IN-SITU BACKFILLING EXPERIMENT OF THE SMALL SCALE DRIFT BY SPRAY METHOD IN MIZUNAMI UNDERGROUND RESEARCH LABORATORY, JAPAN

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ABSTRACT
In-situ backfilling experiment using spray method in the small scale drift (approximately 4 m by 3 m scale) was conducted at a 500 m depth in the Mizunami Underground Research Laboratory (MIU), established by JAEA (Japan Atomic Energy Agency). The aim of this experiment is to demonstrate backfilling by spray method deep underground and establish the quality control methodology as the one of the techniques applied for geological disposal in Japan. The backfill material consists of a sand and bentonite mixture. Specification for the backfill material was designed to satisfy the target permeability of a generic host rock (10^{-8} m/s) assumed by NUMO. In this case, effective clay density should be 0.4 Mg/m^3 or more. Quality control of the material before backfilling was performed by setting the initial water contents (14±2%) based on the results of the Laboratory testing and preliminary spray testing on ground surface. While the quality control of the backfilled material during the experiment was performed by density measurement with the standard method and a 3D-scanning method. Densities of the backfilled material measured at any points satisfied the specification (more than 0.4 Mg/m^3) and the results suggested the establishment of the practical quality control methodology of the backfilling by spray method under actual deep geological environment. Furthermore, the measurement of the moisture transfer characteristics and the swelling of bentonite using several instruments, as well as the amount of the outflowing of bentonite from the backfilled material, was carried out.
Keywords: backfilling, spray method, in-situ experiment, deep underground, crystalline rock.

1 INTRODUCTION

One of the features of the geological disposal policy in Japan is the establishment of multiple URLs. The URLs must be distinct from actual disposal facilities which will be constructed by the Nuclear Waste Management Organization of Japan (NUMO). The URLs of the JAEA projects are distinct from on-site (site-specific) URLs classified as purpose-built generic URLs as described in the OECD/NEA report [1], to be constructed at potential waste disposal sites. JAEA's URL projects aim to improve the reliability of geological disposal technologies and to develop advanced safety assessment methodologies. In order to characterize the general range of geological environments in Japan, two generic URLs were constructed. One is the Mizunami Underground Research Laboratory (MIU) focused on crystalline rock (Fig. 1), and the other is the Horonobe Underground Research Laboratory focused on sedimentary rock. The MIU project has been performed in three overlapping phases: "Phase I: Surface-based investigation," "Phase II: Construction" and "Phase III: Operation." The construction of research galleries in the MIU has completed to –500 m depth. Since 2010, research activities in Phase III have started in the underground. Current R&D activities include a gallery closure test at the GL-500 m level to study recovery processes in the geological environment around a gallery after it has been backfilled, the development of long-term monitoring technology, a post-excavation grouting experiment to demonstrate the feasibility of impermeable grouting and a mass transport experiment in MIU [2].

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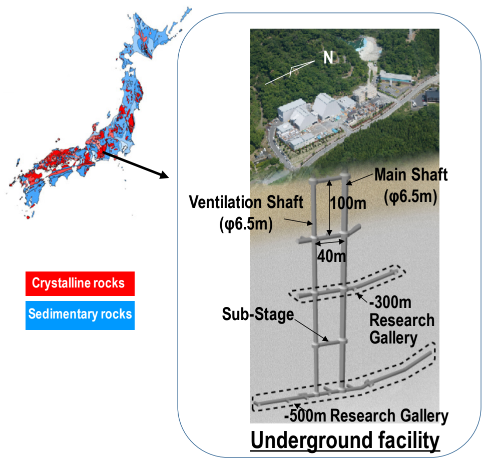

Figure 1: Location of MIU and schematic layout of the gallery [2].

The in-situ backfilling experiment was carried out as a part of development of technology for backfilling the underground structure in MIU excavated in crystalline rock as one of the current R&D items.

2 SITE LOCATION AND GEOLOGICAL ENVIRONMENT

The MIU Construction Site is located at an altitude of 200 m above sea-level in a hilly area adjacent to the urban area of Mizunami City, Gifu Prefecture, central Japan. Around the site, Tertiary sedimentary rocks widely and unconformably overlay the cretaceous Toki Granite (60–70 Ma) [3]. The Toki Granite, a zoned pluton, has three rock facies grading from muscovite-biotite granite at the margin through hornblend-biotite granite to biotite granite [3]. The R&D work of the MIU project conducted mainly in the Toki Granite basement.

Due to the geological disposal of HLW will be under 300 m depth according to Japanese law, experiment site shown in Fig. 2 was located in research gallery excavated 500 m depth as a demonstration. The site was a horseshoe-shaped cross-section drift with a length of about 10 m, a height and a width of about 3 m. Inflow rate in the drift was less than 0.1 L/min and it is relatively small in MIU drift in granite.

