line of defense between waste container and host rock, and 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 (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 into 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 modelling and further investigations.

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. EXPERIMENT MATERIAL

2.1 GMZ-bentonite

The GMZ-bentonite deposit has been selected as the most potential buffer/backfill material supplier for China's HLW repository (Liu et al., 2001). The GMZ-bentonite deposit is a large-scale one, located in the northern China′s Inner Mongolia Autonomous Region, 300 km northwest of Beijing. The transportation from the mine to outside is very convenient. The deposit, with bedded ores, was formed in late Jurassic. Ore minerals include montmorillonite and quartz, feldspar, cristobalite etc. The reserve is about 160×10^6 tons， while with 120×10^6 tons of Na-bentonite.

Comprehensive studies have been conducted on the GMZ-Na-bentonite(Wen, 2006; Chen, 2006; Liu & Cai, 2007b; Ye et al. 2009b). The previous study on GMZ-Na-bentonite shows that the bentonite is characterized by high content of Montmorillonite (70%) and low impurities. Various experiments have revealed that the GMZ-Na-bentonite has cation exchange capacity 77.30 mmol/100g, methylene blue exchange capacity 102 mmol/100g, and alkali index 1.14. The main properties of the bentonite compacted to a dry density of 1.8g/cm^3 are: thermal conductivity of around 1.0 W/m·K at water content of 8.6%, hydraulic conductivity of 1×10^{-13} m/s, and swelling pressure of 10 MPa. Those characteristics indicate that the GMZ-Na-bentonite has the very similar properties as those of the mostly investigated MX-80 and FEBEX bentonites to be used as buffer/backfill material.

2.2 Compacted bentonite blocks and pellet

Compacted bentonite blocks are used as buffer material for HLW disposal. Granular mixtures made of high-density pellets of bentonite are being evaluated as an alternative buffer material for waste isolation (Alonso et al., 2010).

A computer-controlled triaxial experiment machine in combination with specially designed steel molds is used to compact the GMZ-Na-bentonite powders into blocks with five different shapes (Figure 1). The square bar-shaped bentonite blocks are subsequently crushed into small pellets in different grain sizes showed in Figure 2 in order to fill the space between the bentonite blocks and the heater/steel tank walls. The total dry density of compacted bentonite blocks and pellets is 1600 kg/m^3.

Figure 1 compacted bentonite blocks.

Figure 2 Crushed pellets used to fill the space between bentonite blocks and steel tank walls.

2.3 Thermal properties of compacted bentonite blocks

One of the most important roles of the buffer materials is to transfer the decay heat generated from HLW to the host rock. The thermal property of bentonite is one of the key properties for the design of HLW repository system. Hence, a better understanding of thermal properties of bentonite helps us to predict the extent and shape of temperature field in the EBS, and subsequently investigate the distributions of thermal stress and thermal cracking behaviors of the host rock. It is known that the thermal properties of bentonite are closely associated with water content, dry density, mineral composition, microstructure and temperature conditions， and so forth . It is a very complicated and difficult task to investigate the thermal properties of bentonite when considering the all above-mentioned control factors simultaneously. The present work only focuses on the research on the thermal conductivities of compacted bentonite with the same water content, devoid of any additives.

The Hot Disk thermal constants analyser based on the transient plane source (TPS) method is used to measure the thermal conductivity on the different surfaces of each compacted bentonite sample. The average value of thermal conductivity for each surface can be obtained from different measurement points. The measurement system and the distribution of thermal conductivity measurement points are presented in Fig. 3 and Fig. 4 respectively.

Fig. 3 Hot Disk thermal constants analyser and sensors.

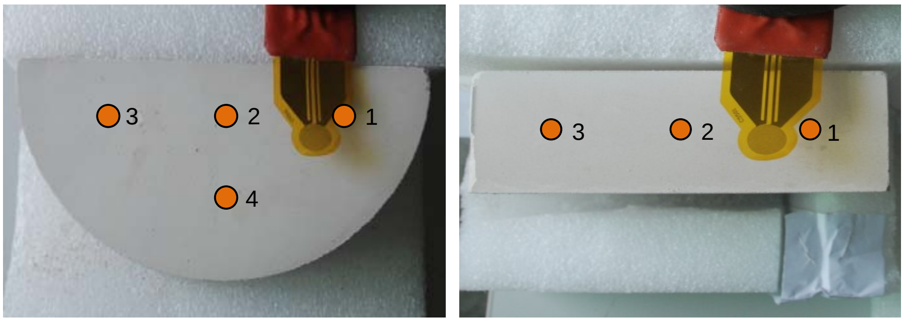

Fig. 4 Distribution of thermal conductivity measurement points.

