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Technical Note:

Report on the Detailed Design of China-Mock-Up Experiment

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1. Background

A bentonite-based material is often proposed or considered as a possible buffer/backfill material for the isolation of high-level radioactive waste (HLW). In order to study the behavior of the GMZ-bentonite under simulative repository conditions, a Mock-Up called China-Mock-Up has been proposed according to the preliminary concept of HLW repository in China since 2009. The China-Mock-Up is used to evaluate the key thermo-hydro-mechanical-chemical (THMC) processes of bentonite, it will be performed in the laboratory of Beijing Research Institute of Uranium Geology (BRIUG). The test is intended to evaluate key THMC processes taking place in the compacted GMZ-bentonite blocks during the early phase of HLW disposal system, and to provide a reliable database for numerical modeling and further investigations.

2. Description of China-Mock-Up design

The China-Mock-Up has been constructed with compacted bentonite blocks in a large steel tank with 900 mm internal diameter and 2200 mm height. An electric heater of 300 mm diameter and 1600 mm length, which is made by the same stainless carbon steel as the substitute of a real HLW container is placed inside the bentonite-buffer. The bentonite blocks will be heated by the heater from ambient temperature to 90°C and then cooled down. The groundwater flow will be simulated by injecting the formation water (taken from the host granite rock in the Beishan site, NW China) around the outer surface of the barrier. It is expected that complex THM-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 China-Mock-Up with a vertical configuration is composed 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 system and monitoring system, as shown in Fig. 1.

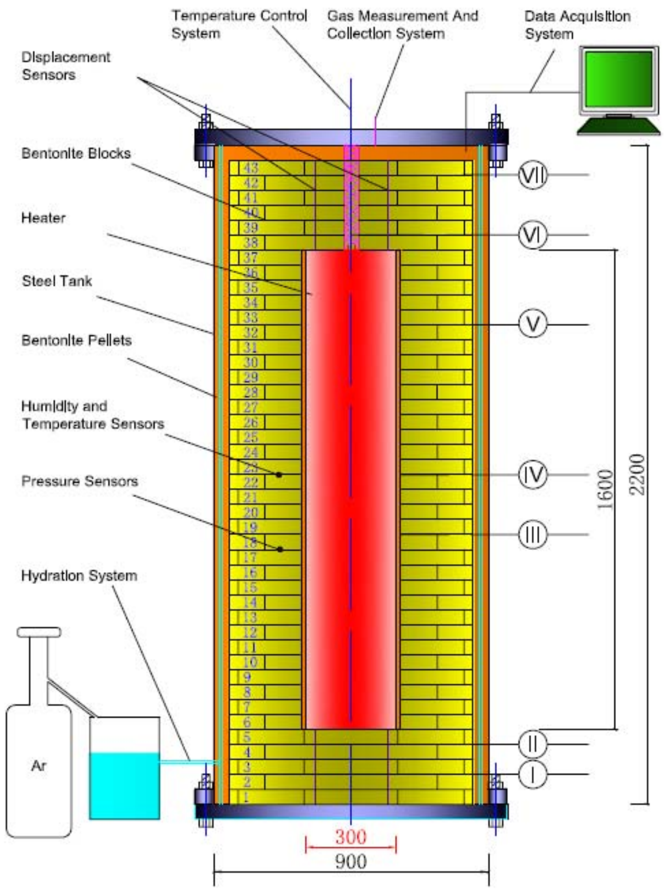

Fig. 1 Sketch of the China-Mock-Up facility (unit: mm).

2.1 Preparation of compacted bentonite blocks and pellets

The bentonite used for the China-Mock-Up comes from the GMZ-bentonite deposit, which is located in Inner Mongolia Autonomous Region, 300 km northwest of Beijing. The deposit, with bedded ores, was formed in late Jurassic. Clay 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. The major bentonite clay layer of the deposit extends about 8,150 m with thickness ranging from 8.78–20.47 m.

The preliminary study on GMZ-bentonite shows that it is characterized by high content of Montmorillonite (>70%) and low impurities. Various tests revealed some of other properties of GMZ-bentonite: cation exchange capacity (77.30 mmol/100g), Methylene blue exchange capacity 102 (mmol/100g) and alkali index (1.14). The properties of the compacted bentonite at dry density 1.8g/cm^3 are: thermal conductivity (around 1.0 W/(m·K) at a water content of 8.6%), hydraulic conductivity (1×10^{-13} m/s), and swelling pressure (10 MPa, at full saturation). Those figures have shown that GMZ-bentonite is a suitable buffer/backfill material.

