Centrifuge model test to gain reliability of the future prediction in terms of long term THM processes in deep geological repository

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Abstract

The long-term behavior in the near-field of deep geological repository is governed by coupled thermal-hydraulic-mechanical (THM) processes. THM processes will continue for hundreds of years in the initial stage of disposal. These processes influence the overpack displacement, the swelling behavior of the buffer, the deformation of the disposal hole, and so on. The overpack displacement is influenced by the swelling behavior of buffer. The swelling pressure of the buffer generated is influenced by the depth of the repository and the stiffness of the surrounding bedrock. To clarify the long term behavior in the near-field, the researches by the full-scale tests and the numerical analyses have been carried out. However, the former are difficult due to location, time, and economic restraints, and the latter are necessary to verify the applicability of the numerical model. Centrifuge model test can be used to replicate an event, similar to what can be done with a prototype, and in fact is a reduced-scale version of a prototype. Based on scaling laws, any two investigations of the same conditions using a centrifuge model test and a prototype are similar and related. However, the centrifuge model test has the advantage that it can greatly shorten the long time needed to see behavior resulting from the typically slow flow of groundwater that satisfies Darcy's law. If the time acceleration test using the reduced-scale model of the near-field is available on the basis of the centrifugal scaling law, then the long-term reliability of the geological repository can be improved by empirical laboratory data. Our aim is; to conduct the time acceleration test using the centrifugal equipment; to measure the equivalent data of long-term behavior of the overpack, buffer and bedrock; and to evaluate the long-term THM behavior of the near-field in a geological repository by laboratory measurements.

1. Introduction

The high level radioactive waste (HLW) disposal repository in Japan will be built in deeper than 300m in the underground[1]. The vitrified waste is enclosed in a metallic overpack. It is then packed, surrounded by buffer material made of clay bentonite, into a disposal hole drilled deep into the bedrock. The near-field is composed of such a heterogeneous composite. The phenomena of the near-field is expected to be very complex. And, it keeps occurring for a very long term. Probably, within current year, the government will announce the scientific suitable area for the disposal. Then, discussion may start at candidate areas.

In the near-field, various processes will occur under the effect of heat from the waste, rock stress and underground water. This THM transition will dominate and continue for hundreds of years in the initial stage, construction, operation, and closure stage. These state are transition period of artificial disturbance and resaturation, and phenomena dominates THM, mechanically unstable (Fig. 1).

In contrast to the initial stage, after resaturation, nuclide gradually leaks and migrates. Chemical phenomena, diffusion and permeation will occur in a long term of more than thousands of years. This period is mechanically stable and slow alternation, permeation, and diffusion keep occurring (Fig. 1). In safety assessment, chemical phenomena, diffusion and permeation after resaturation are the target and evaluated finally. On the other hand, the initial state until resaturation significantly affects the state after resaturation. Therefore, it is important to accurately evaluate the THM transition as the initial state, in hundreds of years in order to improve reliability of safety assessment.

Many researchers have been studying methods of prediction of behavior in HLW disposal repository, prototype test, physical modeling experiment, numerical simulation. Prototype test has a high

