Journal of the Korean Nuclear Society
Volume 32, Number 5, pp.495~503, October, 2000

Hydraulic Conductivity of Bentonite-Sand Mixture for a Potential Backfill Material for a High-level Radioactive Waste Repository

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(Received March 16, 2000)

Abstract

The hydraulic conductivities in the bentonite-sand mixtures with high density were measured, and the effects of sand content and dry density on the hydraulic conductivity were investigated. The hydraulic conductivities of the bentonite-sand mixtures with a dry density of 1.6 Mg/m^3 and 1.8 Mg/m^3 are less than 10^{-11} m/s when the sand content is not higher than 70 wt%. However at the sand content of 90 wt%, the hydraulic conductivity increases rapidly. At the same dry density, the logarithm of hydraulic conductivity increases linearly with increasing sand content. The hydraulic conductivity of the bentonite-sand mixture can be explained by the concept of effective clay dry density, and using this concept, the hydraulic conductivities for the mixtures with various sand contents and dry densities can be estimated.

Key Words : hydraulic conductivity, bentonite-sand mixture, bentonite, backfill material, high-level waste repository

1. Introduction

A repository for high-level radioactive wastes would be constructed in the bedrock at a depth of several hundred meters below the ground surface. The repository would be expected to be of room-and-pillar design, and the waste containers would be deposited in an array of large-diameter boreholes drilled on the floors of the emplacement rooms. After the emplacement of a container, the gap between the container and the wall of the borehole would be filled with a buffer material, and then the room would also be filled with backfill material. Present design concepts [1,2] of a repository in a granite formation include the use of compacted clay-based materials as a buffer and backfill. The required properties of the buffer and backfill material are low hydraulic conductivity, high radionuclide retardation capacity, high swelling potential and good thermal and mechanical properties [3,4]. Among them, one of the primary requirements is low hydraulic conductivity to eliminate the possibility of advective flow through the buffer, and backfill.

Bentonite has been considered as a candidate buffer material. As the high density bentonite has a low hydraulic conductivity, molecular diffusion will be the principal mechanism by which radionuclides will migrate through the buffer, and the release of radionuclides will be limited due to their low ionic diffusion coefficients. The hydraulic conductivity of compacted bentonite decreases with increasing density, and the temperature elevation would also affect the hydraulic conductivity [5,6]. However, as large quantities of bentonite are required to be used as a backfill material for a high-level waste repository, the bentonite-sand or bentonite-crushed rock mixture instead of pure bentonite has been considered as a backfill material from the viewpoint of the availability of the material and the economy. It is however possible that use of the mixture would increase the hydraulic conductivity resulting in the deterioration of the backfill' s sealing performance. Westsik et al.[7] measured the hydraulic conductivity in a mixture of Na-bentonite and sand, and Villar and Rivas[8] reported the hydraulic conductivities in montmorillonite-sand and saponite-sand mixtures. Yong et al.[3] measured the hydraulic conductivity in the Lake Agassiz clay-crushed granite mixture. These results indicate that the hydraulic conductivity of the mixture depends on the characteristics of the bentonite used and the variation is relatively large. Therefore to evaluate the possible use of a domestic bentonite-sand mixture as a backfill material, the hydraulic properties should be measured. Cho et al.[9] reported the hydraulic conductivity of domestic bentonite-crushed granite mixtures with low density for the backfill of low- and intermediate-level waste repository. However, the hydraulic properties of a domestic bentonite-sand mixture with high density have not been reported. In this paper, the hydraulic conductivities in bentonite-sand mixtures with relatively high densities were measured, and the effects of dry density and sand content on the hydraulic conductivity were evaluated.