A computer-controlled triaxial test machine in combination with specially designed steel molds are used to compact the GMZ-bentonite into compacted blocks with five different shapes, as presented in Fig. 2. The square bar-shaped bentonite blocks are subsequently crushed into small pellets in different grain sizes to fill the space between the bentonite blocks and the steel tank walls.

Fig. 2 Compressive test machine and compacted bentonite blocks.

To investigate the influence of crushed pellet sizes on the density of pellet mixtures, a sensitive analysis for different pellet sizes (2 mm, 4 mm, 6 mm, 8 mm, 10 mm) is carried out via a standard orthogonal L_{25} (5^6) array. The orthogonal experiment design as a simple, systematic and efficient method enables us to investigate the relative importance of control factors and identify the best levels for different factors on a performance output; and the results can be analyzed by using a common and rigorous mathematical procedure. This method can significantly reduce experimental time and research cost. Based on twenty-five experiment cases, the optimal mixture ratio of different pellet sizes was obtained from the analysis of means (ANOM) for capturing the reasonable density (1.3 g/cm^3) of pellet mixtures, as presented in Fig. 3.

Fig. 3 Crushed pellets used to fill the space between bentonite blocks and steel tank walls.

2.2 Thermal properties of compacted bentonite blocks

One of the most important roles of the buffer/backfill 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. 4 and Fig. 5 respectively.

Fig. 4 Hot Disk thermal constants analyser and sensors.

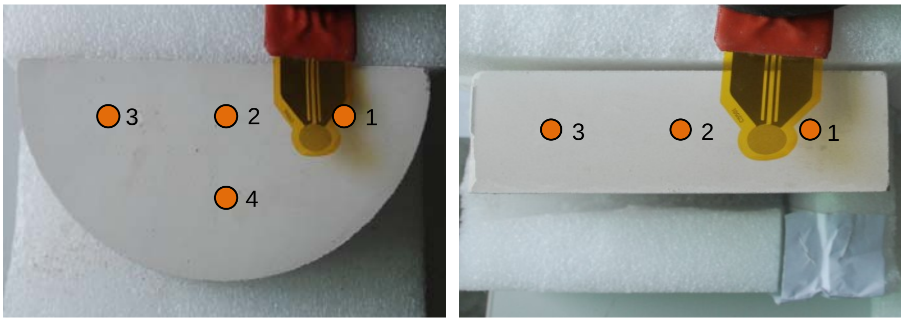

Fig. 5 Distribution of thermal conductivity measurement points.

Fig.6 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. 7. 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.

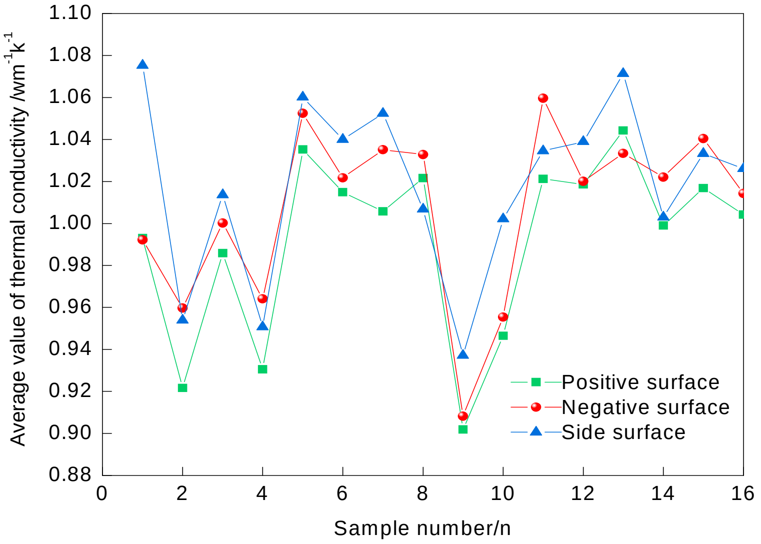

Fig. 6 Distribution of thermal conductivity on different measurement surfaces.