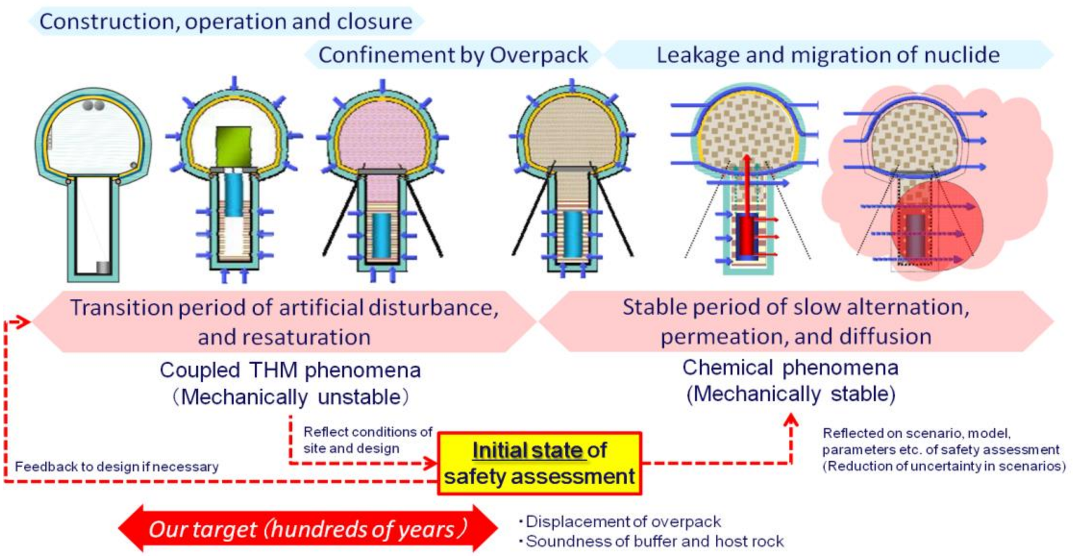

Fig. 1 Schematic of predictable transition in HLW geological disposal repository

demonstration. Approximately actual behavior if using real size and design can be observed. But, it is inevitably a few test and several year of evaluation time because of restrictions of place and economy. On the other hand, numerical simulation can analyze many case and any evaluation time, but if only simulation, the demonstration is low. Physical modeling experiment is in middle. Demonstration, test quantities and evaluation time depend on the model size and the scaling law. These methods have merits and demerits. We think in HLW disposal research, it is necessary to combine and then comprehensive evaluation (Fig. 2).

Here, we focus on the centrifuge physical model testing. On the basis of centrifugal scaling law, future THM behavior is able to predict by time-acceleration test[2)]. Conducting time acceleration test using this centrifuge, we think we can observe the equivalent data of THM long-term behavior of near-field by the laboratory measurements. And then, these results contribute to the verification and validation (V&V) of the numerical simulation in the evaluation of THM long-term behavior of the near-field.

The aim of the study is; to conduct the time acceleration test using the centrifugal equipment; to measure the equivalent data of long-term behavior of the overpack, buffer and bedrock; and to evaluate the long-term THM behavior of the near-field in a HLW disposal repository by laboratory measurements. This application is aiming to enhance the reliability of the prediction of the future of the near-field, hence the safety of the geological disposal.

2. Centrifuge model test

2.1 Our concept of evaluation of THM long term behavior in near-field

We think two phases in the evaluation of THM long term behavior in near-field. One is future prediction by numerical analysis and the other is understanding phenomena by experiment and test. By numerical analysis, we can estimate the future state of target disposal repository. By experiment and test using the similar materials and conditions of the target repository, we can understand THM phenomena. After that, we comparatively discuss using both results, and then evaluate comprehensively evaluate the validity of the predicted phenomenon based on the limit of the numerical simulation.

Here, as points, we think ONLY simulating the future by a numerical analysis is not equal to evaluating long-term behavior in the near-field. And long-term behavior should be evaluated comprehensively with accompanying verification of the simulation by tests (Fig. 2).

Understanding phenomena and contributing data to verify and validate the numerical simulation. Centrifuge model test is small and simplified model, but time scale is equivalent the actual and

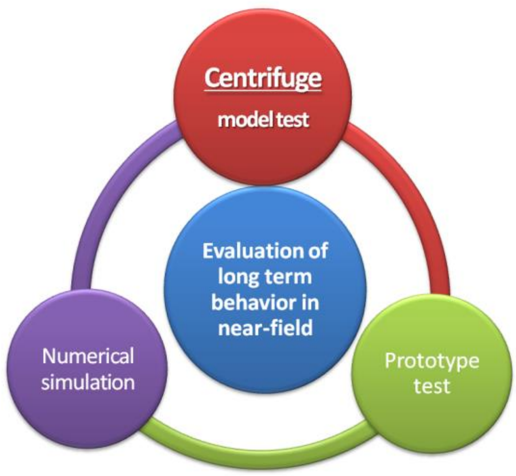

Fig. 2 Improvement of reliability of future prediction of HLW disposal repository

parameterable test. Parameter are stress, elasticity, gap/joint, density of buffer, temperature, and so on... The present study firstly targets stress and elasticity.

2.2 Centrifugal scaling law in the static field

The behaviors expected in the near-field can be attributed to two-phase mixtures that consist of the rock/soil and pore fluid if the centrifugal model is the same material as the prototype. In a centrifugal model test, by subjecting $1/N$ scale model to N times the earth's gravitational/ centrifugal acceleration (G) based on a centrifugal scaling law in a static field (where N is the scale factor and gravity /centrifuge acceleration level), the following are true: (1) the stress-strain behavior of a specimen in the model will be identical to that in the prototype, and (2) the equivalent elapsed time for the migration of underground water that satisfies Darcy’s law, the stress due to consolidation and swelling, and the distribution of elastic strain can be shortened to $1/N^2$, compared with the full-scale elapsed time (Table 1). For instance, the behaviors for 100 yr can be simulated in about 6 weeks using a 30 G centrifugal force field. This study treat the behaviors of the near-field as occurring in a static field.