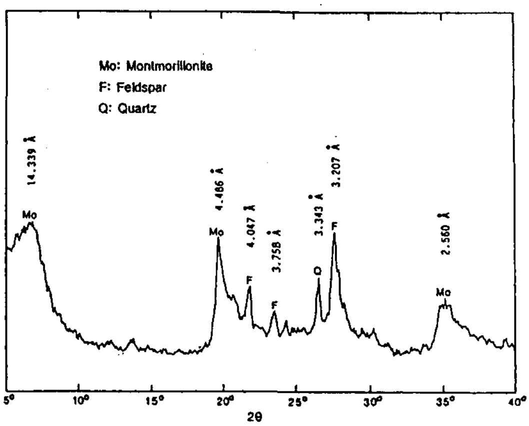

Fig. 1. X-ray Diffraction Patterns of the Kyungju Bentonite

2. Experimental

2.1. Material

The bentonite was a calcium bentonite from Kyungju, Kyungsangbuk-do, Korea. The chemical composition of the bentonite is 56.8 % SiO_2, 20.0 % Al_2O_3, 6.0 % F_2O_3, 2.6 % CaO, 0.8 % MgO, 0.9 % K_2O, 1.3 % Na_2O, 0.2 % FeO, 1.3 % SO_3 and 0.8 % TiO_2. It has a cation-exchange capacity of 58 meq/100 g, and Ca^{2+} is the predominant exchangeable cation (Fig. 1). The bentonite contains montmorillonite (70 %), feldspar (29 %), and small amounts of quartz ($\sim$1 %), and the bentonite was passed through a 200 mesh ASTM standard sieve. The sand was obtained from Jawoldo Kyungki-do, Korea. The sand was washed in water, sieved to remove large particles, and dried. The particle size distribution by ASTM C 136-84 [10] is shown in Fig. 2. The sand consists mainly of quartz, feldspar and muscovite. The detailed physical and mineralogical properties

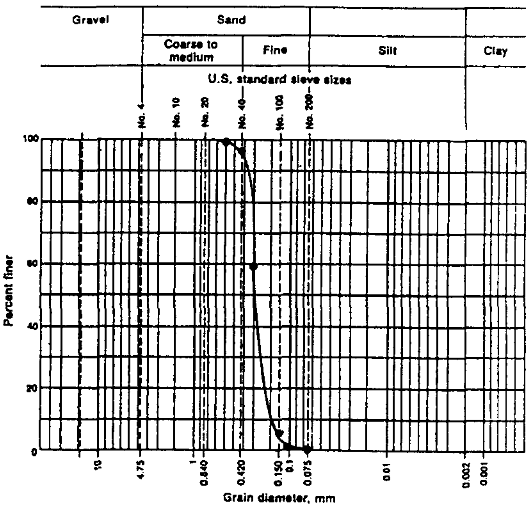

Fig. 2. Particle Size Distribution Curve for Jawoldo Sand

of bentonite and sand were reported by Cho et al. [11].

2.2. Hydraulic Conductivity

The hydraulic conductivities in the bentonite-sand mixtures with dry densities of 1.6 Mg/m^3 and 1.8 Mg/m^3 were measured within a sand content of 0 to 90 wt%, and those in bentonites with a dry density of 1.4 Mg/m^3 were also measured. The mixture was uniaxially compacted to the desired density in a stainless steel cylindrical cell which has an inside diameter of 50 mm and a height of 25 mm or 10 mm depending on the dry density and sand content. The specimen in the cell was rigidly confined in the chamber by using a restraining ram. Demineralized water was supplied from the bottom to the top of the chamber at hydraulic pressure of 9 to 20 kg/cm^2 depending on the dry density and sand content, and the specimen was saturated in the cell (Fig. 3). The water volumes that had penetrated the specimen were measured by weighing. The hydraulic conductivity was determined when equilibrium was reached. All

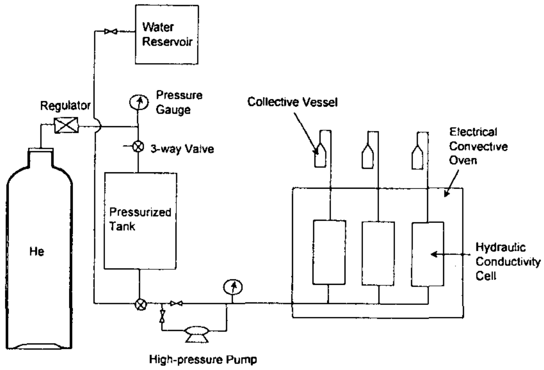

Fig. 3. Schematic Diagram of the Apparatus for Measuring the Hydraulic Conductivity of a Bentonite-Sand Mixture

measurements were done at 20 ℃.

