Design flow for specifications of bentonite-based buffer from the viewpoint of self-sealing capability using theoretical equations for swelling characteristics

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ABSTRACT

Bentonite-based buffer for high-level radioactive waste (HLW) disposal is expected to fill the interstitial spaces around buffer materials by its swelling deformation. This study performs one-dimensional model tests simulating the relation around the buffer and evaluates the self-sealing capability of the buffer quantitatively. It also investigates the applicability of the theoretical equations for evaluating the swelling characteristics of a bentonite-based buffer, first proposed by Komine and Ogata, to analysis of the self-sealing capability by comparing the calculated and experimentally obtained results. Furthermore, this study has shown the design flow for specifications of bentonite-based buffer from the viewpoint of self-sealing capability.

Keywords: bentonite, swelling, high-level radioactive waste disposal, montmorillonite

1 INTRODUCTION

Bentonite is attracting greater attention as a buffer material for use in repositories of high-level radioactive waste (HLW) in Japan and other countries. Bentonite-based buffers for HLW disposal projects are expected to fill up interstitial spaces between buffer materials and a disposal pit wall, and/or between buffer material and a waste container: a phenomenon designated as overpacking that occurs by swelling deformation of buffer materials. That phenomenon provides an important self-sealing capability. Figure 1 depicts schematic drawings of a candidate HLW disposal facility in Japan, and an image of the self-sealing capability of bentonite-based buffer materials.

As presented in Fig. 1, buffer materials fill up spaces remaining among buffer materials and pit/container walls. Bentonite is anticipated for use as a buffer material because it has a high swelling property. Furthermore, dense bentonites have a higher swelling property. Therefore, the compacted bentonite, of which the dry density is 1.6–2.0 Mg/m³, is effective to fill up interstitial spaces (Japan Nuclear Cycle Development Institute, 2000).

To design specifications of bentonite-based buffer materials from the viewpoint of self-sealing capability, the author has already proposed theoretical equations to model the swelling characteristics of bentonite-based buffer (Komine and Ogata, 2003, 2004). To clarify the applicability of the above theoretical equations, this study investigates the self-sealing capability of bentonite-based buffer materials using the one-dimensional model test of the disposal pit and component materials.

The present study also investigates the validity of the theoretical equations, first proposed by Komine and Ogata (2003, 2004), to evaluate the self-sealing capability of bentonite-based buffer materials by comparing the calculations and the experimentally obtained results.

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2 ONE-DIMENSIONAL MODEL TEST OF DISPOSAL PIT AND COMPONENT MATERIALS

This section presents a description of the one-dimensional model test that simulated an HLW disposal pit presented in Fig. 1 and component materials.

This study used commercial bentonite, which is designated as the old Kunigel-V1 (particle density=2.79 Mg/m³), produced at the Tsukinuno Mine in Japan. The fundamental properties of bentonite are well known as changing according to the year of production because bentonite is a natural resource. This study used bentonite, designated as old Kunigel-V1, which was produced before the year 2000. The values of properties of the old Kunigel-V1 are described in reports of previous studies (Komine and Ogata, 2003, 2004) and are presented in Table 1.

The bentonite designated as old Kunigel-V1 is sodium-type bentonite containing nearly 48% montmorillonite. It has been used frequently in studies of the material for artificial barriers against radioactive waste in Japan. The bentonite was kept at a constant temperature (22 ± 1°C) and at almost constant humidity (70-80%). The water content of this material is 6.12–8.54%. This study also used Mikawa silicate sand (70-80%). The water content of this material is 2.66 Mg/m³ and 0.053–0.590 mm diameter.

This study used compacted specimens, of which the bentonite contents were 80% and 100% according to the specifications of dry density and the ratio of sand and bentonite proposed in Ogata et al. (1999). The bentonite is a natural resource. This study used commercial bentonite, which is designated as the old Kunigel-V1, which was produced before the year 2000. The values of properties of the old Kunigel-V1 are described in reports of previous studies (Komine and Ogata, 2003, 2004) and are presented in Table 1.