2.3 Centrifugal model of near-field and centrifugal equipment

The near-field model in this study (Fig. 3a)[3–5], which is 1/30 the size proposed in the provious report[6] (Fig. 3b), consists of a single model-overpack, ring- and cylinder-shaped buffers, and a cylindrical sedimenrary rock mass. The overpack and buffers are placed in the bore hole drilled in the rock mass. The overpack is 27-mm diameter by 62 mm height, and 6160 kg/m^3 density. The buffer is made by compacting a Na-bentonite powder (Kunigel-V1), after it was oven-dried at 110 °C for 24h. Overall volume of the bentonite is about 54 mm in diameter by about 127 mm in height, and the initial dry density is 1740 kg/m^3 (the dry density after swelling is 1550 kg/m^3, including the swelling-filled gap between the overpack, the rock mass and the bentonite).

Table 1. Scaling law of the centrifugal model test.

Physical properties	Model/Prototype	Similitude
Length	l_m/l	$1/N$
Area	A_m/A	$1/N^2$
Volume	V_m/V	$1/N^3$
Stress	σ_m/σ	1
Young's modulus	E_m/E	1
Elastic strain	$\varepsilon_{em}/\varepsilon_e$	1
Temperature	T_m/T	1
Viscosity of pore fluid	η_{wm}/η_w	1
Flow velocity of pore fluid	u_m/u	N
Time	t_m/t	$1/N^2$

The rock mass is a cylinder with a diameter and length of 180 mm. The disposal borehole of 56.7 mm in diameter by 127 mm in height is then created at the center of the cylinder. we used Tage tuff, assuming the repository composed of sedimentary soft rock. The physical properties of Tage tuff in the laboratory tests are: about 2.9 GPa (dry) and 1.2 GPa (wet) in the Young’s modulus of the uniaxial compressional test, about 1720 kg/m^3 (dry) and 2000 kg/m^3 (wet) in the density, and about 10^{-11} m/s in the permeability[5].

Nishimoto et al.[7] developed a geotechnical centrifuge, "CENTURY5000-THM" (Centrifugal Test equipment for Ultra-long time Range of 5000 Years: simulating coupled Thermal-Hydraulic-Mechanical processes) that enables us to perform a long-term operation of up to six months. The main features of the centrifuge are shown in Fig. 4.

We adopted the simple model shown in Fig. 3a in the present centrifugal test. This model does not consider the entire disposal repository from the surface to deep underground, but focuses on the area

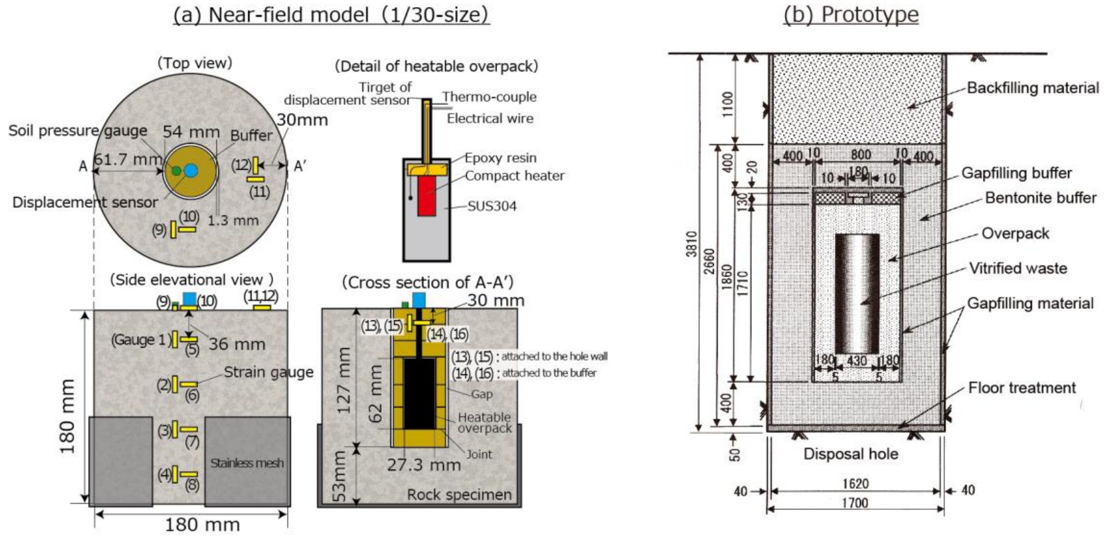

Fig. 3. (a) Near-field model of the centrifugal model test, and (b) the target HLW disposal repository.

