Manufacturing and Handling Techniques of the Monolithic Buffer Material for HLW Disposal*

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Small and large scale tests were performed to evaluate technical feasibility of the monolithic buffer material, defined as a large block of bentonite formed by the cold isostatic pressing, for geological disposal of high-level radioactive waste. Trial manufacturing tests up to approximately 70%-scale of a Japanese disposal concept were carried out and emplacement tests were carried out by vacuum lifting and forklift-type methods for vertical and horizontal emplacement concepts, respectively. Based on the large engineering-scale tests, technical feasibility of the monolithic buffer was demonstrated.

Key Words: Material Testing, Plastic Working, Formability, Material Handling Equipment, Emplacement, Radioactive Waste, Geological Disposal, Bentonite, Buffer Material, Cold Isostatic Pressing, Vacuum Lifting

1. Introduction

Buffer material made of bentonite and silica sand is one of the engineered barriers in Japanese concepts⁽¹⁾ of the geological disposal for high-level radioactive waste (HLW). Though piling up a number of small-sized blocks or in situ compaction is a typical emplacement concept for various national programs⁽²⁾, the monolithic buffer material concept, i.e. usage of a large block of bentonite-based material formed by the cold isostatic pressing (CIP), was proposed to make the buffer emplacement procedure simple and economical^{(3),(4)}. In the monolithic buffer concept, only two blocks, the cup-shaped body and

disk-shaped cap, are used for a waste package of HLW. The monolithic buffer concept can minimize the number of gaps between blocks, which may be advantageous to the performance assessment for a repository. Table 1 and Fig. 1 show the specifications and composition of the monolithic buffer for both vertical pit disposal type and horizontal disposal type in a Japanese concept⁽⁴⁾. The diameter and mass of the body are 1.62 [m] and 7.6 [Mg], respectively. It is necessary to evaluate the technical feasibility of manufacturing and handling of the monolithic buffer as large, brittle material. Especially, it is difficult to handle such a heavy and brittle material with the small clearance between the buffer and wall of the tunnel or pit. In a designing study on the buffer emplacement handling, the vacuum lifting method was proposed for the pit disposal concept and forklift-type method for the tunnel disposal concept⁽⁵⁾.

In this study, trial manufacturing tests of the monolithic buffer were performed up to a scale of 70% to a reference design concept⁽³⁾. The size of the largest existing CIP equipment determined the test scale of 70%. Demonstration tests on both vertical and horizontal emplacement concepts were carried out by

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Table 1 Major specifications of the Monolithic Buffer Material (body)

Items	Specifications
Material	Bentonite (Kunigel V1) 80 [wt%] / Silica sand 20 [wt%]
Dimensions	
Diameter	1.62 [m]
Height	2.26 [m]
Diameter of the hall	0.82 [m]
Depth of the hall	1.86 [m]
Thickness	0.4 [m]
Dry density	2.0 [Mg/m ³]
Weight	Approx.86 [kN]

Fig. 1 Concept of the monolithic buffer material

the vacuum lifting and forklift-type methods with the 70%-scale monolithic buffer specimens obtained in the trial manufacturing.

2. Manufacturing

The forming mold used in a CIP process for the monolithic buffer consists of a rubber cover and a metal mandrel^{(4),(7)}. The buffer material is required to have high density and homogeneous property to ensure the performance as the engineered barrier. Regarding the monolithic buffer, it seemed considerably difficult to obtain the large body with homogeneous density because of its shape. So it is necessary to evaluate the feasibility of the manufacturing technique on an engineering-scale.

2.1 Manufacturing condition

Prior to large scale tests, small scale tests were performed to decide the forming conditions, in particular the appropriate compaction pressure on which the density of compacts highly depends. To evaluate the relationship between the compaction pressure and density of the specimen, the tests were performed at

Fig. 2 Manufacturing conditions

different compaction pressures ranged from 5 to 100 [MPa]. To examine the effect of silica sand content, the mixing ratio of silica sand was varied 0 [wt%], 20 [wt%] and 40 [wt%]. The relation between the compaction pressure and dry density at different silica sand contents is shown in Fig. 2. The dry density is proportional to the logarithm of the compaction pressure and the dry density increases as the sand content increases at a compaction pressure. Based on the result, the compaction pressure to obtain the reference dry density of 2.0 [Mg/m³] turns out to be 65 [MPa] for the reference silica sand content of 20%.

With the specimens obtained in the small scale manufacturing tests, the strength tests were performed to evaluate the mechanical strength of the compacted buffer manufactured by CIP. The applicability of the Weibull statistics to measured strength data and the effects of silica sand content and its particle size on the strength were confirmed⁽⁷⁾.