Fig.5 presents the distributions of thermal conductivity on the different surfaces of the semicircular bentonite blocks when randomly selected from dozens of sets of data. It can be seen from the measurement results that the thermal conductivity exhibits a different distribution on the three different measurement surfaces. In general, the average values of thermal conductivity on the side surface are slightly larger when compared with those of the other two measurement surfaces. The average thermal conductivities on the positive measurement surface, i.e., the surface directly suffered from compressive loading, are generally minimum values, indicating that the thermal conductivity on the measurement surfaces is closely related to the compacted density. A nonlinear relationship between the compacted density and the thermal conductivity of bentonite blocks is shown in Fig. 6. In fact, the compacted density of the different measurement surfaces is associated with the stress state applying to different boundaries of the bentonite sample. During the uniaixal compression test process, the anisotropic stress distributions created from testing machine and mold confinement lead to anisotropic compacted density characteristics, which further result in anisotropic behaviors of thermal conductivity. This phenomenon is also verified from the measurement results of other three different shaped bentonite blocks.

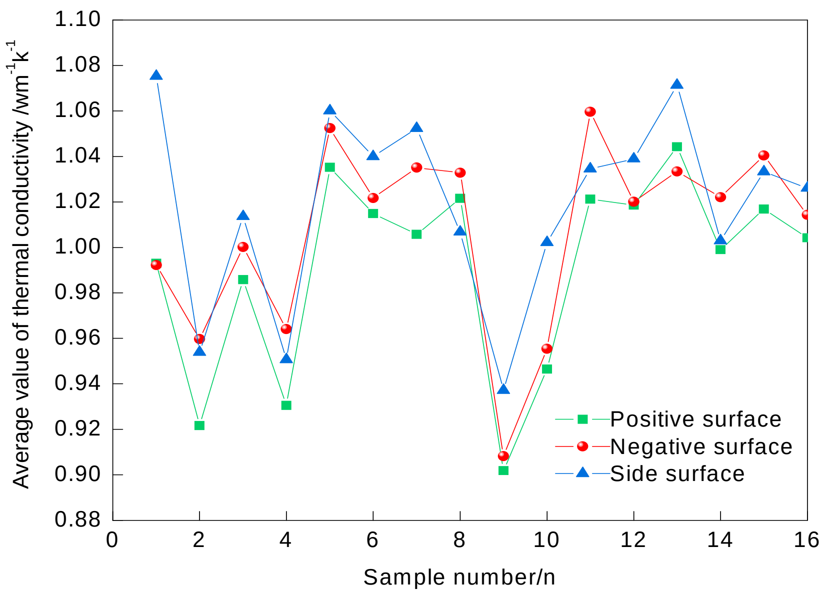

Fig. 5 Distribution of thermal conductivity on different measurement surfaces.

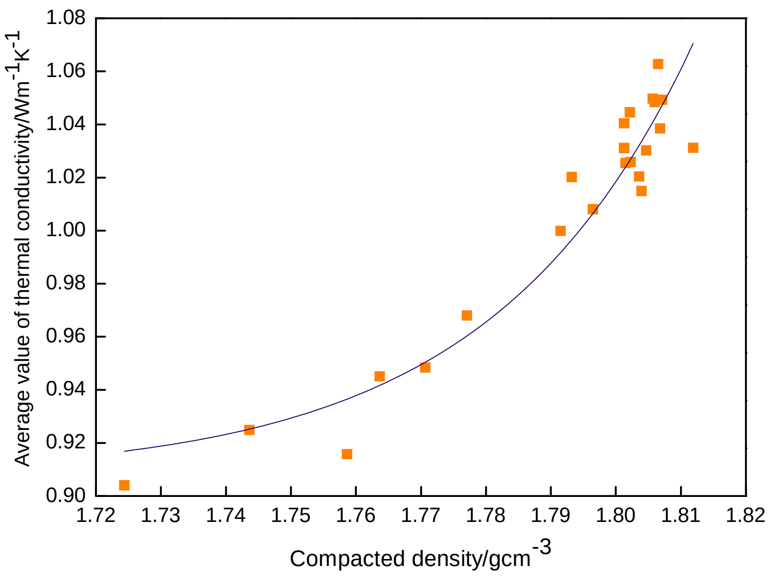

Fig. 6 Relationship between thermal conductivity and compacted density of the bentonite blocks.