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This study used compacted specimens, of which the bentonite contents were 80% and 100% according to the specifications of dry density and the ratio of sand and bentonite proposed in Ogata et al. (1999). The specifications described above were proposed by the Central Research Institute of Electric Power Industry (CRIEPI) and the Federation of Electric Power Companies (FEPC) in Japan. The set points of dry densities of the above specimens were 2.0 Mg/m³ and 1.4 Mg/m³. The specimen diameter and height are, respectively, 60 mm and 10 mm. The compacted specimens were produced using the apparatus, which comprises a cylindrical mold, pistons, and an oil pressure jack. The detailed procedures for producing a compacted specimen were described in previous reports (Komine, 2004).

This study was undertaken to simulate the relations of the space between buffer materials and the disposal pit wall according to as examples of disposal pit specifications as explained by Ogata et al. (1999). The one-dimensional self-sealing capability experiment used for this study can simulate the relations between the bentonite-based buffer and the space in the disposal pit.

The experimental apparatus used in this study is presented in Fig. 2. It simulated a bentonite-based buffer, surrounding rock, and the space between each component.

![Image of self-sealing in the experimental apparatus](image_url)

Table 1. Fundamental properties of the old Kunigel-V1 described in reports of previous studies (Komine and Ogata, 2003, 2004)

| Material                          | Old Kunigel-V1 |
|-----------------------------------|----------------|
| Soil particle density (Mg/m³)     | 2.79           |
| Liquid limit (%)                  | 473.9          |
| Plastic limit (%)                 | 26.61          |
| Plasticity index                  | 447.3          |
| Montmorillonite content, C_m (%)  | 48             |
| CEC (meq./g)                      | 0.732          |
| EXC Na⁺ (meq./g)                  | 0.405          |
| EXC Ca²⁺ (meq./g)                 | 0.287          |
| EXC K⁺ (meq./g)                   | 0.009          |
| EXC Mg²⁺ (meq./g)                 | 0.030          |
minimum scale is 0.001 mm for measuring displacement. From the measurement results, the relation between the buffer pressure after filling up the space and the time required from the start of water supply was then evaluated. The buffer pressure after filling up the space was measured using the load transducer presented in Fig. 2.

After experimental work, the specimen’s water contents were measured. The saturation of the specimen after the experiment was 96–105%.

The space between the specimen and top cap in Fig. 2 was set up according to the space around buffer materials in the disposal pit proposed by CRIEPI and the FEPC (Ogata et al., 1999). The proposition of CRIEPI and the FEPC shows that total space around the buffer was 50 mm, i.e., the space between the buffer and overpack is 10 mm and the space between the buffer and the wall as 40 mm. The buffer thickness was 400 mm in the proposition above. According to the assumption described above, the interstitial space and top cap in Fig. 2 are set up proportionately to the space around the buffer in the disposal pit. Therefore, the space between specimen and top cap in Fig. 2 was set up as 1.25 mm as benchmark value because the specimen height is 10 mm. In all experiment cases, the space was varied: 0.000–3.075 mm at the beginning.

Figure 3 presents a comparison of evaluated results by the theoretical equations with experimentally obtained results of self-sealing capability described in the previous section. Figures 3(a) and 3(b) present the relations between the buffer pressure and the dry density after filling up space. Figures 3(a) and 3(b) show that the theoretical evaluated results concur well with the experimentally obtained results of self-sealing capability.

Comparison of Figs. 3(a) and 3(b) also reveal that the calculated results for bentonite content of 100% show good agreement with the calculated results assumed high concentration of pore water such as 30–40 mol/m³.

From the discussion presented above, the swelling and self-sealing capabilities are strongly dependent on the ion concentration of pore water in bentonite-based buffer materials. Therefore, it is conceivable that the setting of the ion concentration of pore water is important in the design for specifications of theoretical equations for swelling characteristics of bentonite-based buffer materials from the viewpoint of self-sealing capability.