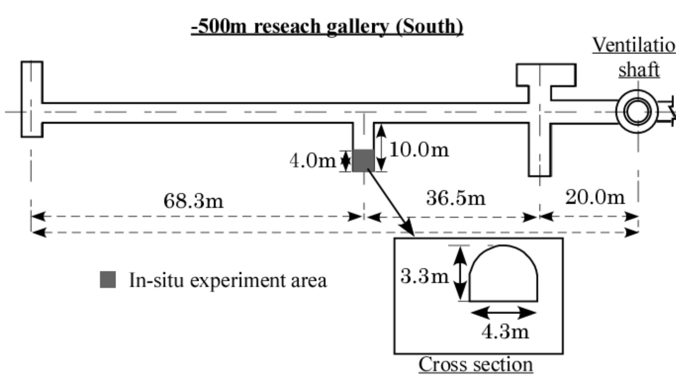

Figure 2: Location of the in-situ experiment site.

3 PLANNING

The Backfilling experiments were carried out both within and outside Japan. Geological disposal in Japan is still R&D phase for geological disposal and engineered barrier system related to the backfilling is not fixed yet. The experiment for horizontal disposal technology has been conducting at Horonobe URL. Therefore, backfilling is assumed the type of KBS-V in this experiment and focused on backfilling of disposal tunnel.

We referred previous studies in Japan and overseas that were subject to literature surveys for planning. Literature surveys were carried out in view of the site-generic perspective in Japan for geological disposal and the in-situ experiment plan was focused on backfilling a drift, in the case of vertical deposition of the MIU project. As a result, advection suppression, chemical stability between materials, buffer position retention, canister lift prevention and tunnel stability of disposal tunnels were extracted as the required performance for backfilling. In addition, the result confirmed that the permeability and swelling pressure of the backfill material were used as performance indicators. These results are the same as required performance for backfilling that NUMO has studied.

From the viewpoint of a site-generic test plan, it was determined that the values of the permeability of backfill was controlled to be less than the one of a host rock presented in NUMO [5]. Specifically, measured averaged hydraulic conductivity of Toki granite around in-situ experiment site in Fig. 3 was 10^{-8} m/s order and the permeability of backfill was less than 10^{-8} m/s order as a target.

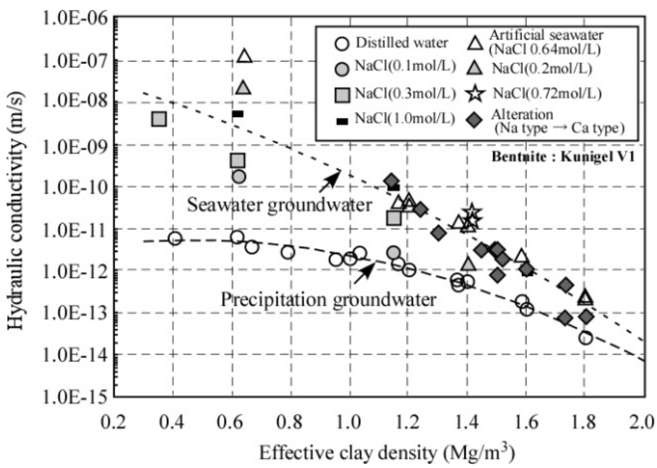

Figure 3: Relationship between hydraulic conductivity and effective clay density [5].

Fig. 3 shows the relationship between the density of the clay material (bentonite) to be applied for geological disposal (effective clay density) and permeability. The result suggested that the effective clay density over 0.4 Mg/m^3 satisfies the permeability of 10^{-8} m/s or less for both groundwater and saline water. Therefore, effective clay density of 0.4 Mg/m^3 or more was adopted as a control parameter for the material specifications in this experiment. Effective clay density (ρ_e) is calculated following equation:

$$\rho_e = \frac{\rho_d (100 - R_s)}{\left(100 - \frac{\rho_d R_s}{\rho_s}\right)}$$

where ρ_d: dry density (Mg/m^3); R_s: mixture rate of dry sand; ρ_s: soil particle density of sand. (Average value of dry density of sand and crushed rock in the case of crushed rock is used.)

On the other hand, it was judged that this test will be able to conduct for only two years due to political situation of MIU project. Therefore, tunnel stability of disposal tunnels, the one of the required performance was not adopted in this study because the presence or absence of backfilling material does not affect the mechanical stability of the in-situ experiment site. In addition, it was decided that a retaining wall that allows drainage was constructed instead of a plug due to the very short period allowed for this experiment.

