〈Technical Note〉

AN ANALYSIS OF THE FACTORS AFFECTING THE HYDRAULIC CONDUCTIVITY AND SWELLING PRESSURE OF KYUNGJU CA-BENTONITE FOR USE AS A CLAY-BASED SEALING MATERIAL FOR A HIGH-LEVEL WASTE REPOSITORY

WON-JIN CHO^{*1}, JAE-OWAN LEE¹, and SANGKI KWON²

¹Korea Atomic Energy Research Institute

P.O. Box 105, Yuseong, Daejeon, 305-600, Korea

²Department of Energy Resources Engineering, Inha University

253 Yonghyun-dong, Nam-gu, Incheon, 402-751, Korea

^{*}Corresponding author. E-mail : wjcho@kaeri.re.kr

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The buffer and backfill are important components of the engineered barrier system in a high-level waste repository, which should be constructed in a hard rock formation at a depth of several hundred meters below the ground surface. The primary function of the buffer and backfill is to seal the underground excavation as a preferred flow path for radionuclide migration from the deposited high-level waste. This study investigates the hydraulic conductivity and swelling pressure of Kyungju Ca-bentonite, which is the candidate material for the buffer and backfill in the Korean reference high-level waste disposal system. The factors that influence the hydraulic conductivity and swelling pressure of the buffer and backfill are analyzed. The factors considered are the dry density, the temperature, the sand content, the salinity and the organic carbon content. The possibility of deterioration in the sealing performance of the buffer and backfill is also assessed.

KEYWORDS : High-level Waste, Repository, Buffer, Backfill, Sealing Performance, Hydraulic Conductivity, Swelling Pressure

1. INTRODUCTION

In Korea, a total of 20 nuclear power plants, 4 CANDU PHWR reactors, and 16 PWR reactors are in operation as of December 2010. The nuclear power plants provide about 34% of the total electricity capacity in Korea. According to the Third Basic Plan for Electricity Supply and Demand [1], eight additional nuclear power plants are planned to be constructed by 2020, and the total number of nuclear power plants will then be 28. The total generation capacity of the nuclear power plants is expected to be 27,320 MW_e, and their share of electricity production will be increased to about 43% in 2020. The promotion of the nuclear energy program will inevitably result in the generation of

a significant amount of spent fuel. By the end of 2009, the accumulated amount of spent fuel in Korea was about 10,761 MTHM (metric ton heavy metal), and it is expected to increase to about 27,000 MTHM by 2030.

To manage this situation, the Korean reference high-level waste disposal system (KRS) has been developed [2]. A candidate site for the high-level waste repository has not yet been identified in Korea, but granite, which is the most common rock type in Korea, is being considered as a potential host rock for the repository. The KRS is expected to be constructed in granitic bedrock at a depth of several hundred meters below the ground surface. The repository, with a room-and-pillar design, will be a network of access tunnels and disposal rooms with vertical shafts extending from the surface to the access tunnels (Fig. 1). The spent fuels will be packed in the disposal canisters each of which will consist of an inner carbon steel vessel and an outer copper shell. The cylindrical canister will be deposited in an array of vertical boreholes with a large diameter drilled on the floors of the emplacement rooms. After the

¹Corresponding author
Korea Atomic Energy Research Institute, P.O. Box 105,
Yuseong, Daejeon, 305-600, Korea
e-mail : wjcho@kaeri.re.kr

Fig. 1. Cutaway View of the Korean Reference High-level Waste Disposal System

emplacement of the container, the gap between the container and the inner wall of the borehole will be filled with buffer material. When all the boreholes in the disposal room are filled, the room will also be filled with backfill material.

The buffer and backfill are major components of the engineered barrier system for the repository and they have three important functions from the viewpoint of radiological safety. The first is the sealing function. The buffer and backfill must control and minimize water flux to eliminate the possibility of advective groundwater flow through the repository i.e., minimize water flow around the waste canister to limit canister corrosion and, consequently, the rate of dissolution of the high-level waste (e.g., the spent fuel). The second is the retention function, which restricts the release rate of radionuclides into the host rock in the event of waste canister failure. The migration of radionuclides through the buffer and backfill should be limited due to the low radionuclide diffusion coefficients in the buffer and backfill. The third is the thermal and mechanical function. The buffer and backfill have to dissipate the decay heat from the waste into the surrounding rock to reduce the thermal stress on the canister and the host rock and any loss of the desirable attributes of the buffer and backfill due to the high temperature. The buffer and backfill also protect the canister from external mechanical stress from the host rock, and they should have good mechanical properties to support the waste canister without any significant deformation due to the weight of the canister and other imposed loads. The required properties of the buffer and backfill material include low hydraulic conductivity, high swelling potential and low swelling pressure, high retention capacity, high thermal conductivity, good mechanical properties and longevity [3-5].

