

HYDRAULIC CONDUCTIVITY OF COMPACTED SOIL-BENTONITE MIXTURE FOR A LINER MATERIAL IN LANDFILL FACILITIES

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Abstract : The hydraulic conductivities of the soil-bentonite mixtures with several densities were measured, and the effects of bentonite content on the hydraulic conductivity of the mixture were investigated. The hydraulic conductivities of the soil-bentonite mixtures with dry densities of 1.4 Mg/m³ and 1.5 Mg/m³ were not significantly decreased with increasing bentonite content up to 20% by weight. However, for the mixtures with a dry density of 1.6 Mg/m³, the hydraulic conductivities decrease rapidly with increasing bentonite content, and were less than 10⁻⁹ m/s when the bentonite content is higher than 10% by weight. The similar trend was obtained for the mixture with a dry density of 1.8 Mg/m³.

Key Words : bentonite content, compaction density, hydraulic conductivity, landfill, liner, soil-bentonite mixture

INTRODUCTION

The quantities of hazardous wastes produced by the industry are increasing along with a growing economy and improved standard of living. As the poorly-disposed wastes would contaminate the surrounding environment, the containment of hazardous waste is certainly one of the most urgent problem facing industrialized country today. The regulations on the performance of barriers in the landfill facilities are therefore recently being strengthened significantly in many countries. The liner is an important barrier to control intrusion of groundwater into the landfill facilities and to prevent the release of leached contaminants to the surrounding environment. The one of primary requirements for liner is low hydraulic

conductivity to eliminate the possibility of advective flow through liner. The EPA regulation requires that the hydraulic conductivity of liner should be below 1×10^{-9} m/sec.¹⁾ In Korea, as a liner in hazardous waste landfill facilities, HDPE (high density polyethylene) sheet or other polymer sheet have been installed, and in the recent design,²⁾ BENTOMAT³⁾ which is a synthetic liner material is added to improve the performance of HDPE liner. However the long-term stability of the synthetic materials is questionable. Although the synthetic liner material is virtually impermeable during early period, there is no long-term field experience as to the performance of synthetic material.⁴⁾ The synthetic liner materials would be degraded and eventually failed with the passage of time after installation of liner in the landfill facilities.

Clays are natural materials and lead to excellent long-term stability in nature. Clays are therefore being considered increasingly as

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barrier materials in the design of disposal facilities for hazardous wastes, and some modern landfills are built using compacted clay liner. The primary function of a clay liner is to prevent the release of contaminants from the landfill into an underlying aquifer, hence the hydraulic conductivity of clay liner should be low to avoid the possibility of advective transport. Bentonite that is a name of natural montmorillonite-rich clays formed by the transformation of volcanic ash has been considered for the liner material because of its low hydraulic conductivity and high toxic cation sorption properties. However, some landfill facilities are located in sites far away from the bentonite producing area, and transportation of large amount of bentonite is required. On the viewpoint of economy, the use of soil-bentonite mixture is being therefore suggested as an attractive design alternative available for constructing an liner for hazardous waste landfill. The hydraulic conductivity of the soil-bentonite mixture depends on the bentonite content and compaction density. This study presents the results of experimental studies to investigate the hydraulic conductivities of soil-bentonite mixtures, and the effects of compaction density and bentonite content on the hydraulic conductivity of the mixture.

EXPERIMENTAL

Materials

The weathered granite soil is used as a major substances of liner material and the bentonite is used as an additive material. The soil was obtained from Changwon, Kyungsan gnam-do where Youngnam hazardous waste landfill facilities is located. The soil contains quartz (63.8%), muscovite (14.3%), chlorite (9.4%), feldspar (8.9%), and hematite (3.6%).

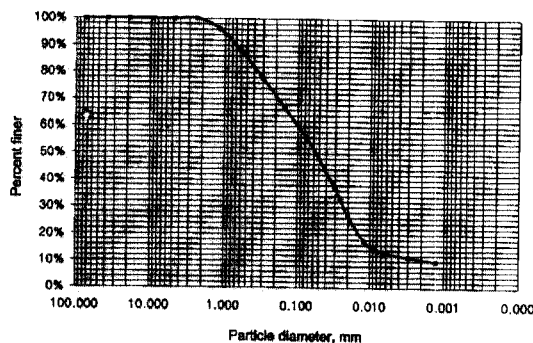


Figure 1. Particle size distribution curve for Changwon soil.