Based on above condition, the preliminary Lab. testing using different compaction energy of mixed soil composed of bentonite (Kunigel V1), sand, and crushed rock was carried out as shown in Table 1 and Table 2. The results show that both materials were satisfied the above described requirement (effective clay density is 0.4 Mg/m^3 or more) under different compaction energy.

Table 1: Specification of the tested backfilling material.

	Composition	Mixture(wt%)	ρ_s(Mg/m^3)
Material A	Kunigel V1	15	2.767
	Sand	35	2.681
	Crushed rock	50	2.686
Material B	Kunigel V1	15	2.759
	Sand	85	2.674

Table 2: Results of laboratory compaction testing.

	Material A			Material B		
Compaction energy	1Ec	0.6Ec	0.4Ec	1Ec	0.6Ec	0.4Ec
$\rho_{d\,max}$(Mg/m^3)	1.933	1.855	1.799	1.747	1.681	1.648
w_{opt} (%)	11.6	12.5	14.8	14.2	14.5	15.9
ρ_e (Mg/m^3)	0.727	0.656	0.609	0.589	0.542	0.519

There are several construction methods of backfill material, which are rolling and compaction, block stacking and spraying and they were demonstrated in Japan and overseas. In this experiment, a full-section spraying method was applied, which is the unprecedented method within and outside Japan. However, there was large limitation of the materials and machines used for the spray construction because they were required to pass through the opening (1.9 m) of the ventilation shaft scaffold of MIU. Thus, examine the quality of backfill materials was planned for the development of quality control methodology, the full-section spraying method. Consequently, the backfilling in this experiment was planned to divide into 8 steps, and the measurement work and the spraying construction are repeated for each step (Fig. 4). Table 3 shows the measurements for quality control. These items were planned based on the results of literature survey as well.

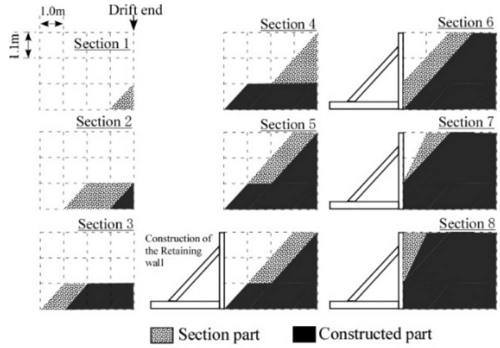

Figure 4: Steps of backfilling in this experiment.

Table 3: Measurement and monitoring items.

Item	Method	Number	Objective
Density	Lab. Test	50	Confirmation of the quality of sprayed buffer material
	Evaluation based on the 3-D scanning data	After spraying of each section	
Total Pressure	Pressure meter	10	Mesurement of the swelling pressure
Water Pressure	Water pressure meter	12	Mesurement of the water pressure
Water content	Soil moisture meter	10	Variation of water content in buffer material
Total outflow volume	Water lebvel indicator	1	Estimation of the outflow of bentnaite from buffer material
Concentration of bentnaite in outflow	Absorbance meter	1	

4 SELECTION OF MATERIALS AND MACHINES FOR THE IN-SITU BACKFILLING EXPERIMENT

According results of planning, the backfill material A and backfill material B were used to investigate the effects on workability and quality due to the difference in materials used for in-situ spray on ground surface (Fig. 5).

Firstly, the test was conducted by spraying of backfill material A (the water content ratio is set to 13.7% on average of 0.4Ec and 0.6Ec optimum water content ratio) using a spraying machine (Ariba 285). The result shows that the effective clay density after spraying was 0.571 to 0.611 Mg/m^3, while a relatively high density was obtained. On the other hand, it required 63 minutes (net spraying time of 13 minutes) for spraying one bag (428 kg). The main reason was that the addition of crushed rock. It made the backfill material agglomerated by compaction during transportation and it was difficult to put into the spraying system. Therefore, material A was not adopted for this experiment due to practical reason.

(a) (b) (c)

Figure 5: Preliminary test on ground surface. (a) Layout of preliminary test on ground surface; (b) Spraying the buffer material with 14% water content; and (c) Spraying the buffer material with 18% water content.

The following test was conducted with material B. In this test, equipment and machine were selected taking into account workability and quality based on the result of the first test shown in Table 4. Especially, spraying machine (AGC PRIBRICO with a small spraying amount per injection) was used to prevent clogging in the material hose. In this test, the requirement was set to be up to the dry density after sprayed material up to that of 0.4Ec in Lab. conservatively. Fig. 6 shows the dry density of material B after sprayed with 14% and 16% water content was expected up to that in the case of 0.4Ec. Regarding workability (Table 4), it was confirmed that a net spray amount of about 1 ton per hour could be secured in the cases of w=14% and 18%. This result shows that improvement from the previous test. The minimum loss rate was obtained at W=14%. On the other hand, stability of sprayed material and density were extremely low in the case of W=18% (shown in Fig. 6).