The disposal rooms of the KRS, including the waste emplacement, boreholes and the surrounding rock, will eventually become saturated with groundwater sometime after the closure of the repository. Therefore, the sealing function provided by the buffer and backfill is to limit the flow rate of groundwater through the repository excavation. Because the release of the radionuclides contained in the canister to the surrounding host rock will occur after the buffer and backfill have become saturated, their release rate depends on the selection of the sealing performance values to eliminate the possibility of advective groundwater flow. The sealing function will also have a great influence on the thermal and mechanical behaviors of the buffer and backfill.

In designing the buffer and backfill, the design concept chosen should first satisfy the requirements for the sealing performance. It should then be checked for retention performance. When the sealing and retention performances are satisfied, the thermal and mechanical performance would finally be evaluated. The design procedure for the buffer and backfill is shown in Fig. 2.

The KRS includes the use of compacted bentonite clay-based material for both the buffer surrounding the waste canister and the backfill for the tunnels and access shafts (Fig. 3). Bentonite clay has been considered as the buffer and backfill material because of its low hydraulic conductivity, high sorption capacity, self-sealing characteristics, and durability in nature [5]. If a compacted bentonite with a high density is used, its good sealing properties would minimize the penetration of groundwater to the repository from the surrounding rock. It would also provide containment of radionuclides for a considerable period when the waste canister is breached. The principal mechanism by which radionuclides will migrate through the buffer and backfill will be molecular diffusion, and

Fig. 2. Design Procedure for the Buffer and Backfill

Fig. 3. Cross Section of the Engineered Barrier System in the Korean Reference High-level Waste Disposal System

the radionuclides will be retarded due to their low diffusion coefficients in the compacted bentonite-based materials.

The sealing performance of bentonite-based materials depends on two major properties, hydraulic conductivity and swelling. Hydraulic conductivity should be low to

eliminate advective groundwater flow through the buffer and backfill. The hydraulic conductivity of bentonite decreases with an increasing dry density. If high density bentonite is used for the buffer and backfill, its hydraulic conductivity will be sufficiently low. The swelling

property is closely related to the hydraulic conductivity. If the bentonite is compacted to a high dry density for obtaining a low hydraulic conductivity, its swelling pressure will also be increased. The swelling pressure of the buffer material will add mechanical stress on the waste canister and the surrounding rock, which could result in canister deformation and failure if the stress is excessive. The dry density of bentonite should be optimized to take into account these two density - dependent properties.

As large quantities of bentonite are necessary for backfill material, bentonite-sand mixtures are being considered from the viewpoints of the availability and economy. Using a given bentonite-sand mixture could decrease the swelling pressure, while increasing the hydraulic conductivity and resulting in a deterioration of the sealing performance.

Our intent in this report is to provide a guideline for designing the buffer and backfill for the Korean reference high-level waste disposal system (KRS). We summarize the information on the hydraulic conductivity and the swelling pressure of Kyungju Ca-bentonite, which is a candidate buffer and backfill material for the KRS; analyze the factors affecting the hydraulic conductivity and the swelling pressure; and evaluate the possibility of deterioration in the sealing performance.

2. MATERIALS

Bentonites can be classified into two groups according to the type of exchangeable cations existing in the interlayers of the bentonite particles, that is, Na-bentonite and Ca-bentonite. In Korea, only Ca-bentonite is produced from deposits that are distributed within the tertiary sediments of eastern Kyungsangbukdo Province.

The chemical composition of the Kyungju bentonite is 56.8% SiO₂, 20.0% Al₂O₃, 6.0% F₂O₃, 2.6% CaO, 0.8% MgO, 0.9% K₂O, 1.3% Na₂O, 0.2% FeO, 1.3% SO₃ and 0.8% TiO₂. It has a cation-exchange capacity of 58 meq/100 g, and Ca²⁺ is the predominant exchangeable cation. The Ca-bentonite contains Ca-montmorillonite (70%), feldspar (29%), and small amounts of quartz (~1%). The bentonite was passed through a 200 mesh of ASTM standard sieve. The sand for the bentonite-sand mixtures was obtained from Jawoldo, Kyungkido Province, Korea. The sand consists mainly of quartz, feldspar and muscovite. The detailed physical and mineralogical properties of bentonite and sand were reported by Cho et al. [6].