The particle size distribution by ASTM C 136 -84⁵⁾ is shown in Figure 1. The soil is composed of sand (44%) and silt/clay (56%). The uniformity coefficient and coefficient of gradation are 73.1 and 4.7, respectively. The bentonite was a calcium bentonite from Kyungju, Kyungsangbuk-do. The chemical composition of the bentonite is shown in Table 1. It has a cation-exchange capacity of 58 meq/100 g, and Ca^{2+} is the predominant exchangeable cation (Figure 2). 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.

Compaction Test

The compaction tests on the soil-bentonite mixtures were performed by using the standard proctor method (KSF2312, A-1 type). The relationship between the dry density and the moisture content for the soil-bentonite mixtures within a bentonite content of 0 to 20% by weight was measured. The results are summarized in Table 2.

Hydraulic Conductivity

For the hydraulic conductivity of soil, two testing methods, namely the constant head test

Table 1. Chemical composition of the Kyungju bentonite

Chemical constituents	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	FeO	SO ₃	TiO ₂
wt.%	56.8	20.0	6.0	2.6	0.8	0.9	1.3	0.2	1.3	0.8

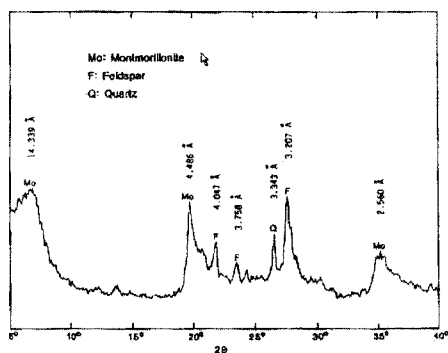


Figure 2. X-ray diffraction patterns of the Kyungju bentonite.

Table 2. Results of compaction tests

	Bentonite content by weight (%)			
	0	5	10	15
Optimum moisture content (%)	28.0	29.5	33.0	33.5
Maximum dry density (mg/m^3)	1.460	1.458	1.361	1.334

and the falling head test are suggested in Korean Industrial Standard (K SF 2322). However these methods are suited to apply to the soils with relatively high hydraulic conductivity, and when hydraulic conductivity is very small, say less than 10^{-7} m/s, the time necessary to perform the test will cause evaporation and equipment leaks to become very significant factors.⁶⁾ Therefore to measure the hydraulic conductivity of compacted clay-based material with very low hydraulic conductivity, the modified constant head test procedure using constant helium gas pressure was used.^{7,8)}

The hydraulic conductivities in the soil-bentonite mixtures with dry densities of 1.4 to $1.8 \text{ mg}/\text{m}^3$ were measured within a bentonite content of 0 to 20% by weight. 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. The specimens were prepared at 2% moist side of optimum water content. The specimen in the cell was rigidly confined in the chamber

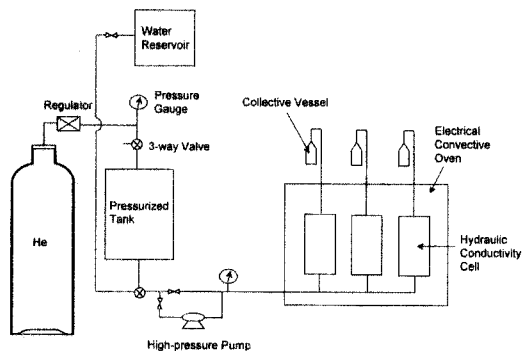


Figure 3. Schematic diagram of the apparatus for measuring the hydraulic conductivity of a soil-bentonite mixture.

by using a restraining ram. Demineralized water was supplied from the bottom to the top of the chamber at hydraulic pressure of 30 to 1,500 kPa depending on the dry density and bentonite content, and the specimen was saturated in the cell (Figure 3). The water volumes that had penetrated the specimen were measured by weighing.