Table 4: Obtained speed of spray method on ground surface.

	W=14%	W=16%	W=18%
Total time(min)	62	79	53
Time of spraying(min)	29	31	20
Weight of sprayed material(kg)	951	858.5	820.5
Speed of backfilling by spraying (kg/h)	1967.6	1661.6	2461.5
Loss rate*	1.287	1.445	1.364

* Loss rate: Total weight of used material / Weight of sprayed material

Based on above series of selection processes and test results, materials and machines were selected for the in-situ experiment. Table 5 shows the material specifications of backfill materials. The moisture content of backfill material was set to 14 ± 2% (considering errors due to mixing), which resulted in high construction density and good workability (construction speed, loss rate).

5 OVERVIEW OF THE IN-SITU BACKFILLING EXPERIMENT

The demonstration test was conducted in the equipment horizontal shaft (GL-500 m) of Mizunami Underground Research Laboratory. Example of the state of in-situ spraying is shown in Fig. 7.

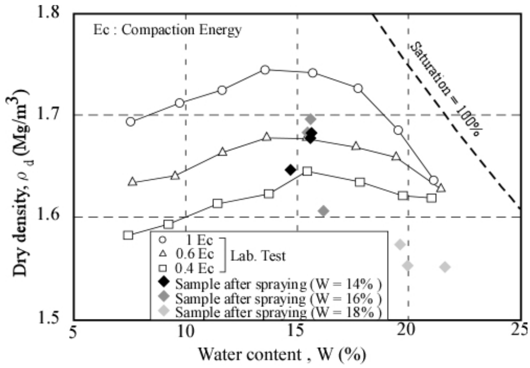

Figure 6: Results of the compaction test with different water content (Lab. test and preliminary test on the ground surface for material B).

Table 5: Final mixture of backfilling material for in-situ experiment.

	Mixture (%)	Water content (%)
Bentnaite (Kunigel-V1)	15	14±2
Sand	85	

Figure 7: Spraying of back fill material.

In this test, construction speed and spraying speed were applied for workability evaluation, and effective clay density (ρ_e) was applied as an index for quality evaluation. Fig. 8 show the water contents of the material at site preparation and after spraying. Most of the material water content just before spraying were satisfied with its specification (14±2%) and well controlled. And the water content after spraying was also in the same range. The

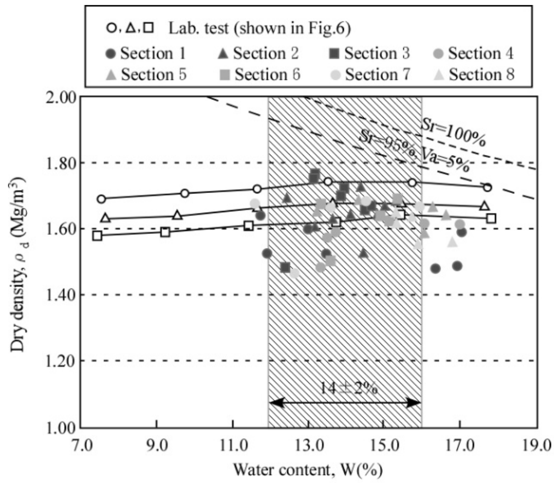

Figure 8: Measured water content of buffer material at site preparation.

Table 6: Results of the evaluated backfilling speed in each section and estimated effective clay density of backfilling material with different methods.

	Weight of Sprayed buffer material(kg)	Speed of backfilling by spraying (kg/h) (Ave.)	Effective bentnite density (Mg/m3)	
			Lab.test (Ave.)	Evaluation based on the 3-D scanning data
Preriminary testing at ground surface	951.0	1967.6	0.534	-
Section 1	6173.0	1119.0	0.447	0.326
Section 2	13689.7	1342.1	0.527	0.450
Section 3	8308.1	1724.9	0.566	0.514
Section 4	22394.4	1514.8	0.477	0.420
Section 5	13542.6	1599.5	0.521	0.408
Section 6	16319.5	1962.3	0.509	0.343
Section 7	9115.8	1905.7	0.513	0.587
Section 8	5015.3	1662.5	0.492	0.631

measurement for material density, water content etc. of sampled backfill material were performed at on-site immediately.