3. HYDRAULIC CONDUCTIVITY

The hydraulic conductivities of the bentonites with dry densities of 1.0 Mg/m³ to 1.8 Mg/m³ were measured within a temperature range of 20 to 150°C, a sand content range of 0 to 30 dry wt% and a salinity range of 0 to 0.4

M NaCl. Bentonite with water content of 10.7 wt% was uniaxially compacted to the desired density in a stainless steel cylindrical cell that had an inside diameter of 50 mm and a height of 25 mm or 10 mm, depending on the dry density. The water was supplied from the bottom to the top of the chamber at a hydraulic pressure of 882 to 1,960 kPa depending on the dry density of the bentonite. The hydraulic conductivity was determined when equilibrium was reached. The detailed measuring technique is described elsewhere [7,8].

The flow of water through the porous media is described by Darcy's law. Darcy's law assumes that the flow rate through a media is directly proportional to the applied hydraulic gradient, and therefore the flow rate versus the hydraulic gradient relationship is linear. It is now widely accepted that the linearity between the flow rate and the hydraulic gradient is generally valid for saturated clays when the gradients are not small [9-11]. When the hydraulic conductivity is considered for the buffer and backfill, the most critical issue is whether or not the hydraulic conductivity is sufficiently low to result in either diffusion being the principal mechanism of radionuclide release through the buffer backfill. If the hydraulic conductivity is high, the principal mechanism of radionuclide release could be advection rather than diffusion. Gillham and Cherry [12] showed that if the hydraulic conductivity is less than 10⁻⁸ m/s when the hydraulic gradient and porosity are 10⁻² and 0.35, respectively, which are the typical values for deep granitic host rock, the migration of radionuclides would be controlled by diffusion. Therefore, the hydraulic conductivity of the buffer and backfill material should at least be less than 10⁻¹⁰ m/s considering the safety margin. The hydraulic conductivity of an impermeable deep bedrock such as a granite mass is in the order of 10⁻¹⁰ to 10⁻¹² m/s [5,13], and if the hydraulic conductivity of the buffer and backfill is less than these values, the groundwater flowing in the surrounding rock will bypass and not advectively penetrate through the buffer and backfill.

The Peclet number (P_e) [14], which is a non-dimensional number expressed in the following equation, was used as a criterion in the investigation of the mechanism of migration through a compacted bentonite.

$$P_e = \frac{vL}{D_e} \quad (1)$$

where v , L and D_e are the water velocity, the characteristic length and the effective diffusion coefficient, respectively. When the diameter of the bentonite particle ($<7.4 \times 10^{-5}$ m) is selected as the characteristic length and the hydraulic gradient and the effective diffusion coefficient are assumed to be 0.05 and 10⁻¹⁰ m²/s, the Peclet number is much less than 1. Considering conservatively with a safety margin, a hydraulic conductivity lower than 10⁻¹⁰ m/s may be enough to avoid the possibility of radionuclide transport by advection through the buffer and backfill.

In this section, the effects of several factors on the

hydraulic conductivity of the Kyungju Ca-bentonite are analyzed.

3.1 Dry Density

Kyungju Ca-bentonite is densely compacted to form the buffer and backfill material. A number of studies [9,15,16] have reported that the hydraulic conductivity of clay decreases with an increasing dry density. The relation between the logarithm of the hydraulic conductivity and the dry density for Kyungju Ca-bentonite can be fitted to a straight line as shown in Fig. 4 [7]:

$$\log K = -4.07 \rho_d - 6.13 \quad (r^2 = 0.92) \quad (2)$$

where K is the hydraulic conductivity (m/s) and ρ_d is the dry density of bentonite (Mg/m^3). The hydraulic conductivities of the compacted bentonite with a dry density higher than 1.4 Mg/m^3 are lower than 10^{-11} m/s . Therefore, if the bentonite is compacted to a dry density higher than 1.4 Mg/m^3 , its hydraulic conductivity is so low that the transport of radionuclides through the bentonite has to be controlled by diffusion.

3.2 Temperature

After closing the repository, the temperature of the buffer and backfill will increase due to the decay heat from the high-level waste. The increase of the temperature will increase the hydraulic conductivity due to the decrease of viscosity, which can then increase the radionuclide release rate from the repository.