3. THE T-H-M-C China-Mock-Up experiment

In order to study the behaviour of the GMZ-Na-bentonite under coupled thermal-hydraulic-mechanical-chemical conditions, a mock-up facility, named China-Mock-Up, has been designed and will be installed soon in the Beijing Research Institute of Uranium Geology.

The main objectives of the China-Mock-Up include:

(1) To study the behavior of GMZ-Na-bentonite under coupled THMC conditions;

(2) To study the bentonite-canister reaction under coupled THMC conditions;

(3) To simulate vertical placement of a container with radioactive waste;

(4) To monitor the behavior of GMZ-Na-bentonite barrier at high temperature and special water;

(5) To experiment the installation method and validity of sensors;

(6) To provide data for future design for engineered barrier system.

3.1 Design

According to the R&D guide of HLW disposal (CAEA 2006), the spent fuel from nuclear power plants will be reprocessed first, followed by vitrification and final disposal. The preliminary concept of geological disposal of HLW will be a shaft-tunnel model based on a multi-barrier system, located in saturated zones in granite. In the China-Mock-up, the host rock is replaced by a steel liner designed to resist to the internal pressure, caused by the porewater pressure and the swelling pressures of the backfill material. The vitrified high level waste is represented by an electric heater.

The China-Mock-up has been constructed with compacted bentonite-blocks in a large steel tank of 900 mm internal diameter and 2200 mm height. An electric heater of 300 mm diameter and 1600 mm length, which is made by carbon steel as the substitute of a real HLW container, is placed inside the bentonite-buffer. The engineered barrier system (EBS) is heated by the heater from ambient temperature to 90°C. The outer layer of buffer material will be 60°C. The groundwater flow is simulated by injecting the formation water (obtained from the host granite rock in the Beishan site, NW China) around the outer surface of the barrier. It can be expected that complex T-H-M-C processes will occur in the bentonite-buffer, which will be monitored by a number of sensors to be installed at various locations in the buffer. The main parameters to be measured in the EBS include temperature, water inflow, relative humidity (suction), swelling and total pressure, as well as displacement of the heater inside the buffer. The experiment is conducting at the BRIUG laboratory in Beijing, China.

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 (Figure 7).

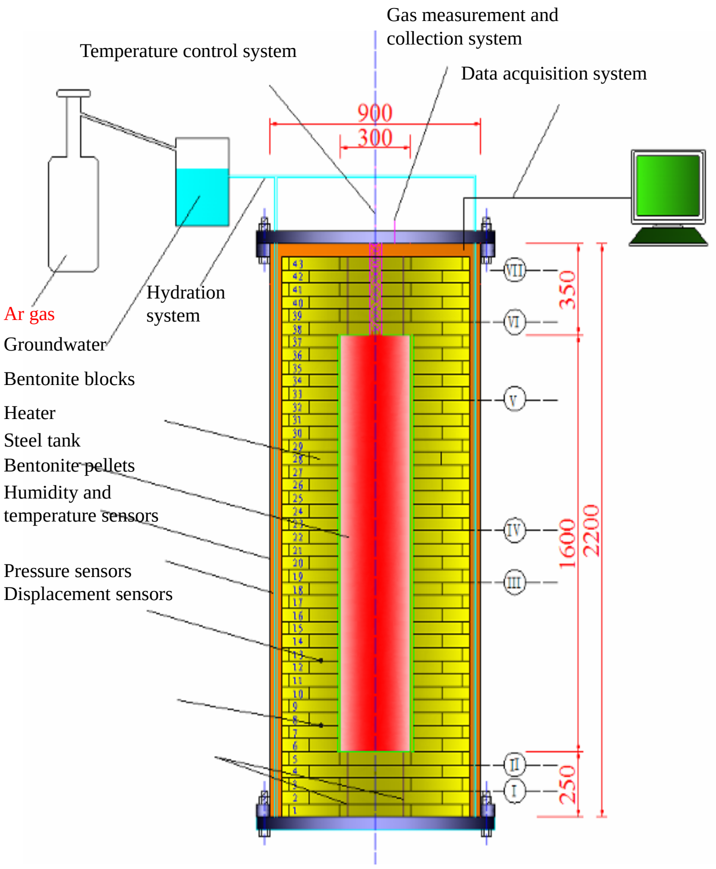

Figure 7 Sketch of the China-Mock-up facility (unit: mm).