RESULTS AND DISCUSSION

The flow of water through the soil can be described well by Darcy's law. Darcy's law assumes that the flow rate through a porous media is directly proportional to the applied hydraulic gradient. 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.⁷⁻¹⁰⁾ Therefore the flow of water through the soil-bentonite mixture is assumed to obey Darcy's law. The hydraulic conductivities were then computed from the slopes of linear relationships between accumulated flow and time, and the results are shown in Figure 4 to 7. As shown in the Figure 4 and 5, the hydraulic conductivities decrease with increasing bentonite content, but the decreasing patterns depend on the compaction density of the mixture. The degree of decrease becomes

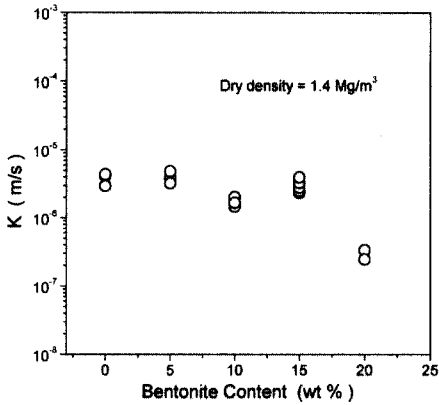


Figure 4. Hydraulic conductivity versus bentonite content of the soil-bentonite mixture with a dry density of 1.4 mg/m³.

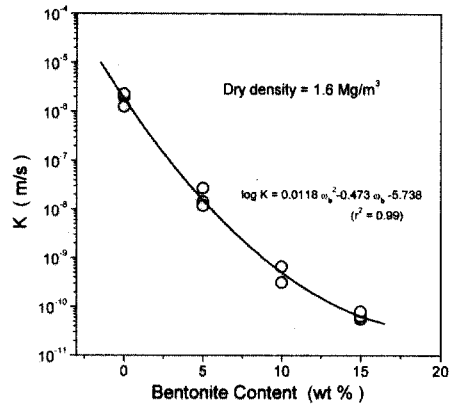


Figure 6. Hydraulic conductivity versus bentonite content of the soil-bentonite mixture with a dry density of 1.6 mg/m³.

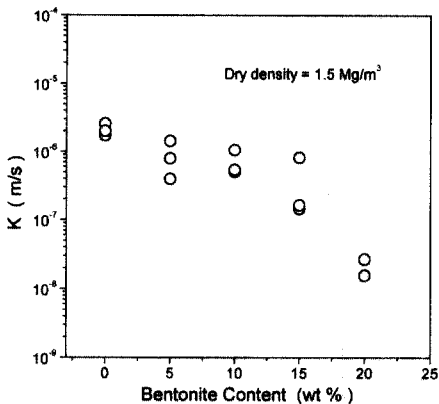


Figure 5. Hydraulic conductivity versus bentonite content of the soil-bentonite mixture with a dry density of 1.5 mg/m³.

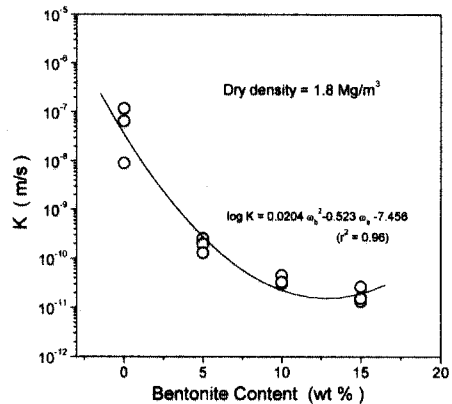


Figure 7. Hydraulic conductivity versus bentonite content of the soil-bentonite mixture with a dry density of 1.8 mg/m³.

more remarkable at a higher compaction density of the mixture. The hydraulic conductivities of the soil-bentonite mixtures with dry densities of 1.4 and 1.5 mg/m³ are not significantly decreased with increasing bentonite content up to 15% by weight, and remain in the ranges of 10⁻⁶~10⁻⁵ m/s and 5×10⁻⁷~5×10⁻⁶ m/s, respectively. At the bentonite content of 20% by weight, the hydraulic conductivity starts to decrease, but still represents considerably higher values compared to EPA regulation.¹⁾ However, as observed in Figure 6,

the hydraulic conductivities of the soil-bentonite mixtures with a dry density of 1.6 mg/m³ decrease rapidly with increasing bentonite content, and are less than 10⁻⁹ m/s when the bentonite content is higher than 10% by weight. However at a bentonite content of 5% by weight, the hydraulic conductivity increases rapidly up to one order higher than 10% by weight. At a dry density of 1.8 mg/m³, a similar trend was obtained. The hydraulic conductivities of the mixture with the bentonite content of 10% by weight decrease to <10⁻¹⁰ m/s. The hydraulic conductivity of soil not containing bentonite is considerably high and