Pusch [17] observed an increase of the hydraulic conductivities of compacted bentonite up to one order of magnitude during heating to 70°C , and Mingarro et al.

[18] reported that the hydraulic conductivities of a high density mixture of bentonite and crushed granite were increased up to about one order of magnitude with an increase of temperature from 20°C to 100°C . Recently, Villar et al. [19,20] also reported that the hydraulic conductivity of water saturated bentonite increases with temperature in the range of 20°C to 80°C . Cho et al. [8,21] reported the hydraulic conductivities of Kyungju Ca-bentonite with dry densities of 1.4 Mg/m^3 , 1.6 Mg/m^3 and 1.8 Mg/m^3 as a function of temperature, and the results are summarized in Figs. 5 to 7. As shown in these

Fig. 5. Hydraulic Conductivity of Compacted Bentonite with a Dry Density of 1.4 Mg/m^3 at Different Temperatures (Demineralized Water, Symbols: Measured Over Six Different Samples) [8,21]

Fig. 4. Hydraulic Conductivity Versus the Dry Density of Compacted Bentonite at 20°C (Demineralized Water) [7]

Fig. 6. Hydraulic Conductivity of Compacted Bentonite with a Dry Density of 1.6 Mg/m^3 at Different Temperatures (Demineralized Water, Symbols: Measured Over Six Different Samples) [8,21]

Fig. 7. Hydraulic Conductivity of Compacted Bentonite with a Dry density of 1.8 Mg/m³ at Different Temperatures (Demineralized Water, Symbols: Measured Over Six Different Samples) [8,21]

figures, the hydraulic conductivities increase with an increasing temperature. The hydraulic conductivities of Kyungju Ca-bentonite with dry densities of 1.4 Mg/m³ to 1.8 Mg/m³ at a temperature of 80°C were up to about three times those at 20°C, and at a temperature of 150°C the hydraulic conductivities were up to about one order of magnitude higher than the hydraulic conductivities at 20°C.

The change of hydraulic conductivities in the Ca-bentonite at elevated temperatures is attributable to changes in the permeability of the bentonite, the viscosity of the and the density of the fluid. These three factors compete with one another. A relationship can be established between the hydraulic conductivity at a given temperature and that at the reference temperature (K'/K), expressed by

$$K'/K = (k'/k) (\mu/\mu') (\gamma_p'/\gamma_p) \quad (3)$$

where $(\frac{k'}{k})$ is the permeability factor, which represents the change of permeability due to an increase of temperature. $(\frac{\mu}{\mu'})$ is the viscosity factor, which represents the increase of hydraulic conductivity due to the decrease of fluid viscosity with an increasing temperature. $(\frac{\gamma_p'}{\gamma_p})$ is the fluid density factor, which indicates the decrease of hydraulic conductivity due to the decrease of fluid density with an increasing temperature. The permeability factors for the Ca-bentonites with dry densities of 1.4 to 1.8 Mg/m³ are nearly unity within the temperature range of 20 to 80°C [8]. Assuming that the permeability factor (k'/k) is unity, and only fluid properties (μ , γ_p) are changed with a changing

Fig. 8. Relative Hydraulic Conductivity (K'/K), Viscosity Factor, and Density Factor as a Function of Temperature

temperature, the hydraulic conductivities at an elevated temperature can be estimated from those at 20°C using Eq. (3). The relative values of hydraulic conductivity, which are plotted in Fig. 8, is the ratios of hydraulic conductivities at an elevated temperature and those at 20°C, K'/K . The change in viscosity and density with the temperature is also shown in the same figure. The change in viscosity is most sensitive to the increase in temperature and contributes greatly to the increase of hydraulic conductivity with an increasing temperature.

Although the hydraulic conductivity increases with temperature, the hydraulic conductivities of the Ca-bentonites with a dry density of 1.6 and 1.8 Mg/m³ are in the order of 10^{-12} m/s even at a temperature of 150°C. Therefore, if the maximum temperature is maintained below 100°C, the hydraulic conductivities of a buffer with a dry density above 1.6 Mg/m³ should be low enough to inhibit radionuclide transport by advection from the waste to the surrounding rock.