3.2 Numerical modelling

In order to design the power of the heater and the parameter of the heat insulation layer, as well as the evolution of the heat, water flow and stress in the buffer material, numerical modeling was conducted. Figure 8 shows the 3D geometry model of China-Mock-up established by FLAC3D.

The power of the heater is suggested 1000W. If the thermal conductivity of the heat insulation material is 0.04W/m℃, the thickness of the heat insulation layer is 35mm.

To take into account heat, water flow, swelling pressure and permeability of buffer/ backfill material, and thermal relief, the evolution of temperature, saturation, stress and displacement of heater under TM, HM, and THM coupling conditions was analyzed respectively. Figure 9 shows the saturation contours of compacted bentonite in the China-Mock-up. Because of the lower permeability of the compacted bentonite, it will need more than 10 years to saturate the compacted bentonite in China-Mock-up.

The development of stresses which is induced by different mechanisms: first, thermal expansion may induce stresses due to the confinement of the bentonite by the steel tank; then, the swelling pressure of the compacted bentonite, as a result of the resaturation. The stress concentration occurs in the middle and the corner of the steel tank in Figure 10.

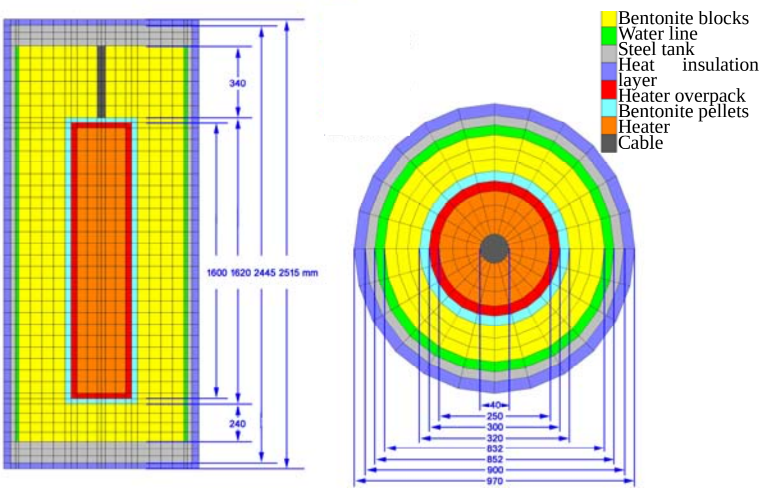

Figure 8 Geometry of China-Mock-up

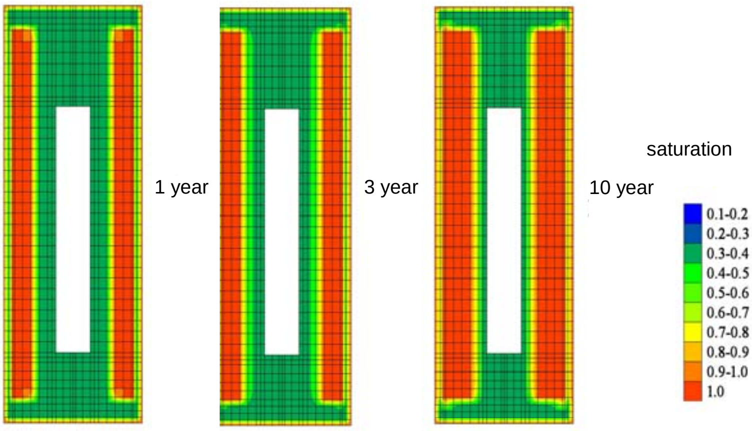

Figure 9 Saturation contours of China-Mock-up

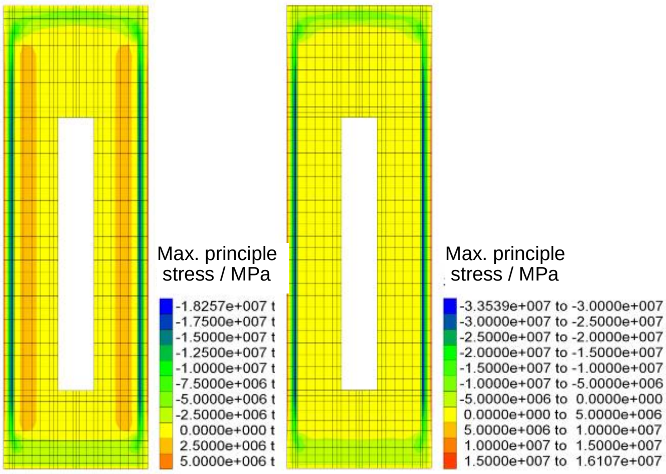

Figure 10 Maximum principle stress contours at 1& 4 years

3.3 Sensors used in the 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 6 sensor types inside the China-Mock-up include stress sensor, hydraulic pressure sensor, LVDT displacement sensor, temperature sensor, RH sensor and electrochemical corrosion sensor. In addition, a series of metal corrosion samples are placed inside the bentonite blocks and crushed pellets to investigate the influence of internal environment of the Mock-up on metal corrosion behaviors. Another 4 sensor types consisting of Coriolis mass flowmeter, fiber Bragg grating (FBG) strain/temperature sensor, resistance strain gauge and dial gauge are located outside the Mock-up.

Measurements based on the 10 types of sensors are mainly carried out at seven measurement profiles located from the top to the bottom of the Mock-up vertical model (see Fig.1). The overall sensing system involved in the Mock-up is expected to provide reliable data for numerical modeling and future design of EBS.