3. Results and Discussion

Darcy' s law assumes that the flow rate through a porous media is directly proportional to the applied hydraulic gradient, and therefore the flow rate versus the hydraulic gradient is linear. The linearity of flow rate versus hydraulic gradient in compacted clay has been reported by many investigators, and it is now widely accepted that the linearity between flow rate and hydraulic gradient is generally valid for saturated clays when the gradients are not small [3, 12, 13]. Cho et al.[5,6] also reported the similar results for the domestic bentonite. Therefore the flow of water through the bentonite-sand mixture is assumed to obey Darcy' s law. The typical water flow characteristics of the bentonite-sand mixtures are presented in Fig. 4 and 5. The hydraulic conductivities were then computed from the slopes of linear relationships, and the results are shown in Fig. 6 and 7.

As observed in Fig. 6, the hydraulic conductivities for the bentonite-sand mixtures with a dry density of 1.8 Mg/m^3 are less than 10^{-11} m/s when the sand content is not higher than 70 wt%.

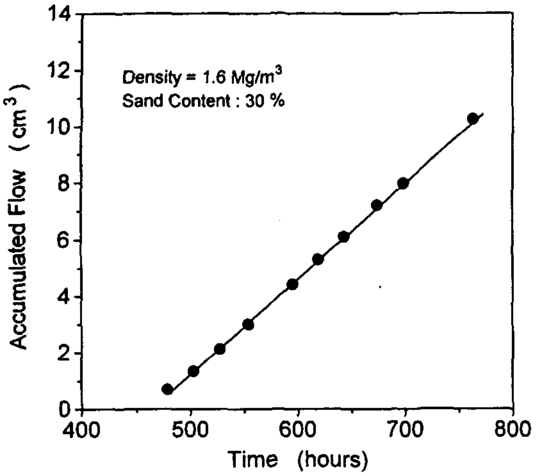

Fig. 4. Typical Flow Rate-Time Relationships at Equilibrium for a Bentonite-Sand Mixture with a Dry Density of 1.6 Mg/m³ and Sand Content of 30 wt%

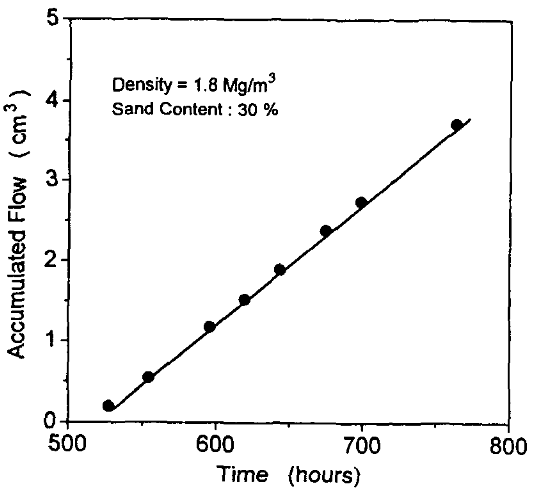

Fig. 5. Typical Flow Rate-Time Relationships at Equilibrium for a Bentonite-Sand Mixture with a Dry Density of 1.8 Mg/m³ and Sand Content of 30 wt%

It is reasoned that the high swelling potential of the bentonite contributes significantly to development of low resultant hydraulic conductivities. However at a sand content of 90 wt%, the hydraulic conductivity increases rapidly