3 DESIGN FLOW OF BENTONITE-BASED BUFFER FROM THE VIEWPOINT OF SELF-SEALING CAPABILITY USING THEORETICAL EQUATIONS FOR SWELLING CHARACTERISTICS

This section presents a description of the design flow of specifications such as dry density, bentonite content, and the dimension of bentonite-based buffer from the viewpoint of self-sealing capability using the theoretical equations proposed by Komine and Ogata (2003, 2004) for swelling characteristics. As described in the Introduction and as shown in Fig. 1, bentonite-based buffer materials will be expected to fill interstitial spaces among buffer materials and a disposal pit wall, and/or between buffer materials and an overpack by swelling deformation of buffer materials. Therefore, the theoretical equations for swelling characteristics will be available as design specifications of buffer materials from the viewpoint of self-sealing capability.

For designing the specifications of buffer, the conditions of the disposal pit shown in the lower right drawings of Fig. 1 are simulated by analytical models and theoretical equations for swelling characteristics proposed by Komine and Ogata (2003, 2004). Presumably, the swelling deformation of bentonite-based buffer materials is equal to the spaces filled up by swelling deformation of buffer materials.
Consequently, the relation of the maximum swelling strain (%) of buffer $\varepsilon_{\text{max}}$ can be calculated by the initial volume of buffer materials and the initial volume of spaces.

In the design of buffer, the following are assumed.

Assumption 1: buffer material pressure is homogeneous after the spaces are filled.

Assumption 2: the one-dimensional model consists of a waste container, buffer materials, the disposal pit wall, and interstitial spaces.

Buffer materials are presumably inhomogeneous when they are manufactured because the thin layered montmorillonite minerals that are arranged in a certain direction during compaction. The direction of montmorillonite minerals, however, will be disturbed during the unrestricted swelling process by which spaces are filled. Therefore, the author adopted assumption 1 presented above, and the analytical model is established as a one-dimensional model.

In calculating for design of bentonite-based buffer from the viewpoint of self-sealing capability, the key point is to consider and calculate the maximum swelling strain (%) of buffer by derivation from the relation between the width of space and the bentonite-based buffer thickness by assuming a one-dimensional model of buffer materials and space.

The required specifications of buffer can be ascertained provided that the buffer pressure after filling up space to create an effective self-sealing capability is configurable. In the design, it is presumed that self-sealing capability is effective when the buffer pressure after filling up space is greater than 1000 kPa. Some earlier research conducted in Canada (Atomic Energy of Canada Limited, 1994) indicates that the required buffer pressure having effective low permeability is greater than 1000 kPa. Therefore, the above condition related to pressure of the buffer for effective self-sealing is assumed.

Consequently, this study proposes the design method shown in Fig. 4 for specifications of bentonite-based buffer from the viewpoint of self-sealing capability using theoretical equations for swelling characteristics described by Komine and Ogata (2003, 2004).

The trial design results have been calculated with some assumptions such as 1000 kPa of the buffer pressure for effective self-sealing capability. At this stage, some assumptions have not been established yet. Therefore, it is necessary to develop the accuracy of the assumption described above. Provided that some assumptions will provide better accuracy, the required specifications of bentonite-based buffer from the viewpoint of effective self-sealing capability are calculable and can be obtained with greater accuracy by following the calculation flow presented in Fig. 4.

4 CONCLUSIONS

This study performed the one-dimensional model tests simulating the relation around the buffer and evaluates the self-sealing capability of the buffer quantitatively. It also investigated the applicability of the theoretical equations for evaluating the swelling characteristics of a bentonite-based buffer, proposed by Komine and Ogata, to analysis of the self-sealing capability by comparing the calculated and experimental results. Consequently, this study showed the design flow for specifications of bentonite-based buffer from the viewpoint of self-sealing capability.

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