3.3 Sand Contents

As the repository needs backfill material in large quantities, a bentonite-sand mixture instead of pure bentonite has been considered from the viewpoint of material availability and economy. The hydraulic conductivities of the bentonite-sand mixture and the clay-crushed rock mixture increase with an increasing sand/crushed rock (aggregate) content [4,16,22,23]. The existence of a threshold inert material content that brings about a sharp increase of hydraulic conductivity has also been reported

Fig. 9. Hydraulic Conductivity Versus Sand Content of the Bentonite-sand Mixture [25]

Fig. 10. Void Ratio For Bentonite Versus Sand Content of the Bentonite-sand Mixture

[24]. The threshold value is not a fixed value and depends on the swelling capacity of the clay and the dry density of the mixture. It is also highly dependent on the particle size distribution of the aggregate, which ultimately forms the soil skeletal structure that resists the compaction forces, and the magnitude of the compaction efforts. The threshold value represents the point where further compaction of the interstitial bentonite-clay fraction is no longer effective due to the compaction resistance of the aggregate structure it comes in contact with. Thus, the dry density of the bentonite-clay fraction between the aggregate particles decreases as the aggregate fraction of the mixture increases for a given compaction effort.

The hydraulic conductivities for the Kyungju Ca-bentonite-sand mixtures with a dry density of 1.8 Mg/m³ are less than 10⁻¹¹ m/s when the sand content is not higher than 70 wt%. However at a sand content of 90 wt%, the hydraulic conductivity increases rapidly up to one order of magnitude higher than 70 wt%. At a dry density of 1.6 Mg/m³, a similar trend was obtained. Therefore, the threshold sand content of the Kyungju Ca-bentonite-sand mixtures with dry densities of 1.6 Mg/m³ and 1.8 Mg/m³ is around 70 wt%. Under the threshold sand content, the logarithm of the hydraulic conductivity increases linearly with an increasing sand content as shown in Fig. 9, and the relations can be expressed as follows [25]:

$$\log K = 0.015 \omega_s - 12.67 \quad (\text{at } \rho_d = 1.6 \text{ Mg/m}^3) \quad r^2 = 0.83 \quad (4)$$

$$\log K = 0.024 \omega_s - 13.53 \quad (\text{at } \rho_d = 1.8 \text{ Mg/m}^3) \quad r^2 = 0.91 \quad (5)$$

where K is the hydraulic conductivity (m/s), ρ_d is the dry density (Mg/m³) and ω_s is the weight percentage of sand. These results indicate that the bentonite-sand mixture has a low hydraulic conductivity if the mixing ratio of bentonite and sand is appropriate. If the sand content is maintained below 70 wt%, the hydraulic conductivities of a Kyungju Ca-bentonite-sand mixture with a dry density above 1.6 Mg/m³ would be low enough to inhibit radionuclide transport by advection from the waste to the surrounding rock.

The presence of the threshold sand content can be explained by the change of voids between sand and bentonite or the bentonite particles. Bentonite in the bentonite-sand mixture hydrates and swells in the presence of water. Saturated bentonite has a high swelling capacity and the swollen bentonite gel completely fills the volume between the sand particles. The sand particles simply act as impervious inclusions. However at high sand: bentonite fractions (i.e., >70 wt%), the porosity of the bentonite fraction can be very high, thus permitting the potential for advective water flow.

The change of the void ratio of bentonite with an increasing sand content in the mixture is shown in Fig. 10. As shown in the figure, for both mixtures with dry densities of 1.6 Mg/m³ and 1.8 Mg/m³, the void ratio of bentonite increases rapidly resulting in a potential for a "fingering" water flow when the sand content is higher than 70%. The hydraulic conductivities of the bentonite-sand mixtures can be explained by the effective clay dry density ρ_e [41] defined as the ratio of the mass of clay in the system and the combined volume of clay plus void. For pure bentonite,

Fig. 11. Hydraulic Conductivity Versus Effective Clay Dry Density of the Bentonite-sand Mixture

ρ_e is equal to ρ_d . The effective clay dry density of the bentonite-sand mixture decreases with an increasing sand content. The logarithm of the hydraulic conductivity of Kyungju Ca-bentonite-sand mixture decreases almost linearly with an increasing effective clay dry density (Fig. 11).