3.4 Layout of the bentonite blocks inside the China-Mock-up

For the China-Mock-up, 44 bentonite block sections, each with a thickness of 50 cm, are installed across the entire length of the tank. Each complete buffer section consists of two or three concentric rings, which are dependent on the space in which the heater is placed, formed by compacted bentonite blocks with different shapes and numbers. The inevitable spaces between buffer layers and blocks may provide the preferential paths for water penetration, resulting in a negative impact on the inner THM environment and sensors' working performance. To reduce or eliminate the effect of adverse penetration paths and maintain an uniform and stable water penetration rate in the bentonite, a standard layer (i.e. the bottom layer) has been designed. Once the bottom layer is determined, the second layer above the standard layer can be rotated 15° clockwise or counterclockwise so that the potential coalescence of penetrating water between the bentonite layers can be suppressed as far as possible. Every two layers/sections follow the same principle, and the optimal overlapping layer can be found. The determination of the standard and overlapping layers provides with a basis precondition for the further layout design of sensors.

Figure 11 shows the installation of the bentonite blocks, the instruments and the hydration tubes at the periphery of the steel structure. The bentonite pellets in different grain sizes showed in Figure 2 were filled in the space between the bentonite blocks and the heater/steel tank walls.

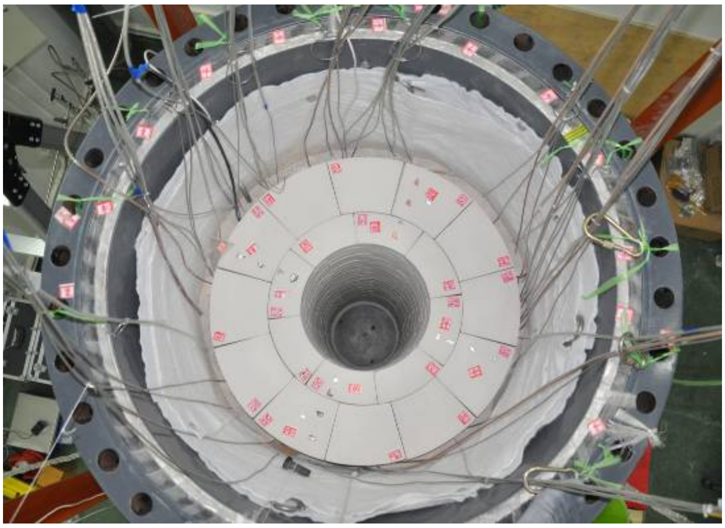

Figure 11 Installation of the bentonite blocks

3.5 Distributions of the sensors in the measurement profiles

A reasonable layout design of the sensors inside the China-Mock-up is an essential consideration for the successful implementation of the Mock-up experiment. During the experiment's operational stage, the experimental data and information revealing bentonite behaviors under coupled THM conditions only can be effectively obtained from the different kinds of sensors if these sensors are reasonably distributed in the Mock-up physical model. Besides, in order to provide a correct guidance of the construction process and improve work efficiency, each sensor must be precisely positioned in the Mock-up before being installed due to a large number of sensors involved in the present experiment. A layout design of sensors is therefore proposed in order to meet the requirements mentioned above.