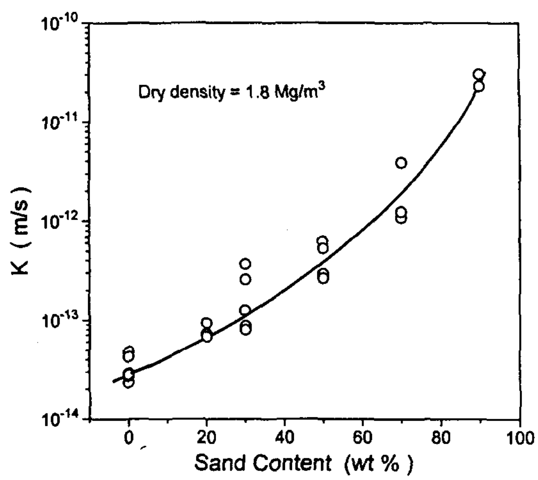

Fig. 6. Hydraulic Conductivity Versus Sand Content of the Bentonite-Sand Mixture with a Dry Density of 1.8 Mg/m³

up to one order higher than 70 wt%. At a dry density of 1.6 Mg/m³, a similar trend was obtained. These results indicate that the bentonite-sand mixture has a low hydraulic conductivity if the mixing ratio of bentonite and sand is appropriate. However, when the sand content is higher than the threshold value, the hydraulic conductivity increases rapidly. This phenomenon can be explained by the change of voids between sand and bentonite or the bentonite particles. The void ratio, e is widely used to describe the degree of the void, and the void ratio of bentonite, e_b is defined as:

$$e_b = V_{void} / V_{bentonite} \tag{1}$$

where V_{void} is the total void volume, and $V_{bentonite}$ is the volume occupied by bentonite in the mixture. The change of void ratio with increasing sand content in the mixture is shown in Fig. 8. As shown in the figure, for both mixtures with dry densities of 1.6 Mg/m³ and 1.8 Mg/m³, the void ratio increases rapidly resulting in the deterioration

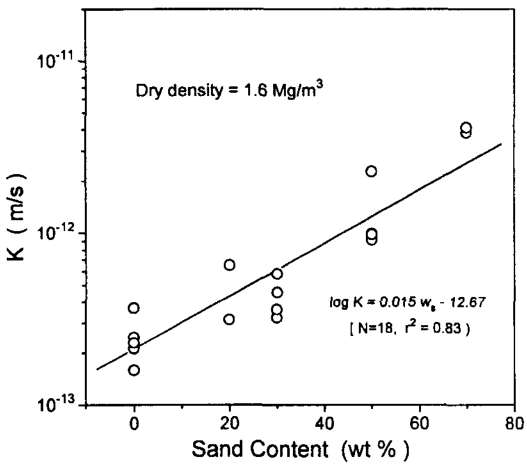

Fig. 7. Hydraulic Conductivity Versus Sand Content of the Bentonite-Sand Mixture with a Dry Density of 1.6 Mg/m^3