Table 6 shows the summary of the results of averaged construction speed by in-situ spraying and density at each section. Measured density except existing gutter part showed 0.41–0.60 Mg/m^3 of effective clay density and it is confirmed to satisfy the requirement of ρe (0.4 Mg/m^3 or more). The averaged backfilling speed by spray method in in-situ obtained

1119.0–1962.3 kg/h. The speeds of the first 2 sections were relatively low due to inexperience of workers. However, the speed after section 2 is close to it of second test on ground surface and the total system for in-situ spraying was concluded with productive work in this experiment.

Fig. 9 shows the planed and actual sampling points of splayed material. Coordination of actual sampling points were obtained from 3D scanning data. The planned sampling positions were determined with consideration of the reliable results of 3-D contour map. The difference between detail planed and actual positions was mainly due to practical reason. Fig. 10 shows the 3-D distribution of effective clay density of backfill material using measured actual sampling position as an example. The results suggested that the effective clay density close

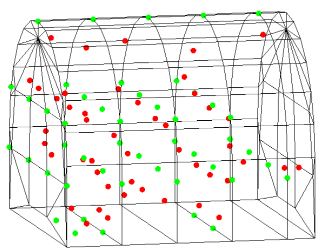

Figure 9: Sampling points (planned: red; actual: green).

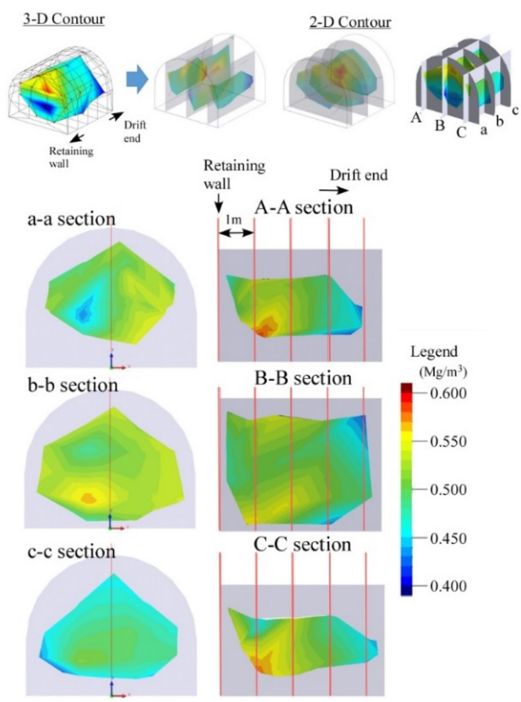

Figure 10: An example of distribution of the measured properties of backfill material based on 3-D contour map (effective clay density).

to drift end was relatively low, Section 1 and Section 6 in this case. In Section 1, the splaying pressure might be low because of inexperience of workers and energy loss by upward splaying affect for the density in Section 6.

Fig. 11 shows an example of the 3D scanning results. 3D-scanner was Focus3D S120(FARO Co.ltd.) and averaged time for 3D scanning in this experiment was about 20 min/1 scanning. Fig. 12 shows the comparing of the effective clay density between measured and calculated based on 3D scanning data and actual weight by spraying. Error bar shows the variation of the measured effective clay density in each section. Variation range of measured effective clay density was max. 0.1 Mg/m^3. The effective clay bulk density of Sections 1–6 wa smaller than that of measured. It might be caused by the overestimate of the volume due to insufficient extract of rebound at those sprayed parts. While effective clay bulk density of the Sections 7 and 8 was higher, which was caused by the underestimation of the sprayed volume due to some obstacles (retraining wall etc.). The estimation of the bulk density based on 3D scanning has several advantages (no damage at backfilled part, minimize the impact on the backfilling schedule because of its short-term measurement and safety of backfilling work) and it may be useful if the calibration curve like indicated in Fig. 12 will be made in the future geological disposal.

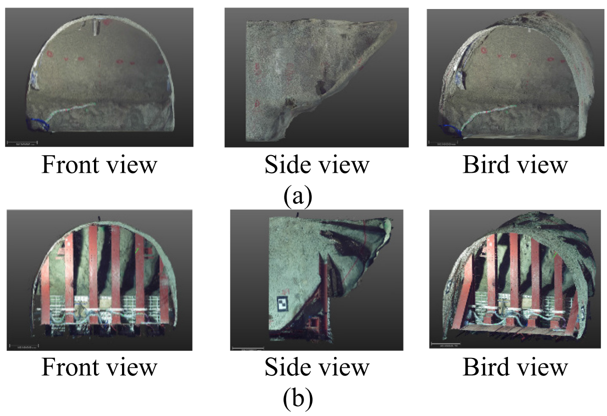

Figure 11: An example of 3D scanning results. (a) Section 5; and (b) Section 6.