2.2 Manufacturing test

To evaluate the feasibility to manufacture the full-scale monolithic buffer and to provide specimens for the emplacement tests, large scale manufacturing tests were performed on the scale of 70%. The specified dimensions of the 70% scale monolithic buffer material after machine finishing were as follows: outer diameter 1.16 [m]; height 1.6 [m]; inner diameter 0.6 [m]; inner depth 1.32 [m]; wall thickness 0.28 [m]. The forming molds used for the tests were basically the same as those for small scale tests.

The specimen after the machining is shown in Fig. 3. No visible defect was found in the specimens. The density distribution of the compact was examined using the core-drilling method. Figure 4 shows the locations where the density was measured and obtained results, respectively. The density distributes in the range 1.99 to 2.06 [Mg/m³]. Since the scatter-

Fig. 3 Specimen (70% scale)

Fig. 4 Density distribution of the large-scale test

Fig. 5 Test equipment (Left : 20% scale, Right : 70% scale)

ing of the dry densities is within 3%, the homogeneity of the buffer formed by CIP is confirmed.

3. Vacuum Lifting for Vertical Handling

Theoretically, vacuum lifting force F_t can be obtained as

$$F_t = P_v A \quad (1)$$

where the P_v is vacuum pressure and A is the vacuum area which is the part of the top surface of the handling object faced on the vacuum compartment. When the handling object can be lifted up, $F_t > W$ is satisfied, where W is the weight of the handling object. And to evaluate the reliability of the vacuum lifting system, the theoretical safety factor S_t is defined as

$$S_t = F_t / W \quad (2)$$

The maximum value of the theoretical safety factor for the monolithic buffer reference shown in Fig. 1 is 2.8 when $P_v = 100$ [kPa] (approx. atmospheric pressure) and $A = 2.01$ [m²] (full area of the top).

3.1 Functional tests

Small scale functional tests⁽⁶⁾ with the monolithic buffer specimens (□ 300×400L [mm]) were performed to select the elements for the vacuum lifting system (Fig. 5). Test results are summarized in

Table 2 Results of small scale functional test

	Type	Diameter [mm]	Efficiency%
A	Single lip pad (Rubber)	50	85
B	Single lip pad (Rubber)	125	74
C	Single lip pad (Rubber)	250	49
D	Ring pad (Sponge)	50	75
E	Ring pad (Sponge)	232	99

Table 2. There were five suction cups that were used in the tests. Single lip pad type cups (cups A, B and C) and cup D were commercially available and cup E was originally designed for the tests. In the case of single lip pad type, the efficiency decreased as the diameter of the cup increased. The efficiency of the single lip pad type, obtained as 49 - 85%, was lower than that of the ring type pad, 75 - 99%, which is thought to be due to the deformations of the lip pads caused by vacuum pressure. And in the ring pad type cup, the efficiency of the pad E was higher than that of pad D, because the frame of the cup E held the pad tighter than that of cup D, and the deformation of the pad of cup E was smaller than that of cup D. Therefore, the pad E was selected as the candidate suction cup for the buffer material.

Next, the prototype functional tests⁽⁶⁾ were performed with the monolithic buffer specimens (lower half of 70% scale body, $\square 1.16 \times 0.825\text{L}$ [m]) using the selected pad type to obtain design data for 70% and full-scale systems. Variations of the lifting force and vacuum pressure with time were measured in the tests. The gradual decrease in the vacuum pressure, i.e. increase in the leak rate, was observed during 4 repeated tests, which was thought to be due to the drying of the bentonite specimen by heating or air-conditioning for the test room. The lifting force of 67.4 [kN] was obtained at a vacuum pressure of 75.6 [kPa].

The performance of the 70% scale and full-scale vacuum lifting system designed based on the results of the prototype tests is shown in Table 3. For the system of 70% scale demonstration described below, values of the vacuum pressure and lifting force were the same as those obtained in the prototype tests. For the full scale system, values of the vacuum pressure and lifting force were assumed to be the same as the 70% scale system and the safety factor of 1.9 was expected⁽⁶⁾.

3.2 Demonstration of the vacuum lifting system

Based on the results of functional tests, 70% scale demonstration tests of the emplacement equipment for the vertical emplacement were performed. The

Table 3 Performance of the full-scale vacuum lifting system for a repository

Item	70% scale	Full scale
Vacuum pressure [kPa]	75.6	75.6
Vacuum area [m ²]	0.89	1.83
Efficiency%	98	98
Lifting force [kN]	67.4	137.4
Weight of the monolithic buffer [kN]	26.60	74.21
Safety factor	2.5	1.9

vacuum lifting system worked well and monolithic buffer specimens were successfully emplaced without collision and damage as shown in Fig. 6.

4. Forklift System for Horizontal Handling

Because of the small clearance between monolithic buffer material and disposal tunnel in case of horizontal disposal, it is difficult to support the outside of the buffer material for lifting up. So, forklift system, using the inside of the hole to support the monolithic buffer during the transportation, was selected as the candidate handling method. To evaluate the feasibility of the forklift system, it is important to confirm the soundness of the monolithic buffer material during the transportation, i.e. to confirm the soundness against the vibration during the transportation. Therefore, vibration tests for monolithic buffer material were performed prior to demonstration tests of horizontal emplacement.