3.4 Salinity

After closing a repository located in a coastal area, the salinity of the groundwater in the host rock is expected to be higher due to seawater intrusion. The salinity of the groundwater in a repository can be high even if it is not located in a coastal area, since deep groundwater is ancient and its origins can be very different from those prevailing in the area at the time of the repository construction. The increase of the salinity might increase the hydraulic conductivity in the buffer and backfill and enhance the water movement through the buffer and backfill. Several researchers [26-28] have reported that a dramatic increase in hydraulic conductivity may occur when a concentrated salt solution is introduced into a clay. Castellanos et al. [29] reported that the hydraulic conductivity of a highly compacted saturated FEBEX bentonite increases when high-salinity permeants are used, especially for low densities. Villar [30] found that the intrinsic permeability of the granite/bentonite mixture is higher when it is permeated with saline water. Dixon et al. [31] investigated the effects of saline water at a relatively low salt concentration on the hydraulic conductivity of compacted bentonite.

The influence of the NaCl concentration on the hydraulic

Fig. 12. Hydraulic Conductivity of Compacted Bentonite at Different Levels of Salinity

conductivity of Kyungju Ca-bentonite is shown in Fig. 12. The samples were prepared with fresh water. The hydraulic conductivity increases with increasing salinity, and the degree of the increase becomes more marked as the bentonite dry density decreases. For bentonites with a density of 1.0 Mg/m³ and 1.2 Mg/m³, the hydraulic conductivities of the 0.4 M NaCl solution which simulates sea water [32] increased by about seven times and three times, respectively, higher than that of freshwater-based samples. However for the Ca-bentonite with a dry density greater than 1.4 Mg/m³, the salinity has an insignificant effect on the hydraulic conductivities, and the hydraulic conductivity is nearly constant within a salinity range of 0 to 0.4 M NaCl.

When saline water intrudes into bentonite, the cation concentration in pore water increases, which causes the diffuse double layer to contract. A reduction in the double layer thickness may result in changes in the net repulsive forces between the sheet of montmorillonite particles, which is the major mineral of bentonite [28,33,34]. The decrease of the net repulsive force in turn decreases the tendency of the sheet to separate. As the sample was prepared with freshwater, it may be in a relatively dispersed particle state. The shrinkage may lead to an alternation of the macro and micro structure of the bentonite. This in turn causes a change in hydraulic conductivity.

The experimental results obtained from this study show that the change in the hydraulic conductivity is not large and that the microstructural change of the Kyungju Ca-bentonite fabric might not occur in a NaCl concentration range of 0 to 0.4 M.

Fig. 13. Dissolution of Organic Carbon in Bentonite Suspension Versus Reaction Time at 20°C [21]

Fig. 14. Dissolution of Organic Carbon in Bentonite Suspension at Different Temperatures [21]

3.5 Organic Carbon

Bentonite generally contains organic matter. When the bentonite comes in contact with the groundwater, the organic carbon dissolves from the bentonite, which results in an increase of the organic carbon content in the groundwater. The organic carbon may affect the hydraulic conductivity of the bentonite through its effects on the fabric and pore space relationships. To test the possibility of an organic carbon effect, the dissolution of organic carbon from the Kyungju Ca-bentonite was measured [21].

As shown in Fig. 13, the aqueous phase carbon in the bentonite suspension is mainly inorganic carbon, even though the carbon in bentonite is mainly organic carbon. The organic matter in clay is either adsorbed on the surface of minerals or is found in the interlayer space of layered silicate [35]. Therefore, the organic carbon contained in clay has limited solubility in water. In contrast, the inorganic carbon, of which the major ingredient is CaCO_3 , is more soluble, although the solubility of CaCO_3 is not high. The effect of temperature on the dissolution of the carbon contained in bentonite is shown in Fig. 14. The aqueous phase organic carbon concentrations increase with a temperature increase from 20 to 80°C. At an elevated temperature, the decomposition rate of organic matter increases [36], and this may result in an increase of the aqueous phase organic carbon concentration. However, the organic carbon concentrations were in the range of only 2 to 18 ppm which is less than the organic carbon concentration of deep groundwater in granite (10 to 50 ppm) [37]. It is, therefore, unlikely that the organic carbon dissolved from the bentonite will have any

significant effect on the hydraulic conductivity of the buffer and backfill.

4. SWELLING PRESSURE

Buffer material should have a high swelling potential to fill the void in deposition holes and the fracture in the surrounding rock, but the swelling pressure should not exceed the pressure limit on the waste canister after it is saturated with groundwater. The criteria for swelling pressure depend on the repository concept and the design strength of the waste canister. The design concepts of the repository and waste canister adopted in each country are different, and, therefore, the criteria for the swelling pressure of the buffer material have not been specified. In Sweden, it is required that the swelling pressure is 980 kPa higher than the hydrostatic pressure of the groundwater in order to seal the fracture and fissure in the near-field rock of the repository [38].