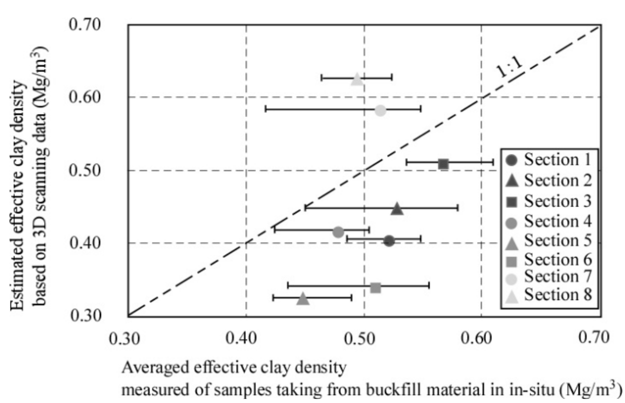

Figure 12: Relation between estimated effective clay densities.

Fig. 13 shows the used equipment, arrangement of monitoring during and after backfilling. Fig. 14 shows the schematic layout for the in-situ measurement of erosion of bentonite from backfill material. Monitoring results are summarized below.

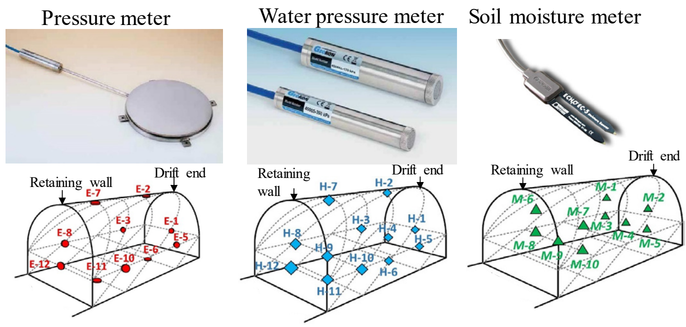

Figure 13: Monitoring equipment and its arrangement.

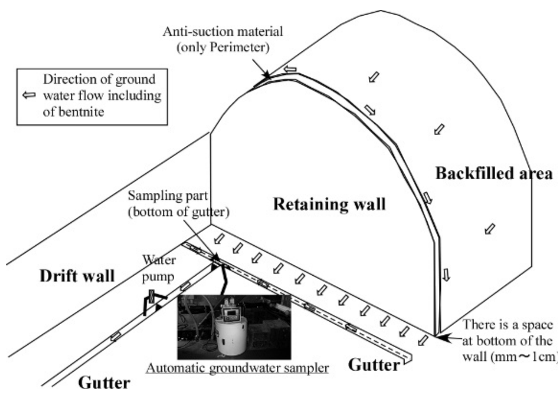

Figure 14: Monitoring of the outflow of ground water including of a bentonite.

The soil moisture meter (M-1, M-2, M-6, M-7) installed on the top end shows a value of 80% or more of water content immediately after installation, and those parts maintain stable condition. Moisture in other backfill materials also gradually rose until around May 2019, indicating a moisture content of more than 60%. The soil moisture meter at the M4 point showed a value of 100% immediately after installation; however, the value suddenly dropped in the middle of February 2019 then showed unstable behavior. Possible cause of the behavior is failure of measuring instrument (Fig. 15(a)).

Most of water pressure gauges resulted in a slight increase in negative pressure over time. On the other hand, qualitatively, H-1 and H-5 that are closest to the face turned to positive pressure, which is consistent with the infiltration of groundwater from the boundary of backfilled area and drift wall (Fig. 15(b)).

For total earth pressure, the E-11 point on the bottom and the E-1 point on the face tend to rise slowly until May 2019 while fluctuating. On the other hand, the point at E-10 tends to decrease gradually. Other than that, it rose immediately after installation and then levelled