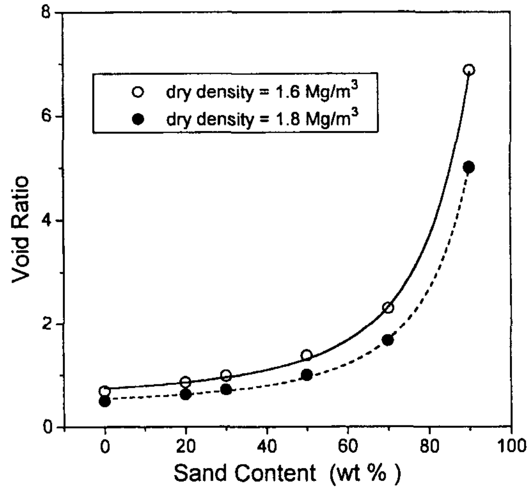

Fig. 8. Void Ratio Versus Sand Content of the Bentonite-sand Mixture

of the continuity of the bentonite matrix when the sand content is higher than 70%. Bentonite in the bentonite-sand mixture hydrates and swells in the presence of water. Saturated bentonite has a high swelling capacity, and completely fills the voids between the sand particles, and the sand particles act simply as impervious inclusions. However, if the void spaces in the mixture exceed the swelling capacity of bentonite, the spaces will not become completely filled with hydrated bentonite, and some will act as a pathway for water flow. For the bentonite-sand mixtures with dry densities of 1.6 Mg/m^3 and 1.8 Mg/m^3, the threshold sand content that brings about a sharp increase of hydraulic conductivity is around 70 wt%. Yong et al.[3], Cho et al.[9], and Westsik et al.[7] have also reported the presence of a threshold inert material content for clay-crushed rock mixture, and the bentonite-sand mixture. However, the threshold value is not a fixed value, and depends on the swelling capacity of bentonite and the dry density. Generally the threshold sand content increases with increasing dry density and swelling capacity.

Gillham and Cherry[14] showed that if the hydraulic conductivity is less than 10^{-8} m/s when the value of the hydraulic gradient and porosity of the host rock are typical of deep granite, contaminant migration would be controlled by diffusion. Therefore, if the sand content is maintained below 70 wt%, the hydraulic conductivities of domestic bentonite-sand mixture with a dry density above 1.6 Mg/m^3 would be low enough to inhibit radionuclide transport by advection from the waste to the surrounding rock. If the hydraulic conductivity data at a sand content above the threshold value are excluded, the logarithm of the hydraulic conductivity increases linearly with increasing sand content as shown in Fig. 7 and Fig. 9, and the relations can be expressed as follows:

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

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

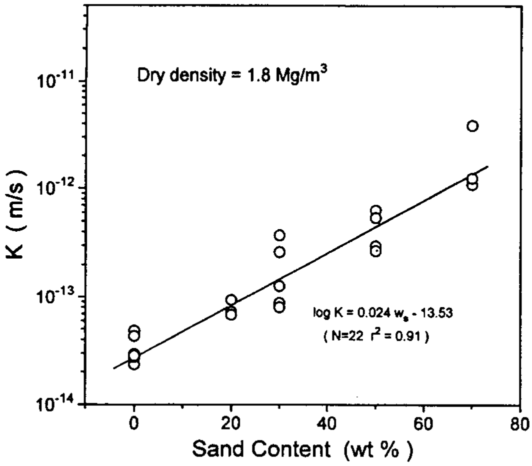

Fig. 9. Hydraulic Conductivity Versus Sand Content of the Bentonite-Sand Mixture with a Dry Density of 1.8 Mg/m³ (excluding the data for a sand content of 90 wt%)

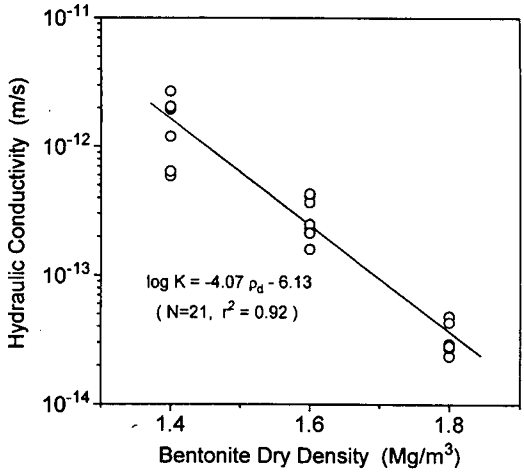

Fig. 10. Hydraulic Conductivity Versus the Dry Density of the Bentonite

$$r^2 = 0.91 \tag{3}$$

where K is the hydraulic conductivity (m/s), ρ_d is the dry density (Mg/m^3) and ω_s is the weight percentage of sand.