4.1 Vibration test

It is necessary to have information about the disposal tunnel such as dimensions, tolerance, gaps and so on, to determine the condition of the vibration tests. However, in Japan, the repository site has not been decided yet and there was no information about the gaps and accuracy of the tunnel. Thus, the conditions of the vibration during the transportation were determined based on the survey of the existing data on the vibration during the transportation such as train, trailer and track and theoretical consideration. Concerning the conditions of the vibration, important items are acceleration, frequency and time. The conditions of the vibration tests were decided from the reference design⁽⁵⁾ of the repository and literature survey as follows:

- Vibration frequency: 3 [Hz]
- Maximum acceleration: 0.9 [G]
- Vibration time: 75 [min]

The frequency was determined from literature survey. The maximum acceleration was determined to test in the severest condition without a bounce of

Fig. 6 Demonstration of vertical emplacement

the buffer. The vibration time was determined considering the transportation time in the disposal tunnel in a repository.

The vibration tests were performed using 20% scale and 70% scale monolithic buffer specimens with the test conditions above. Figure 7 shows the setup of 70% scale tests. On visual inspection after vibration tests, no visible defects caused by the vibration were found for the monolithic buffer specimens in all tests. Because of the non-linear behavior, the maximum measured value of the acceleration was 1.9 [G].

FEM analysis was also performed to evaluate the vibration conditions for the full-scale buffer. As the result of analysis, the value of the maximum principal stress under the 1.9 [G] of load on 70% scale was almost equal to that under the 1.33 [G] of load on full scale (Table 4.), without consideration of the volumetric effects on the material strength.

4.2 Demonstration of the forklift system

The demonstration tests of the buffer emplacement for the horizontal disposal concept on the scale of 70% were performed.

Forklift system worked well and monolithic buffer material was successfully transported without collisions and emplaced without damage (Figs. 8 and 9). Since the test tunnel, simulating a disposal tunnel

in a repository, has no bumps and the tolerance is small, it was not a realistic model for an actual disposal tunnel. Actual tolerance of the disposal tunnel depends on the kind of host rock, method to excavate tunnel and support. So it is necessary to investigate the conditions of the disposal tunnel after the site selection to incorporate them to the design and selection of the method of the positioning, state and traction control for the emplacement equipment.

Table 4 Principal stress of the monolithic buffer (result of the FEM analysis)

Scale%	Acceleration [G]	Maximum value [MPa]	Minimum value [MPa]
70	1.9	0.847	-0.470
100	2.0	1.274	-0.671
100	1.8	1.147	-0.604
100	1.6	1.019	-0.537
100	1.4	0.892	-0.470
100	1.2	0.764	-0.403
100	1.0	0.637	-0.336

Fig. 7 Test equipment for vibration test (70% scale)

Fig. 8 Demonstration equipment for horizontal emplacement

Fig. 9 Demonstration of horizontal emplacement

5. Conclusions

The technology employed in the manufacture of a monolithic buffer material at 70% scale model was evaluated, and the feasibility of using the CIP method to manufacture a cup-shaped, high-density and homogeneous buffer material, with the outer diameter of 1.16 [m], the height of 1.6 [m] and the wall thickness of 0.28 [m], was confirmed. The density scattering of the formed compact was 3% of the targeted value of 2.0 [Mg/m³]. Based on these results, it is judged that the manufacture of the full-scale buffer material can be technically feasible by the CIP method. However, full-scale manufacturing trial tests are indispensable.

The vacuum lifting system for vertical disposal concept and the forklift type system for horizontal disposal system are investigated as candidate methods of the emplacement of the monolithic buffer material. The ring pad type suction cup was selected for the vacuum lifting system for the monolithic bentonite buffer from the results of the functional tests. The vacuum lifting system on the scale of 70% was designed based on the results of the functional tests, and was manufactured to carry out prototype tests to evaluate its performance. The measured result of the lifting force in the prototype tests was 67.4 [kN] at the vacuum pressure of 75.6 [kPa] and efficiency was 98%. From the results of the prototype tests, the performance of full-scale system for a repository was evaluated and the safety factor of the lifting force was evaluated as about 1.9.

The vibration tests using up to 70% monolithic buffer specimens, simulating horizontal emplacement, were performed with the vibration frequency of 3 [Hz], the maximum acceleration of 0.9 [G] and vibration time of 75 [min]. No visible defect caused by the vibration was found in the tests.

Demonstration emplacement tests were performed with the 70% scale monolithic buffer specimens for both the vacuum lifting and forklift type systems. The two systems worked well and the monolithic buffer specimens were successfully transported and emplaced without any damage.

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