WATER INTERCEPTION OF LANDFILL COVER SYSTEMS UNDER UNSATURATED CONDITIONS

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ABSTRACT

Soil-water characteristic curves for paper sludge (PS) and construction sludge (CS), applied as landfill barrier materials, are examined to estimate the unsaturated infiltration parameters. A prediction of water interception, based on the unsaturated infiltration characteristics of each type of the compacted sludge constituting the cover systems, is made using the UNSAT-H model. The data obtained from soil-water retention tests are identified by representative fitting models such as the van Genuchten and the Brooks-Corey models. From the soil-water characteristic curves and the fitting parameters, the effects of molding water content of the compacted sludge on the soil-water characteristic curves are clarified. It is found that PS compacted at a higher water content retains water greatly, because α and n (fitting parameters for the van Genuchten model) of PS decrease with an increase in the molding water content of the specimen. In the case of CS, macroscopic pore space forms when the compacted CS has a lower level of molding water content, while the CS at a higher water content can be compacted without the formation of clod structures. Such formation of clod structures contributes to the water retentiveness of CS. The results of an evaluation of the water interception performance of the cover systems, using a sludge barrier, show that the cumulative quantity of percolation water through the cover systems is less than 15 cm, which is approximately 1% of the total rainfall during the three-year analyzing period. Although the occurrence of leakage depends on the molding water content and rainfall condition at each site, over 99% of the rainfall can be intercepted by the installation of a cover system, even under a heavy raining condition such as that at Owase, Kyoto, and Tokyo in Japan.

Key words: Brooks-Corey model, construction sludge, cover system, paper sludge, soil-water characteristic curve, soil-water retention test, unsaturated condition, van Genuchten model, water balance analysis (IGC: D4/H11)

INTRODUCTION

The construction of landfill facilities to contain enormous quantities of waste is an important task for minimizing the adverse impact of leachate generated from waste on the peripheral geo-environment. The final defense against leachate leaking out to the peripheral geo-environment is the construction of bottom liner systems in containment facilities. Cover systems overlying landfilled waste masses minimize the infiltration of rainwater into underlying waste layers and control the emission of landfill gas (Daniel and Koerner, 1995). Thus, cover systems are effective in reducing leachate generation from waste layers. In the United States and most European countries, the installation of bottom liners and cover systems has already been recognized as an effective containment strategy, and a technique to evaluate the effects of water interception has been established (Sharma and

Lewis, 1994). However, there are no clear regulations for cover systems in the field of landfill management in Japan, such as for bottom liner systems. In fact, the concept of landfill management in Japan which is generally limited to the concept of semi-aerobic landfills means having rainwater infiltrate into organic waste layers and promoting aerobic conditions (Hanashima and Furuichi, 2000). Consequently, semi-aerobic landfills promote the biodegradation of organic waste. However, this can not achieve the biodegradation of incinerated ash and in recent years waste transported to landfill sites is mostly processed into incinerated ash. Thus the importance of cover systems as landfill containment facilities should be emphasized even under severe raining conditions in Japan.

Compacted clay has generally been used as barrier in cover systems, because it can maintain low hydraulic conductivity (Koerner and Daniel, 1997). In the United

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Manuscript was received for review on February 8, 2002.

Written discussions on this paper should be submitted before November 1, 2003 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.

States and European countries, tests have been performed by several researchers to construct barrier layers using suitable waste materials with low hydraulic conductivity (e.g., Zimmie and Moo-Young, 1995; Moo-Young and Zimmie, 1996; Benson and Wang, 2000; Quiroz and Zimmie, 2000). In waste management in Japan, social requests to rationally reduce waste to be landfilled, and to reduce landfill site construction costs are critical issues. Kamon et al. (2000, 2001, 2002a, 2002b) and Rajasekaran et al. (2000a, 2000b) have experimentally examined the potential utilization of waste sludge, such as paper sludge (PS) and construction sludge (CS), as a barrier material for cover systems.