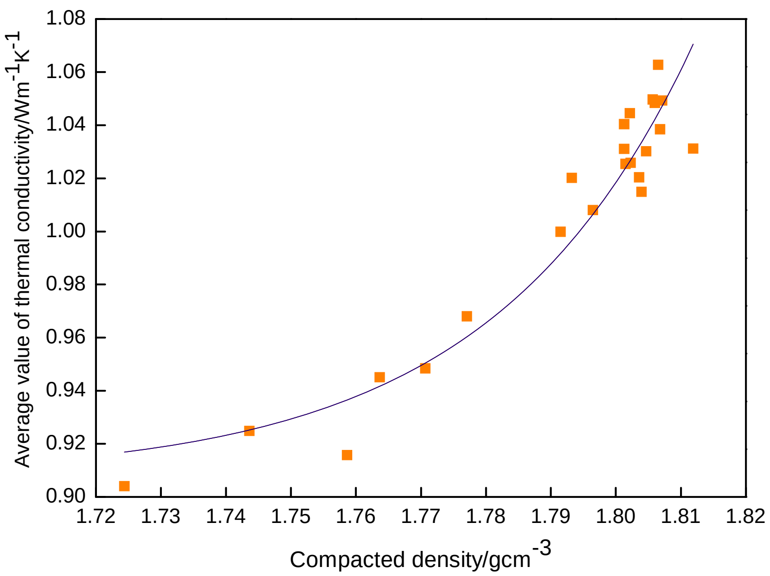

Fig. 7 Relationship between thermal conductivity and compacted density of the bentonite blocks.

2.3 Sensor types

The China-Mock-Up is equipped with 9 different types of sensors to monitor the comprehensive performances of GMZ Na-bentonite under coupled THMC conditions. The 5 sensor types inside the China-Mock-Up include stress sensor, hydraulic pressure sensor, LVDT displacement sensor, temperature sensor and RH 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 9 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.

2.3.1 Stress sensor

Measurements of swelling stress are carried out by using electric signal stress sensors installed in two or three different directions, i.e., x-, y- and z-directions, in each measurement profile. Moreover, there are another three stress sensors directly contacting with the inner top, bottom and side walls of the steel tank, respectively. The stress sensor is capable of withstanding temperatures up to +100 °C with a stress measurement range from 0 to 20 MPa, as shown in Fig. 8.

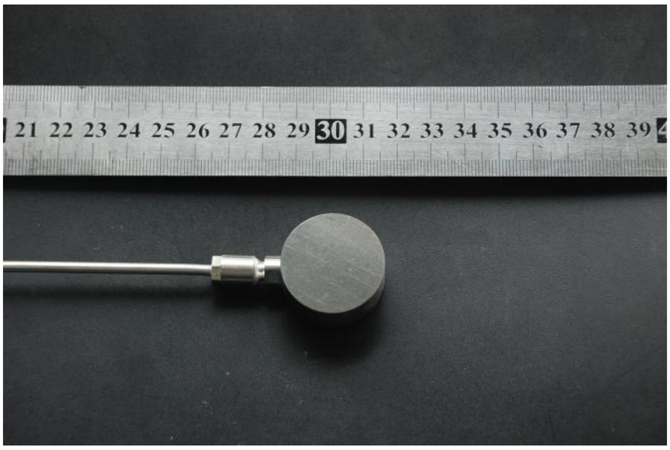

Fig. 8 Stress sensor.

2.3.2 Hydraulic pressure sensor

The hydraulic pressure sensors with a shape similar to the stress sensors are used to measure hydraulic pressure distributions in the bentonite under the long term coupled THMC conditions. The hydraulic pressure sensor is capable of withstanding temperatures up to +100 °C with a stress measurement range from 0 to 2 MPa, as shown in Fig. 9. The hydraulic pressure sensors are mainly installed in the crushed bentonite pellets close to the water inlets to monitor water flow state and to record the values of pore water pressure.

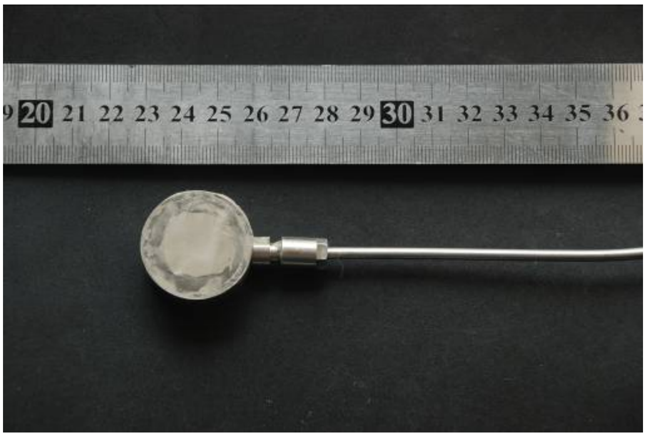

Fig. 9 Hydraulic pressure sensor.