The swelling pressures of the bentonites with dry densities of 1.4 Mg/m^3 , 1.6 Mg/m^3 and 1.8 Mg/m^3 were measured within a temperature range of 20 to 150°C, with a sand content of 0 to 70 wt% and a salinity range of 0 to 0.1 M NaCl. The bentonite was uniaxially compacted to the desired density in a stainless steel cylindrical cell with an inside diameter of 50 mm and a height of 50 mm. Water was supplied into the compacted sample to achieve saturation at a hydraulic pressure of up to 1,960 kPa. The swelling pressures were obtained by subtracting the applied pressure from the measured pressures when the pressure

reached a steady-state value after 30 days. The detailed measuring techniques are described elsewhere [39].

4.1 Dry Density

It has been reported that the swelling pressure of bentonite increases with an increasing dry density of bentonite [13,23,40,41]. When the dry densities were 1.4 to 1.8 Mg/m³, the swelling pressures of Kyungju Ca-bentonite were in the range of 647 kPa to 14,070 kPa and increased with an increasing dry density [39].

For Kyungju Ca-bentonite, the relation between the swelling pressure P_s (kPa) and the dry density of the bentonite ρ_d (Mg/m³) can be expressed as follows (Fig. 15):

$$P_s = 1.514 \times 10^{-1} \exp(\rho_d / 1.586 \times 10^{-1}) + 8.284 \times 10^2 \quad r^2 = 0.98 \quad (5)$$

The volume of bentonite increases because of water adsorbing into the interlayer of montmorillonite. Under confined conditions, the increased volume fills the interparticle voids in the bentonite. The voids are filled up completely and the swelling pressure develops. With an increasing dry density, the interparticle voids of bentonite decrease, which results in the increase of the swelling pressure.

4.2 Temperature

The swelling pressures of Kyungju Ca-bentonite in a range of temperatures of 20°C to 80°C are 1,180 kPa to

1,830 kPa for dry densities of 1.4 Mg/m³ and 4,530 kPa to 5,020 kPa for a dry density of 1.6 Mg/m³ (Fig. 16) [21]. As shown in the figures, the swelling pressures of the bentonite increase with an increasing temperature, but the change is less than a factor of two. These results show that the influence of temperature on swelling pressure is not important if the maximum temperature is maintained at below 80°C.

The dependency of swelling pressure on the temperature can be explained by changes of hydration pressure, osmotic pressure and pore water pressure with an increasing temperature. The hydration pressure decreases rapidly with an increasing temperature because of the reduction of the water molecular layer on the surface of the bentonite [42]. The osmotic pressure increases because of the reduction of the thickness of the electric double layer [42,43], and the pore water pressure also increases because of the differential expansion of the pore water and the skeleton [44,45]. The latter two effects almost exactly counterbalance the former effects.

4.3 Sand Content

A number of studies [13,24,41,46,47] have reported that the swelling pressure of a bentonite-sand mixture decreases with an increasing sand content. There is a threshold sand content for the bentonite-sand mixture that brings about a sharp decrease of swelling pressure. The threshold sand content increases with an increasing dry density of the mixture. It is also highly dependent on the particle size distribution of the aggregate, which ultimately forms the soil skeletal structure and resists the

Fig. 15. Swelling Pressure of the Bentonite as a Function of the Dry Density

Fig. 16. Swelling Pressure of Compacted Bentonite at Different Temperatures

compaction forces and the magnitude of the compaction forces themselves. The montmorillonite clay dry density decreases as the aggregate fraction of the mixture increases for a given compaction force [24].

For Kyungju Ca-bentonite-sand mixtures with dry densities of 1.4 and 1.6 Mg/m³, the change of swelling pressure with an increasing sand content is shown in Fig. 17. As shown in the figure, when the sand content is higher than 30 wt%, the swelling pressure of the bentonite-sand mixture decreases rapidly to about a fifth of that of pure bentonite. The relationships between the swelling pressures of the bentonite-sand mixtures and the sand content can be expressed as follows:

$$P_s = 1.290 \times 10^3 \exp(-w_s/14.922) + 82.243$$

$$r^2 = 0.85 \quad (\text{at } \rho_d = 1.4 \text{ Mg/m}^3) \quad (7)$$

$$P_s = 4.288 \times 10^3 \exp(-w_s/16.241) + 53.145$$

$$r^2 = 0.98 \quad (\text{at } \rho_d = 1.6 \text{ Mg/m}^3) \quad (8)$$

where P_s is the swelling pressures (kPa), w_s is the weight percentage of sand and ρ_d is the dry density (Mg/m³).