The installation, calibration and debugging works on the sensors have been carried out at seven measurement profiles to monitor the behaviors of bentonite under coupled T-H-M-C conditions. The main considerations on how to distribute the sensors in each measurement profile can be summarized as follows:

(1) Balance and complementation. Balance control on the amount of the sensors between the measurement profiles or in the each measurement profile is an important issue needed to be considered firstly. Due to limited sensors, a high or low spatial distribution density of the sensors in a given measurement profile or side is not desirable, which will not only leads to

the imbalance of obtaining measurement data in the whole measurement space, but also results in the imbalance of buffer mass loss generated from drilling and sculpting work on bentonite blocks for the installation of sensors. In addition, subjected to various uncertainties, a few sensors during the Mock-up long-term operation may become invalid, causing the monitoring data based on these failed sensors to loss. It is necessary to install some complementary sensors in corresponding positions in advance to compensate the losing measurement information.

(2) Parameters associated. For each measurement profile, the characteristic parameters such as temperature, relative humidity and swelling stress with three directions obtained from the measurement system should be closely associated with each other. Take the I measurement profile as an example, different types of sensors are located in the series of concentric circles in which the characteristic behaviors of bentonite under multi-field coupled conditions can be effectively revealed from the axisymmetric model of the China-Mock-up. This layout of sensors can also provide with a scientific guidance and reliable data for further numerical simulation. On the other hand, the characteristic parameters between seven measurement profiles are needed to be related mutually. According to the layout design of the sensors in the I measurement profile, the senor distributions in other measurement profile can be easily obtained in a rotation way with different multiples of 90°.

(3) Effective Installation. To design the layout of sensors in the measurement profiles, the operability, efficiency and convenience in the process of installing these sensors need to be taken in account.

4. Future work of the experiment

The assembly works started in March 2010. The China-Mock-Up is showed in Figure 12. After the assemblage and sealing, the heater started to work. The temperature level is gradually increased during the first six months experiment. The maximum of temperature will be reached, with a temperature at the central tube of about 90°C. Then keep the temperature about four years.

The water will be slowly injected into the hydration system. The pellets around blocks will be first filled with water and afterwards the water pressure was gradually increased to reach 1 MPa after 1 year. Then keep the water pressure about four years.

Figure 12 China-Mock-Up facility

After experimenting, the Mock-up facility will be dismantled and samples will be extracted from the buffer. Possible changes of the bentonite properties will be investigated by determination of geochemical, physico-chemical and mineralogical components of the buffer and special attention will be given to the interfaces of bentonite/canister.

The mock-up will be numerically modeled to verify the constitutive models and the computer codes to be used, such as CODE-BRIGHT, LAGAMINE and FLAC3D, for THM processes modelling; and EQ3/6 and Crunchflow for modelling THC processes. The modelling work includes blind predictions at the beginning of the experiment, calibrated predictions in the mid-term of the monitoring time, and final simulations at the end of the monitoring period.

5. Conclusion

The buffer material is one of the main engineered barriers for the HLW repository. In order to study the behaviour 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 China-Mock-Up model consists of a barrier of compacted GMZ-Na-bentonite blocks and a heater which substitutes a container with radioactive waste. Water inflow through the barrier from its outer surface is to simulate the intake of groundwater. 10 different types of sensors were equipped to monitor the comprehensive performances of GMZ Na-bentonite under coupled THMC conditions.

The experiment procedures of China-Mock-Up include experiment design, preparation, installation, conduction (heating and cooling), dismantling and post-experiment, evaluation and report. The modelling work will be performed parallel to the experiment. A successful experiment requires a good control of experiment conditions, especially the boundary conditions, which are important to interpret and understand the experiment results.