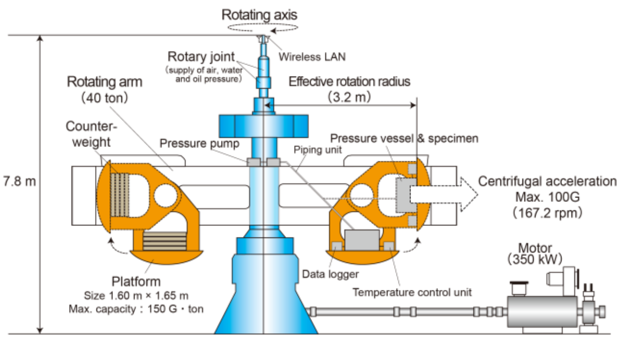

Fig. 4. Schematics of "CENTURY5000-THM".

surrounding the overpack. Therefore, the stress corresponding to the lithostatic pressure is supported by the pressure vessel. As for the scaling law of the self-weight stress, we considered only the surroundings of the overpack, including the bentonite buffer and bedrock.

2.4 Test condition

We conducted the normal temperature- [3, 5] and heating-test [4] (Table 2) as the parameter of the confining pressure (the STRESS-constraint condition, that is, surrounding of the bentonite DEFORM). And, we referred the centrifugal data of Nakamura and Tanaka[8] under the STRAIN- constraint and normal temperature condition. Their study used a model composed of bentonite and an overpack with a steel container, and did not include the bedrock under the strain-constraint condition, that is, surrounding of the bentonite DOES NOT DEFORM.

The temperature conditions of the overpack are constantly 25 °C and 95 °C (normal temperature- and heating-test, respectively). We measure the change in the strain of the rock mass and the bentonite, the soil pressure of the bentonite (called the "bentonite pressure"), and the displacement of the overpack. In addition, we attach the thermocouples in the heating-test at the same place as a part of the strain gauges. Centrifuge model tests are conducted with a centrifugal force field of 30 G, along with predetermined confining pressures and injection pore pressures. Confining pressure (Pc) is applied at 6 to 10 MPa as a result of the isotropic hydraulic pressure (Table 2). The predetermined pore pressure (Pp) of the injected distilled-water is constantly controlled at the bottom end of the model. The back pressure is also constantly controlled under the consolidation-drainage (CD) condition of 0.5 MPa at the top end of the model. In contrast, the test condition of Nakamura and Tanaka [5] is the consolidation-undrainage (CU). The model uses initially dry conditions to measure the saturating and swelling processes of the rock mass and bentonite. Test procedures are, (1) the predetermined confining pressure and the ambient temperature are loaded to the model, (2) the centrifugal acceleration of 30 G is applied after all measuring sensor values are steady, and then, (3) pore water injection and heating of the overpack are started. The injection pressure of pore water is constantly controlled after it approaches the predetermined value.

3. Result and discussion

In the centrifugal model tests, the displacement of the overpack, the bentonite pressure, the strain of the rock mass, and temperature (only the heating-test) were measured under the confining pressures. As for the example of results obtained by the tests, we show the temporal change of bentonite pressure in the normal temperature- and heating-test under the stress-constraint conditions (Fig. 5). We define the bentonite pressure as the value obtained when the back pressure is subtracted from the measured soil pressure. The data plotted in the figure are the values over time starting from the injection of the water (and the heating of the overpack). And, we describe them using the test elapsed time (lower horizontal axis) in the following paragraph.

3.1 Stress- and time-dependency

The bentonite buffer placed into the disposal hole of the rock mass swells by the injected water that permeates the bottom and lower half-side of the rock mass, and then fills the gaps and joints in the hole from the lower part sequentially. The bentonite pressure is measured at the top of the model in the present tests (Fig. 3). Therefore, the soil pressure transducer showed little change from the start of the 20 to about 200 h, because the bentonite pressure could only be measured at the soil pressure

Table 2. Test conditions of the centrifugal model tests.