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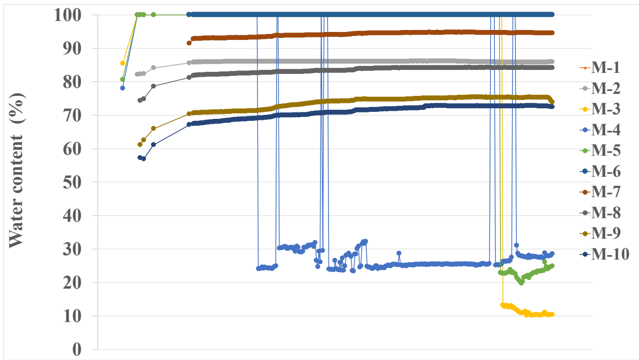
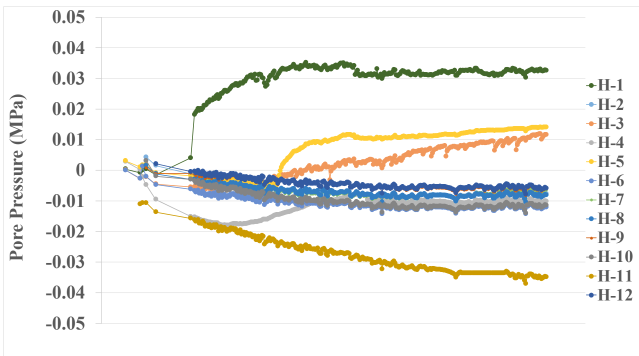
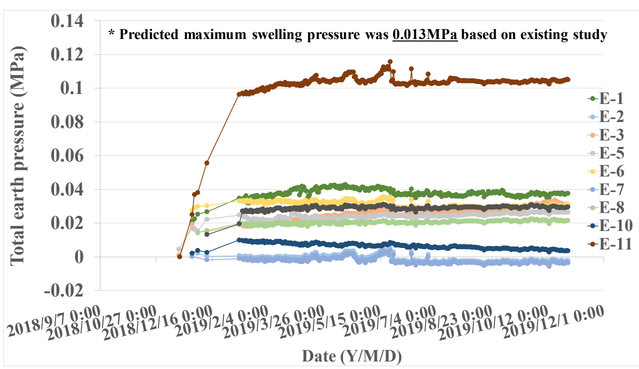
off (Fig. 15(c)). E12 installed on the retaining wall has been almost staying at the same value and there is no appearance of swelling pressure behavior on the retaining wall. It was not able to extract the swelling pressure of bentonite in total earth pressure quantitatively due to its quite small value (averaged swelling pressure predicted based on the previous study result was 0.013 MPa [6]).



(a)



(b)



(c)

Figure 15: Monitoring results. (a) Soil moisture; (b) Water pressure; and (c) Total earth pressure.

From the variation in the total earth pressure, the state changes during the backfilling can be roughly divided into two stages (Stage 1: Start – middle of May, Stage II: Middle of May – Monitoring end). The state and its possible reason in each stage as follows:

Stage I: All earth pressures including the two earth pressure at the top increase gradually and suddenly drop at some point. During this period, soil moisture also showed a relatively increasing trend, and the water pressure also increased to positive pressure in some cases. It is supposed that the degree of saturation increases and the swelling behavior occurs due to the infiltration of groundwater into the backfill material, however, when the pressure behavior on the drift wall reaches the certain level, the pressure drops rapidly due to some deformation in backfilling part.

Stage II: Moisture rise almost constantly and the total earth pressure moves up and down on the spike. Water pressure shows a tendency to being stable. The infiltration of groundwater in the test area has reached the steady state (not full saturation). Flow paths through, which may be made by backfill material. Changes in the spike of the earth pressure seem to be linked to the behavior of groundwater infiltrated in the backfill material through the paths.

It is estimated that above different conditions are observed due to the fact that outflow from backfilling part is allowed for the in-situ measurement of erosion of bentonite and the local heterogeneity of the physical properties in the backfill area.

Fig. 16 shows the comparing of the bentonite erosion between the results of an existing study [7] and this experiment. The results are consistent with existing study for Kunigel V1 bentonite. In addition, amount of erosion volume with total outflow is also similar with SKB's results using MX-80. Although the bentonite used and experiment condition were different, it is interested and the results of our experiment will provide useful information for predicting the bentonite erosion when the future geological disposal is designed.

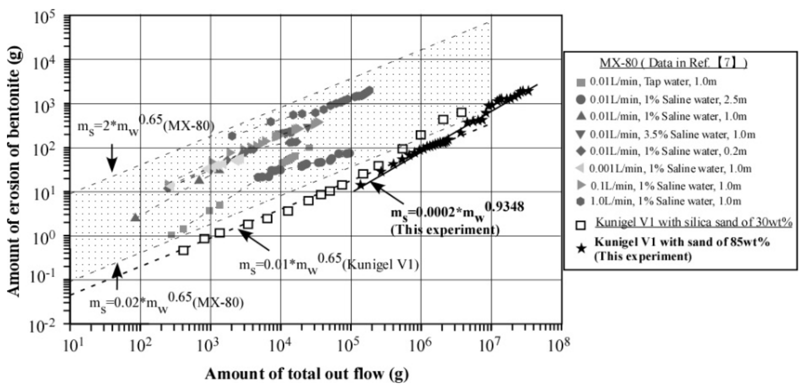


Figure 16: Comparing between existing results and the result of in-situ measurement for erosion of clay (bentonite) in the backfilled material of this study.