The hydraulic conductivities of pure bentonites were found to decrease with the increasing dry density of the bentonite. The relation between the logarithm of the hydraulic conductivity, K (m/s) and the dry density of bentonite, ρ_d (Mg/m^3) can be fitted to a straight line expressed as follows (Fig. 11):

$$\log K = -4.07\,\rho_d - 6.13$$
$$r^2 = 0.92 \tag{4}$$

where r is linear correlation coefficient. The hydraulic conductivities decrease faster with increasing dry density at a higher porosity. The primary particles in a clay mass may be arranged in groups such as aggregates or packets [15], and the total porosity may be distributed among the inter- and intra-group components. Hence, water flows through the larger cluster pores and the smaller inter-cluster pores. The flow channels surrounding the particle groups may be considerably larger than those passing through the groups and between the individual particles. Therefore, because of the contraction of the intercluster pores, the hydraulic conductivity at high porosity diminishes faster with increasing dry density than at low porosity. The hydraulic conductivities versus dry densities for the sand-bentonite mixtures are presented in Fig. 11. As shown in the figure, the hydraulic conductivities decrease with increasing dry density, but are distributed over a wide range depending on the sand content. Although the dry density of the mixture is the same, the void ratio increases with increasing sand content (Fig. 8). Therefore, if an increase of void with an increasing sand content is incorporated properly, the hydraulic conductivities of the bentonites and bentonite-sand mixtures can be described using a single expression. For this purpose, the following assumptions were

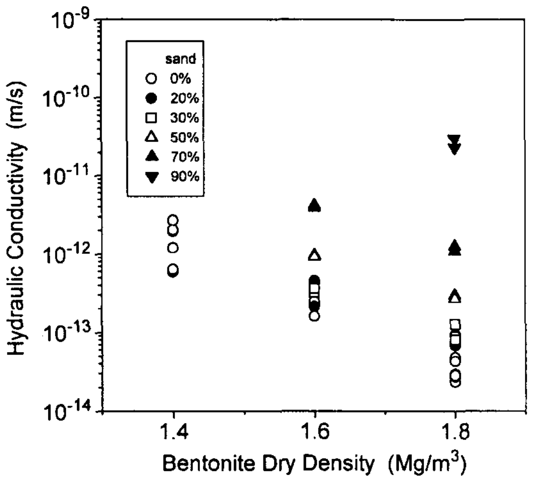

Fig. 11. Hydraulic Conductivity Versus the Dry Density of the Bentonite-Sand

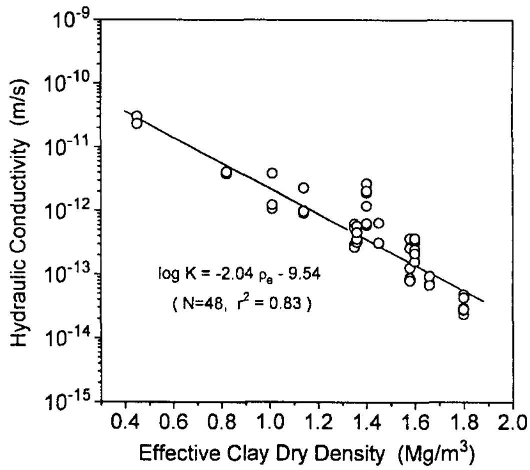

Fig. 12. Hydraulic Conductivity Versus the Effective Clay Dry Density of the Bentonite-Sand Mixture

introduced.

- Bentonite and sand form a homogeneous, two-component mixture.
- The mixture consists of a continuous matrix of bentonite, and the sand particles act simply as impervious inclusions in the matrix.
- The fabric of the bentonite is unaffected by the presence of sand particles.

The hydraulic conductivity can then be explained by the "effective clay dry density" [9,16]. The effective clay dry density of a bentonite-sand mixture ρ_e is defined as

$$\rho_e = \frac{\text{mass of clay in the system}}{\text{combined volume of clay plus void}} \tag{5}$$
$$= [\rho_d (1 - \omega_{sd})] / [1 - \rho_d \omega_{sd} / \rho_s]$$