	Normal temperature-test						Heating-test	
Sample No.	TG-03*	TG-10*	TG-11*	TG-12*	TG-05*	(NT*2)	TG-17*3	TG-19*3
Confining pressure, MPa	5.0	6.0	7.0	9.0	10.0	–	6.0	10.0
Injection (pore) pressure, MPa	2.5	3.0	3.5	4.5	5.0	4.9	3.0	5.0
Back pressure, MPa	0.5	0.5	0.5	0.5	0.5	–	0.5	0.5
Overpack, °C	25					25	**95**	
Ambience, °C	25					25	31	35
Centrifugal acceleration, G	30					30	30	
Test time, d	34	24	39	67	40	39	80	52
Equivalent time, yr	83.8	59.2	96.2	165.2	98.6	96.1	197.3	128.2

*Nishimoto et al. [3, 5]; *2Nakamura and Tanaka [5]; *3Nishimoto et al. [4]

transducer after the gaps and joints were filled. Then, the bentonite pressure increased rapidly by the swelling of the bentonite and was measured the local maximum. In the normal temperature test, beyond the local maximum values of the soil pressure of bentonite were measured, the values changed to gradual decrease and were not convergent through the tests. In contrast, the values in the heating-tests were measured the additional second local maximum, and then, changed to gradual decrease.

The general trend of the bentonite pressure were similar between our data and NT [8], but the variations in our data are larger than their results. In addition, our data clearly had a confining pressure-dependency in terms of the local maximum value, as well as a time-dependency after the local maximum values because the measured values were not convergent. Similar trend were obtain in the results of the displacement of the overpack.

The long-term behaviors of the near-field are qualitatively considered due to the following factors: (1) the disposal hole drilled in the deep underground shrinks due to the lithostatic pressure; (2) the bentonite buffer generates swelling pressure due to the imbibition caused by the reflood of groundwater; and (3) geomechanical interactions occur between the bedrock around the disposal hole and the bentonite buffer. In terms of the change from the local maximum to the test-end value of the bentonite

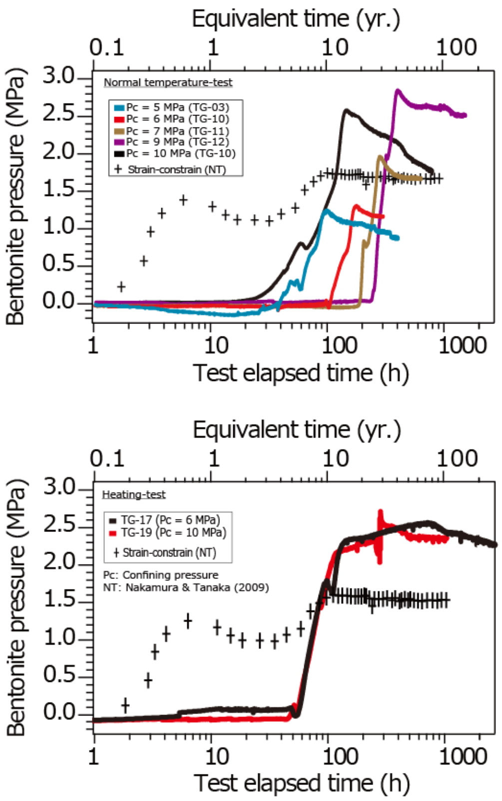

Fig. 5. Temporal change of bentonite pressure. (Upper) normal temperature-test, (lower) heating-test.

pressure, the test results of NT [8] were convergent when about 40 equivalent years passed (Fig. 5). By contrast, our data were not convergent with the gradual change. No observation of the convergence in the test results of TG-12 (normal temperature-test) and TG-17 (heating-test) for the longest period of about two and three months which correspond to 165 and 197 equivalent years, respectively, that is, they have the time-dependency obviously.

The deformation of the disposal hole (host rock) yields to the convergent swelling pressure of the bentonite by the geomechanical interaction between the bentonite and the surrounding bedrock[5]. In addition, the disposal hole/bedrock surrounding bentonite deforms in our tests under stress-constraint conditions, and it is considered that the stiffness in the bedrock decreases and the suction disappears gradually while the condition changes from dry to wet by the pore water, and then the bedrock softens[5].

Consequently, we interpret that the bentonite pressure keeps decreasing gradually until the geomechanical interaction between the stress of the deformation of the disposal hole/bedrock and swelling of the bentonite balanced. Due to the gradual and continuous deformation of the disposal hole/bedrock surrounding the bentonite, we infer that the convergent time of the displacement of the overpack and the bentonite pressure becomes longer than that of Nakamura and Tanaka [5].