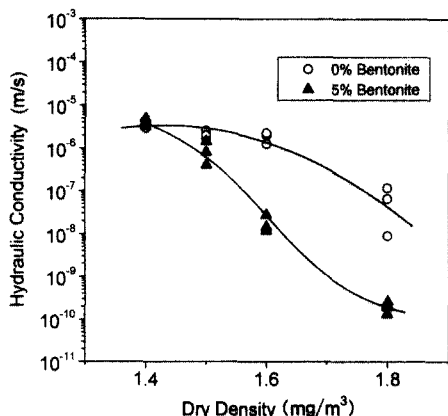


Figure 8. Hydraulic conductivity versus dry density of the soil-bentonite mixture with bentonite content of 0% and 5% by weight.

the degree of decrease is not large even if the compaction density increases from 1.4 to 1.8 mg/m³(Figure 8). For the soil-bentonite mixture, the effects of compaction density become more important as the bentonite content increases. That is, at higher bentonite content, the hydraulic conductivity decreases more sharply with increasing the compaction density (Figure 8, 9).

One of the well-known classical theory to relate the permeability to properties of the porous medium and fluid is the Kozeny-Carman equation.¹¹⁾

$$k = \frac{n^3}{m t^2 S_0^2 (1-n)^2} \tag{1}$$

where k is intrinsic permeability and n is porosity. m , t , and S_0 are the shape factor of conducting pore, tortuosity and specific surface of particle, respectively. The relationship between permeability(k) and hydraulic conductivity(K) is

$$K = k \left(\frac{\gamma_p g}{\mu} \right)$$

where μ is viscosity of fluid, γ_p is density of fluid, and g is gravitational acceleration.¹²⁾

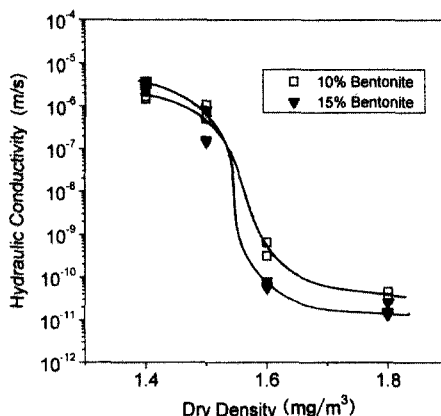


Figure 9. Hydraulic conductivity versus dry density of the soil-bentonite mixture with bentonite content of 10% and 15% by weight.

Therefore the hydraulic conductivity is

$$K \propto \frac{n^3}{(1-n)^2}$$

The hydraulic conductivities versus $n^3/(1-n)^2$ for the mixtures with the bentonite content of 0% and 5% by weight were plotted in Figure 10. As shown in this figure, the linearity between hydraulic conductivity and $n^3/(1-n)^2$ exists for the soil not containing bentonite, but does not exist for the mixture with bentonite content of 5% by weight. The results imply that Kozeny-Carman equation is only valid for non-swelling soil and is not applicable to the soil-bentonite mixture even if the bentonite content is as low as 5% by weight. It is reasoned that the high swelling potential of the bentonite contributes significantly to development of low resultant hydraulic conductivities. For the mixture with densities of 1.6 and 1.8 mg/m³, the logarithm of the hydraulic conductivity decreases with increasing bentonite content, the relations can be expressed as follows:

$$\log K = 0.0118 \omega_b^2 - 0.473 \omega_b - 5.738 \tag{2}$$

(at $\rho_d = 1.6 \text{ mg/m}^3$) $r^2 = 0.99$

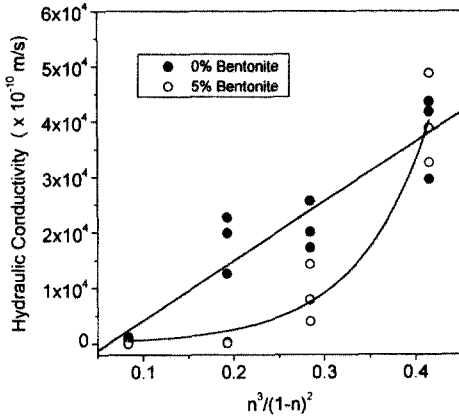


Figure 10. Hydraulic conductivity versus $n^3/(1-n)^2$.