2.3.3 LVDT displacement sensor

6 LVDT displacement sensors installed in the China-Mock-Up serve for measuring the displacement of the heater. According to the vertical model of the China-Mock-Up, each 3 LVDT displacement sensors (see Fig.10) with different angles are fixed on the top and bottom parts of the heater respectively. The other sides of the displacement sensors are screwed on the top lid and bottom surface of the steel tank. This approach is designed to measure the vertical displacement variations of the heater throughout the entire duration of the experiment.

Fig. 10 LVDT displacement sensor.

2.3.4 Temperature sensor

There are 4 temperature sensors (see Fig. 11) installed in each measurement profile, and the range of measured temperature is from 0 up to 300°C, with an accuracy of 0.1 °C. Based on the previous numerical simulation results, for each measurement profile, a radial sensor layout with an increasing distance gradient from the heater to the inner walls of the experimental tank is adopted to capture the distributions of temperature field around the heater. All cable routes will be led through the crushed bentonite pellets towards the top lid of the steel tank.

Fig. 11 Temperature sensor.

2.3.5 RH sensor

It is noted that acquisition of the accurate moisture profile in the Mock-up is very difficult because the measurement results might be negatively influenced by having installed the sensors and cables in recessed hollows thus creating preferential paths for water penetration. Hence, the use of RH sensors (see Fig.12) only provides with an initial judgment on the moisture content changes in the compacted bentonite blocks. The layout of the RH sensors complies with the similar distribution principle of the temperature sensors in each measurement profile, monitoring the variations of relative humidity and temperature under varied environmental conditions.

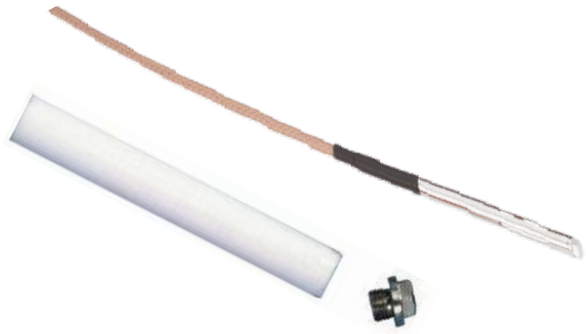

Fig. 12 RH sensor.

2.3.6 Fiber Bragg grating (FBG) strain/temperature sensor

As a newly developed stain/temperature measurement technique, the FBG sensing system has been installed to monitor the long term variations of deformation and temperature occuring on the outside surface of the steel tank due to the generation of swelling stress and diffusing heat from the inner environment of the facility. The FBG monitoring system is desinged to cover the overall regions of the tank surface using a series of FBG sensor groups with a quasi-distributed measuremnt mode. Every FBG sensor group is made up of three gratings, namely two strain measurement gratings and one temperature compensation grating, as presented in Fig. 13. The two strain measurement gratings welded on the tank surface are used to monitor the changes of strain along the vertical and lateral directions of the tank respectively, but the inclining temperature compensation grating bonded on the tank surface is only influenced by the temperature variations rather than mechanical effects of the steel structure. The moritoring system provides us with an effective means to understand the characteristics of deformation of the experimental tank, and subsequently to take necessary measures if the strain or stress exceeds stipulated limits.