3.2 Effect of heating

Fig. 6 shows cross-sectional images of the model made by X-ray CT after the centrifugal tests. In the normal temperature-test, the density both the bedrock and the bentonite reaches the supposed saturated density (about 1900-2000 kg/m^3). In the heating-test, the density of the bedrock reaches the supposed saturated density, in contrast, that of bentonite dose note reaches the supposed saturated density, and the CT value (equivalent density) decreases toward the overpack (1700-1800 kg/m^3).

It is considered that the a little evaporation of pore water is generated in the heating-test because the temperature of the overpack is set to 95°C. It is highly unlikely to the boiling of water due to 0.5 MPa of the back pressure. However, it is a possible that water vapor is relatively generated more in the bentonite around the overpack with high temperature compared with the bedrock, and then, the differential pressure is formed. As a result, it is inferred that pore water is pushed away from the bentonite to the bedrock, and the zone of a low density in the bentonite is formed.

In other word, it is suggested in the heating-test that (1) the density of the bentonite decreases because the unsaturated zone in the bentonite is formed [Fig. 6(right)], (2) the bentonite pressure and the stiffness in the disposal hole decreased, and then, (3) the trend

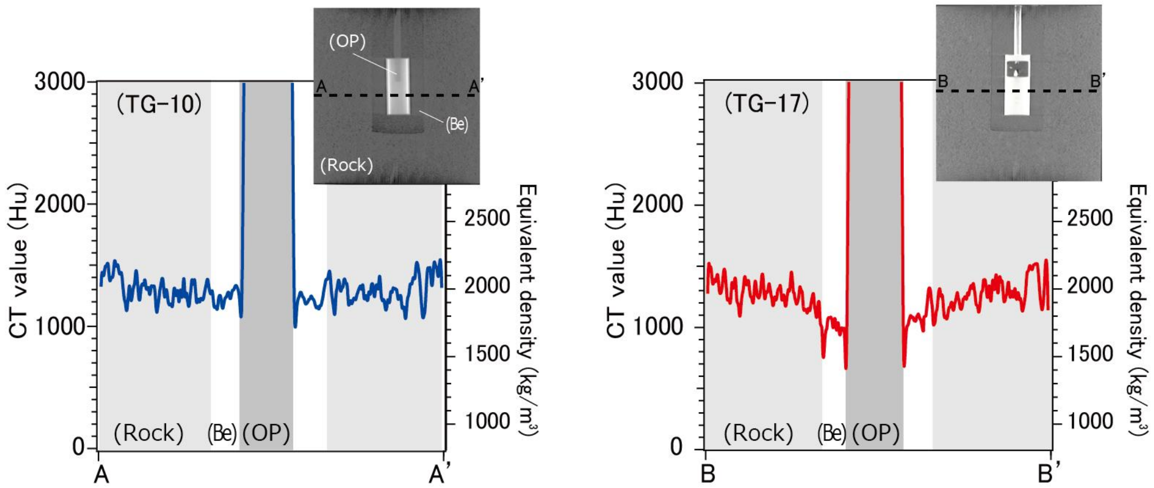

Fig. 6. Cross sectional image of the model by X-ray CT in the prost-test, (left) normal temperature-test, and (right) heating- test. Be: bentonite, OP: overpack.

in the displacement of the overpack and the strain of the bedrock [expansion to compression, Fig. 5 (lower)] change because of a stress constant condition. Moreover, it is inferred that the unsaturation in the bentonite moves on to the saturation eventually, however, the disappearance of the unsaturated zone is necessary in order that the geomechanical interaction between the stress by the deformation of bedrock and the swelling pressure of the bentonite reach equilibrium under the high temperature condition.

4. Conclusion

We carried out the centrifugal model tests to evaluate a long term behavior in the near-field of a geological repository for HLW disposal. The results and conclusions are as follows.

(1) In results of the local maximum value of the bentonite pressure in the present tests, these values were obviously different depending on confining pressure ('stress- dependency'). In addition, these values after the local maximum values were not converged in test-time ('time-dependency'). These behaviors are distinctly different from the results of the previous centrifugal model test in a strain-constraint condition.

(2) X-ray CT scanning of the model after the centrifugal tests show that the CT value (equivalent density) of the bedrock in the heating-test reaches the supposed saturated value, in contrast, that of bentonite dose note reaches the supposed saturated value, and the density decreases toward the overpack.

These results contribute to the validation of numerical analysis.

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