6 CONCLUDING REMARKS

In this in-situ experiment, the applicability of spray method for backfilling was evaluated from both the "workability" and "quality" aspects. In the evaluation of workability, parameters directly related to the construction work such as "spraying speed" were calculated, and “effective clay density” was used as an evaluation index of “quality”. The target value of the effective clay density is set to 0.4 Mg/m^3, which correspond with the averaged permeability of host rock around test site (10^{-8} m/s order). It is difficult to compare the construction results in other places in Japan and overseas and the applicable construction methods (rolling and compaction, block construction, etc.), because of the various geological environment and the environmental conditions of a place where it can actually be used. However, the full-section spraying method applied in this experiment can be evaluated as one of the practical methods for backfilling in the future geological disposal project for the following reason:

- The spraying speed, which are the parameters of “workability,” are comparable to the results of preliminary tests on the ground surface where there are almost no restrictions except for the Section 8, that was final part.
- Regarding the “quality” of the backfill material required, all sections can achieve a value up to 0.4 Mg/m^3 or more which required low permeability (at least 10^{-8} m/s order of host rock).

On the other hand, from the data of construction in this in-situ experiment, the operator’s experience, spraying conditions (nozzle position and orientation) and construction environment (ventilation environment and sufficient electric energy) can affect the workability and quality. In particular, the available utilities in underground such as electricity, ventilation system etc. may become a practical problem even in an actual geological disposal site and it is necessary to consider the design of the future geological disposal facility. The decreasing of spraying pressure was observed when spraying with the nozzle facing upward. It may be resulted in decreasing of density of the backfill material. In this case, the control of the nozzle direction keeping either horizontal or downward as possible and the improvement of the spray nozzle and sufficient discharge volume at least for the height of the backfill area (3 m in this test) were performed. As a result, the influence was minimized.

In addition, after spraying, a slight gap of a level was observed near the top, which caused the self-weight settlement with time of the backfill material mainly and backfilled material close to the drift wall was loosed by only a small amount of ground water from the drift surface. It was presumed that the backfill material was made near the optimal moisture content for compaction. This also causes the degraded quality of the backfill material. It seems that one of the countermeasures is to use a backfill material with a high bentonite content at spraying close to drift wall and it is desirable to incorporate the use of shoring without rock bolts when designing and constructing the facility.

One of the purposes of this in-situ experiment was to obtain scientific basis for the development of a quality control methodology when all sections are sprayed in the future geological disposal facility. The results of planned laboratory testing during backfilling by spraying and preliminary tests on the ground surface indicate that the applied quality control methodology was highly evaluated and appropriate for the quality control of backfill material as described above. The bulk density measurement with the 3D scanner tended to be slightly smaller than the values obtained by Lab. testing. However, the measurement method has the several advantages such as a certain volume can be calculated in about 20 minutes with no damage of backfilled area and worker’s safety. These are important issues for the quality control related to backfilling of long tunnels focused on the actual geological disposal projects and the results suggested that the quantitative estimation of bulk density should be made calibration curve between the Lab. testing and 3D scanning.

As regards the monitoring, in the view of quality control, it was difficult to conclude in this experiment due to its small swelling pressure, allowance of outflow from backfilled part and in-situ experiment duration. However, the results showed changes of state in backfilled parts, which is important information to understand the real phenomenon in the area and to support the quality of backfilling.

Finally, measurement of the erosion rate of bentonite in backfilled material was performed. The method was simple. The results suggested that it will be roughly predicted the amount of erosion of Kunigel V1 in in-situ with time. It is also valuable result for the design of the backfilling in actual geological disposal.

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REFERENCES

[1] JNC, H17:Development and management of the technical knowledge base for the geological disposal of HLW, JNC TN1400 2005-022, 2005.

[2] Mikake, S., Iwatsuki, T., Matsui, H. & Sasao, S., Current status and next five-year plan of R&D activities of Mizunami Underground Research Laboratory, *Proceedings of DOPAS Seminar*, 2016.

[3] Ohsawa, H. et al., Current status of R&D activities and future plan of Mizunami Underground Research Laboratory. *Proceedings of 2015 International High-Level Radioactive Waste Management Conference (IHLRWM 2015)* (CD-ROM), pp. 371–378, 2015.

[4] JAEA, Planning for in-situ backfilling test to the gallery in the Mizunami Underground Research Laboratory, JAEA Technology 2018-017, 2018. (In Japanese with English abstract.)

[5] NUMO, www.numo.or.jp/topics/safetycase_setsumei4.pdf. Accessed on: Aug. 2018. (In Japanese.)

[6] JNC, H17: Development and management of the technical knowledge base for the geological disposal of HLW -Repository engineering technology, JNC TN1400 2005-015, pp. 32–35, 2005. (In Japanese.)

[7] SKB, Deep repository-engineered barrier system. Piping and erosion in tunnel backfill, SKB P-06-72, 2008.