$$\log K = 0.0204 \omega_b^2 - 0.523 \omega_b - 7.456$$

(at $\rho_d = 1.8 \text{ mg/m}^3$) $r^2 = 0.96$ (3)

where K is the hydraulic conductivity (m/s), ρ_d is the dry density (mg/m^3) and ω_b is the weight fraction of bentonite. When the bentonite content is lower than the threshold value, the hydraulic conductivity of soil-bentonite mixture increases rapidly. This phenomenon can be explained by the change of voids between soil and 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:

$$e_b = V_{\text{void}} / V_{\text{bentonite}} \quad (4)$$

where V_{void} is the total void volume, and $V_{\text{bentonite}}$ is the volume occupied by bentonite in the mixture. The change of void ratio of bentonite with increasing bentonite content in the mixture is shown in Figure 11. As shown in the figure, for both mixtures with dry densities of 1.6 and 1.8 mg/m^3 , the void ratio increases rapidly resulting in the deterioration of the continuity of the bentonite matrix when the bentonite content of the mixture is lower than 10% by weight. Bentonite in the soil-bentonite mixture hydrates and swells in the presence of water. Saturated bentonite has a high swelling capacity, and completely fills the voids between the soil particles, and

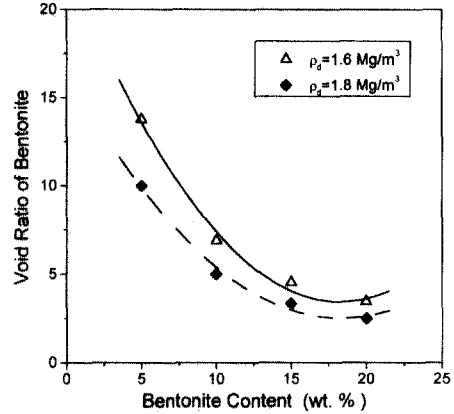


Figure 11. Void ratio versus sand content of the bentonite-sand mixture.

the soil 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 soil-bentonite mixtures with dry densities of 1.6 and 1.8 mg/m^3 , the threshold bentonite content that brings about a sharp increase of hydraulic conductivity is around 10% by weight. Yong et al.,⁷⁾ Cho et al.,¹³⁾ and Westsik et al.¹⁴⁾ 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 of the mixture. Generally the threshold bentonite content decreases with increasing dry density and swelling capacity. These results indicate that if the bentonite content of the mixture is appropriate, the hydraulic conductivity of soil-bentonite mixture with a dry density above 1.6 mg/m^3 would be low enough to inhibit contaminant transport by advection through landfill liner. Sometimes, the in-situ compaction of the mixture with bentonite content above 10% by weight might not be easy because of the sponge effect, and further studies are recommended.

CONCLUSIONS

The effects of dry density and bentonite content on the hydraulic conductivity of soil-bentonite mixture were investigated. The hydraulic conductivities of the soil-bentonite mixtures with dry densities of 1.4 and 1.5 mg/m³ are not significantly decreased with increasing bentonite content up to 20% by weight, and represents considerably higher values compared to EPA requirement. However, the hydraulic conductivities for the soil-bentonite mixtures with a dry density of 1.6 mg/m³ decrease rapidly with increasing bentonite content, and are less than 10⁻⁹ m/s when the bentonite content is higher than 10% by weight. The similar trend was obtained for the mixture with a dry density of 1.8 mg/m³, and the hydraulic conductivities of the mixture with the bentonite content of 10% by weight decreases to <10⁻¹⁰ m/s. Therefore, if the compaction density of the mixture is appropriate, the soil-bentonite mixture has a low hydraulic conductivity enough to inhibit contaminant transport by advection through landfill liner.

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