The China-Mock-Up experiment is an important milestone in the buffer material study for HLW disposal in China. The parameters and evaluation of 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.

References

Alonso E.E., Hoffmann C. & Romero E., 2010. Pellet mixtures in isolation barriers. *Journal of Rock Mechanics and Geotechnical Engineering.* 2010, 2 (1): 12-31

CAEA (China Atomic Energy Authority), Ministry of Environment Protection & Ministry of Science and Technology, 2006. *Guidelines for the R&D for geological disposal of high level radioactive waste in China*. (in Chinese)

Chen, B., Qian, L.X., Ye, W.M., Cui, Y.J. & Wang, J. 2006. Soil-water characteristic curves of Gaomiaozi bentonite. *Chinese Journal of Rock Mechanics and Engineering,* 25 (4): 1054-1058.

Gens, A., Guimarães, L. do N., Olivella, S. & Sánchez, M. 2010. Modelling thermo-hydro-mechano-chemical interactions for nuclear waste disposal. *Journal of Rock Mechanics and Geotechnical Engineering*. 2010, 2 (2): 97-102.

Karnland, O., Sandén T., Johannesson Lars-Erik, et al. 2000. *Long term experiment of buffer material, Final report on the pilot parcels,* SKB Technical Report, TR-00-22.

Li, X. L., Frédéric, B & Johan, B. 2006. The Belgian HLW repository design and associated R&D on the THM behaviour of the host rock and EBS. *Chinese Journal of Rock Mechanics and Engineering,* 2006, 25 (4): 682-692.

Li, X. L., Bastiaens, P., VanMarcke, P, et al. 2010. Design and development of large-scale in-situ PRACLAY heater experiment and horizontal high-level radioactive waste disposal gallery seal experiment in Belgian HADES. *Journal of Rock Mechanics and Geotechnical Engineering*. 2010, 2 (2): 103–110.

Lloret, A. & Villar, M.V. 2007. Advances on the knowledge of the thermo-hydro-mechanical behaviour of heavily compacted “FEBEX” bentonite. *Physics and Chemistry of the Earth*. 2007, 32: 701-715.

Liu, Y.M., Xu, G.Q., Liu, S.F & Chen Z.R. 2001. *Study on the basic property of Gaomiaozi bentonite, Inner Mongolia*. Beijing：China Nuclear Industry Audio & Visual Publishing House, 1-20. (in Chinese)

Liu, Y.M., Wen, Z.J., 2003. Study on clay-based materials for the repository of high level radioactive waste. *Journal of Mineralogy And Petrology*, 2003, 23(4): 42-45. (in Chinese)

Liu, Y.M., Cai M.F., Wang J., 2007a. Compressibility of buffer material for HLW disposal in China. *Uranium Geology*, 23, 91-95. (in Chinese)

Liu, Y.M., Cai M.F. & Wang J., 2007b. Thermal conductivity of buffer mate-rial for high-level waste diaposal. *Chinese Journal of Rock Mechanics and Engineering*, 26(S1), 3891-3896. (in Chinese)

Pacovsky J., Svoboda J. & Zapletal L., 2007. Saturation development in the bentonite barrier of the Mock-Up-CZ geotechnical experiment. *Physics and Chemistry of the Earth*, 32(2007), 767-779.

Romero, E., Li, X. L. 2006. Thermo-hydro-mechanical characterization of OPHELIE backfill mixture. *Chinese Journal of Rock Mechanics and Engineering*, 2006, 25 (4): 733-740.

Wang, J. 2010. High-level radioactive waste disposal in China: update 2010. *Journal of Rock Mechanics and Geotechnical Engineering*, 2010, 2 (1): 1–11.

Wen Z.J. 2006. Physical property of china's buffer material for high-level radioactive waste repositories. *Chinese Journal of Rock Mechanics and Engineering*, 2006, 25 (4): 794-800.

Ye, W.M., Cui, Y.J., Qian L.X. & Chen, B., 2009a. An experimental study of the water transfer through confined compacted GMZ-bentonite. *Engineering Geology*, 108(3-4): 169-176.

Ye, W.M., Qian L.X., 2009b. Laboratory test on unsaturated hydraulic conductivity of densely compacted Gaomiaozi Bentonite under confined conditions. *Chinese Journal of Geotechnical Engineering*, 31(1): 105-108. (in Chinese)