and for pure bentonite

$$\rho_e = \rho_d \tag{6}$$

where ω_{sd} and ρ_s are the weight fraction of sand and the true density of the sand particle, respectively. For the same dry densities of the mixtures, the effective clay dry density decreases with an increasing inert material content. For pure clay, the logarithm of hydraulic conductivity (log K) decreased almost linearly with an increase in the clay dry density (Fig. 10). If the concept of effective clay dry density is appropriate to explain the hydraulic conductivity of the mixture, log K should decrease almost linearly with increasing effective clay dry density. The relation between the logarithm of the hydraulic conductivity and the effective clay dry density of the bentonite-sand mixture is shown in Fig. 12. The hydraulic conductivity decreases with increasing effective clay dry density, but the correlation coefficient is relatively low. To improve the dependency, a reduction of the cross-sectional area available to water flow due to the addition of sand is also considered. According to Darcy' s law,

$$Q = K A (dh/dl) \tag{7}$$

where Q is the volumetric flow rate, A is the area normal to flow, (dh/dl) is the hydraulic gradient, and K is the hydraulic conductivity. For the

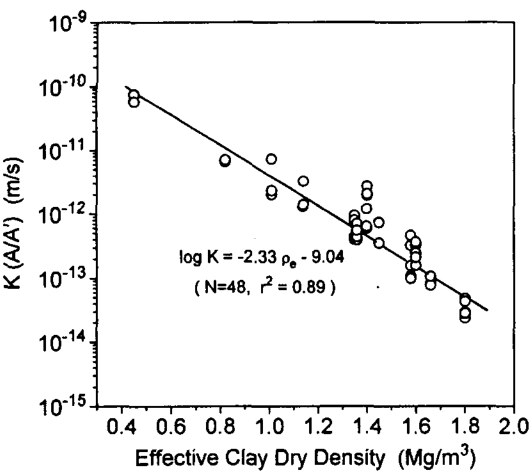

Fig. 13. K(A/A') versus the Effective Clay Dry Density of the Bentonite-Sand Mixture

bentonite-sand mixture, the area available to the flow might be reduced because sand is impermeable, and Eq. (7) becomes

$$Q = K' \ A' \ (dh/dl) \tag{8}$$

where K' is the hydraulic conductivity of the mixture based on the available cross sectional area to flow, A', and A/A' is given as

$$\begin{aligned} A/A' &= \frac{\text{total cross-sectional area of the mixture}}{\text{cross-sectional area through bentonite}} \\ &= 1/[1 - (\text{cross-sectional area of sand / total cross-sectional area})] \\ &= 1/[1 - (\rho_d \omega_{sd} / \rho_s)] \\ &= \rho_e / [\rho_d (1 - \omega_{sd})] \end{aligned} \tag{9}$$

Therefore if the introduction of A' is appropriate, the dependency between log [K(A/A')] and the effective clay dry density should be improved. Also K(A/A') of the mixture should show a similar value as K for pure bentonite with the same effective clay dry density. The relationship between the effective clay dry density and log K(A/A') for the mixture is shown in Fig. 13, and it can be fitted to a straight line expressed as follows:

$$\log K(A/A') = -2.33\rho_e - 9.04 \quad (r^2 = 0.89) \tag{10}$$

The results show that the dependency is stronger than in Fig. 12, and when the effective clay dry densities are the same, K(A/A') for the mixture and pure bentonite gives a similar value except for some data. From these results, the concept of the effective clay dry density is proven to be useful to describe the hydraulic conductivity of a bentonite-sand mixture. Therefore the hydraulic conductivities of the mixtures with various sand contents and dry densities can be estimated using Eq. (2), (3), and (10).

4. Conclusions

The effects of dry density and sand content on the hydraulic conductivity of bentonite-sand mixture were investigated. The hydraulic conductivities for the bentonite-sand mixtures with a dry density of 1.6 Mg/m^3 and 1.8 Mg/m^3 are less than 10^{-11} m/s when the sand content is not higher than 70 wt%. At the same dry density, the logarithm of the hydraulic conductivity increases linearly with increasing sand content. However, at a sand content of 90 wt%, the hydraulic conductivity increases rapidly. The hydraulic conductivity of the bentonite-sand mixture can be explained by the concept of effective clay dry density, and using this concept, the hydraulic conductivities for the mixtures with various sand contents and dry densities can be estimated.

Acknowledgement

This project has been carried out under the Nuclear R&D program by MOST.

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