The degree of decrease is more remarkable in a mixture with a dry density of 1.4 Mg/m³ as compared to that with a dry density of 1.6 Mg/m³. The montmorillonite swells to provide a uniform clay particle distribution throughout the void volume of the bentonite-sand mixture. The reduction of swelling pressure with an increasing sand content is due to a reduction in the montmorillonite dry density in the

the mixture skeleton structure provided by the much larger sand particles. The swelling pressure of the bentonite-sand mixtures can be expressed using the effective clay dry density in a manner similar to the case of hydraulic conductivity. The swelling pressure of a Kyungju Ca-bentonite-sand mixture increases exponentially with an increasing effective clay dry density (Fig. 18).

4.4 Salinity

To investigate the effects of salinity on the swelling pressure, the swelling pressures of Kyungju bentonite were measured using three permeants, demineralized water, a 0.01 M solution and a 0.1 M NaCl solution [48]. The change of the swelling pressures of Kyungju bentonite with a dry density of 1.4 and 1.6 Mg/m³ at various NaCl concentrations are presented in Fig. 19. The salinity has an influence on the swelling pressure and the swelling pressure decreases with an increasing salinity. The swelling pressure of Kyungju bentonite with a dry density of 1.4 Mg/m³ in the case of 0.1 M decreases to about 50% of that for the demineralized water. However the salinity has an insignificant effect on the swelling pressure with a dry density of 1.6 Mg/m³ within a salinity range of 0 to 0.1 M NaCl.

When saline water intrudes into bentonite, the cation concentration in the pore water increases, and it causes the diffuse double layer to contract. A reduction in the double layer thickness may result in changes in the net repulsive forces between the montmorillonite sheet, which

Fig. 17. Swelling Pressure Versus Sand Content of the Bentonite-sand Mixture

Fig. 18. Swelling Pressure Versus Effective Clay Dry Density of the Bentonite-sand Mixture

Fig. 19. Swelling Pressure of Compacted Bentonite at Different Levels of Salinity

in turn decreases the tendency to separate. The shrinkage may lead to a decrease of the swelling pressure of the bentonite.

5. CONCLUSIONS

The major factors influencing the sealing performance of the engineered barriers in a high-level waste repository were investigated and their effects were evaluated. The sealing properties considered in this study were the hydraulic conductivity and swelling pressure of Ca-Kyungju bentonite, which is a candidate material for the buffer and backfill in the Korean reference high-level waste disposal system.

The hydraulic conductivity of bentonite decreases with an increasing dry density and the relation between the logarithm of the hydraulic conductivity and the bentonite dry density is linear. When the bentonite is compacted to dry densities higher than 1.4 Mg/m^3 , its hydraulic conductivity is so low that the dominant mechanism of radionuclide transport will be the diffusion. The hydraulic conductivity of bentonite increases with temperature, but the hydraulic conductivities of bentonites with dry densities of 1.6 and 1.8 Mg/m^3 are still low even at a temperature of 150°C . The hydraulic conductivities of a bentonite-sand mixture increase with an increasing sand content, and the logarithm of the hydraulic conductivity increases linearly with an increasing sand content. For bentonite with a density higher than 1.4 Mg/m^3 , salinity had an insignificant effect on the hydraulic conductivities in a salinity range of 0 to 0.4 M NaCl . The quantity of organic carbon dissolved from the bentonite is not enough to cause any significant effect on the hydraulic conductivity of bentonite.

The swelling pressure of bentonite increases exponentially with an increasing dry density of bentonite. When the dry densities are 1.4 to 1.8 Mg/m^3 , the swelling pressures of Kyungju bentonite are in a range of 647 kPa to $14,070 \text{ kPa}$. The influence of temperature on the swelling pressure is not important if the maximum temperature is maintained at below 100°C . The swelling pressure of the bentonite-sand mixture with a dry density of 1.4 to 1.8 Mg/m^3 decreases exponentially with an increasing sand content. The salinity has an insignificant effect on the swelling pressure in a salinity range of 0 to 0.1 M NaCl .

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