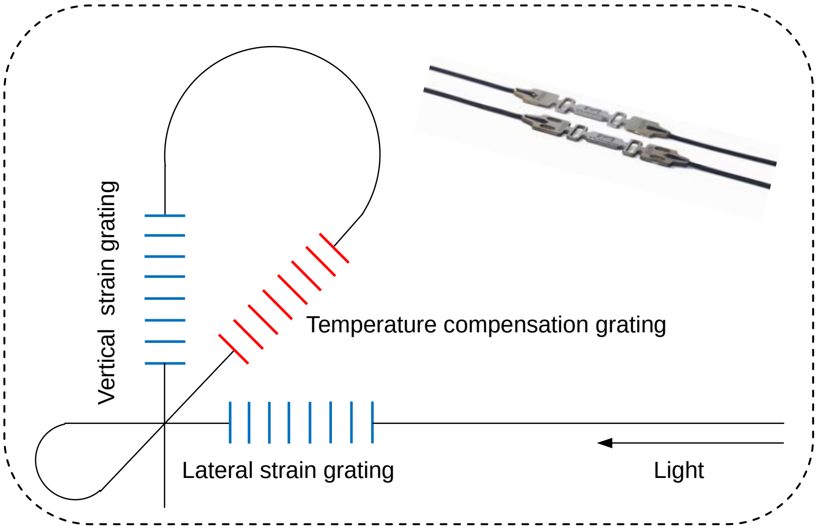

Fig. 13 Fiber Bragg grating (FBG) strain/temperature sensor.

2.3.7 Resistance strain gauge

A series of common resistance strain gauges as conventional electro-sensors are also installed to measure vertical and lateral deformations of the outside surface of the steel tank. The resistance strain gauge consists of an insulating flexible backing which supports a metallic foil pattern, as shown in Fig.14. The gauge is attached to the structure by a suitable adhesive. As the tank surface is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change measured by a Wheatstone bridge, is related to the strain by the quantity known as gauge factor. From the measured electrical resistance of the strain gauge, the amount of applied stress on the surface may be inferred. However, the most strain guage materials are sensitive to temperature variations and tend to change resistance as they age. Hence, for tests of short duration, this may not be a serious concern, but for continuous measurement such as Mock-up testing, the FBG sensing system would be a more desirable choice.

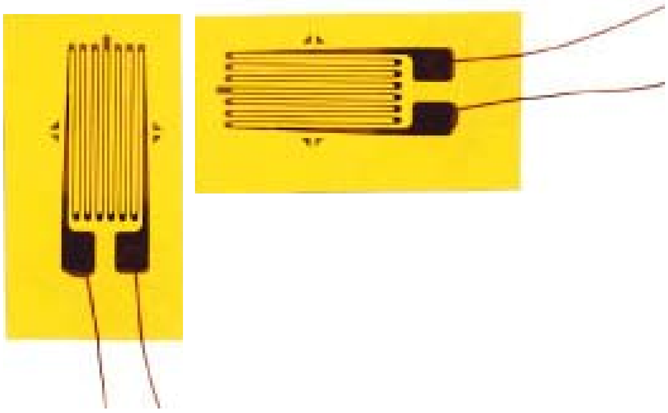

Fig. 14 Resistance strain gauges.

2.3.8 Mass flowmeter

A pair of Coriolis-based mass flowmeters is selected to control and monitor the inlet flow for the duration of the China-Mock-Up experiment. A Coriolis meter requires two basic components (see Fig. 15): a sensing element and a transmitter that interprets the signals from the sensor and converts the signals into useable outputs, usually pulse and digital outputs. Unlike traditional flow measuring techniques, Coriolis mass flowmeters respond directly to mass flow. As the flow passes through the tubes the fluid momentum coupled with the oscillatory motion created by the vibration induces a Coriolis force along the length of the tubes. This force translates into a phase shift along the length of the tube .The phase shift is directly proportional to mass flow rate. Another advantage of the mass flowmeter is that the decreasing overall piping requirement helps to reduce the overall size of the system.

Fig. 15 Coriolis-based mass flowmeters.

2.3.9 Dial gauge

Dial gauges, also known as dial indicators and probe indicators, are instruments used to accurately measure small linear distances, and the measurement results are displayed in a magnified way by means of a dial, as shown in Fig. 16. The spring-loaded probe moves perpendicular to the object being tested by either retracting or extending from the indicator's body. Dial gauges typically measure ranges from 0.25 mm to 300 mm, with graduations of 0.001 mm to 0.01 mm. In the present experiment, three dial gauges are installed to check the linear subsidence of the steel tank.

Fig. 16 Dial gauge.

3. Future actions

In the next phase of this project, the experimental data based on the China-Mock-Up experiment will be initialy analyzed. The constitutive models to describe the bentonite behaviors under coupled THMC conditions will be developed from theoretical analysis in combination with experimental results, and subsequently, the China-Mock-Up will be numerically modeled to verify the constitutive models and the computer codes to be used, such as FLAC3D, LAGAMINE and CODE-BRIGHT, for THM processes modelling; and EQ3/6 and Crunchflow for modelling THC processes.