In evaluating the water interception of cover systems, it is necessary to estimate the amount of rainfall infiltrating into the cover systems and the quantity percolating from the cover systems to the underlying waste layers. The United States Environmental Protection Agency (US EPA) has distributed some hydrological simulation models such as the Hydrologic Evaluation of Landfill Performance model (HELP model). Most of these models have mainly been used to evaluate the water interception of cover systems based on the saturated hydraulic conductivity of the barrier layers; but the unsaturated behavior of the constituent layers of the cover systems has not been sufficiently considered. The constituent layers of cover systems are generally constructed using cohesive soil with low hydraulic conductivity. It is usually compacted under an unsaturated condition during the construction stage. Thus, the compacted layers exhibit water interception based on the unsaturated infiltration behavior until they reach the saturated condition under specified weather conditions. Consequently, an evaluation of the water interception of cover systems, which can consider both the unsaturated infiltration characteristics of the constituent layers and the weather conditions at each construction site, is more desirable. When cover systems are constructed in Japan, where there is a monsoon climate, it is believed that the impact of rainfall on the cover systems will be much larger than that in the United States and European countries. Furthermore, cover systems installed in Japan will be subjected to intense annual change in weather throughout the four seasons.

Khire et al. (1997) have carried out research on unsaturated water transport in cover systems, and have demonstrated cover systems which can sufficiently exhibit water interception based on the unsaturated infiltration theory for aired regions. However, the effects of the water interception of cover systems in areas with heavy rainfalls, such as Japan, have never been evaluated.

In this paper, the effects of the water interception of cover systems which apply paper sludge (PS) and construction sludge (CS) barriers are predicted using the unsaturated infiltration characteristics of the compacted PS and CS obtained experimentally, and meteorological data on each place in Japan. The soil-water characteristic curves (unsaturated infiltration characteristics) of PS and CS are examined by conducting the proposed soil-water retention tests to estimate the unsaturated infiltration

parameters (e.g., unsaturated hydraulic conductivity). The data obtained from the soil-water retention tests are identified using the representative fitting models (van Genuchten and Brooks-Corey models). The applicability of the fitting models is evaluated, and the relevance of the fitting parameters to the molding water content and the dry density of the compacted sludge is evaluated. Finally, predictions of rainwater interception, based on each unsaturated infiltration characteristic of the cover systems, are performed using the UNSAT-H model which introduces the unsaturated infiltration theory into the water balance analysis (Fayer and Jones, 1990).

BACKGROUND

Soil-Water Characteristic Curve

There is a correlation between the matric potential and the water content of soil under equilibrium conditions, and it can be expressed by plotting water content versus suction, which is known as a soil-water characteristic curve. In soil science, this curve is more commonly referred to as a soil-water retention curve (Leong and Rahardjo, 1997). In this paper, the term soil-water characteristic curve is used. Soil-water characteristic curves clarify the relationship between the gravimetric water content, w , the volumetric water content, θ , or the degree of saturation, S_r , and the matric suction, ϕ . Soil-water characteristic curves are highly controlled by the compositions of the soil particles and the soil pores because the matric suction is an absolute value of the potential energy arising from the curvature of the interface between the pore water and the pore air. In addition, the hysteresis is observed in the typical soil-water characteristic curve as shown in Fig. 1. The relationship between ϕ and θ , obtained by the drying process, is different from the relationship obtained by the wetting process. Generally speaking, the drying process provides a higher volumetric water content than the wetting process at the same level of matric suction. The hysteresis by size between the primary pores and the interconnecting pore throats, is sometimes called the "ink bottle effect". Experimental measurements of the soil-water characteristic curves in the wetting process are essentially difficult to conduct, and usually only the curves in the drying process are measured (Meerdink et al., 1996). Thus, only soil-water characteristic curves for the drying process of the compacted sludge are discussed in this study, without giving consideration to the effects of the hysteresis. The shape of the soil-water characteristic curves depends on the soil type. Soils with a wide range of pore sizes exhibit greater changes in matric suction according to the water content (Tinjum et al., 1997).

As shown in Fig. 1, the air-entry suction, ϕ_a , indicates the smallest suction value necessary to remove water from the water-saturated soil pores. When microscopic soil pores exist within such soil as cohesive soil, ϕ_a provides a larger value. The water content corresponding to the asymptote of the soil-water characteristic curve is called the residual volumetric water content, θ_r , which is the

Fig. 1. Concept of soil-water characteristic curve

amount of water that cannot be removed from the soil. θ_r is the saturated volumetric water content, and this value should be used to indicate the total porosity of the soil. Practically, however, θ_s shows approximately 90% of the total porosity, because entrapped air may remain in the soil pores when they are saturated during the wetting process.

Soil-Water Characteristic Models

Soil-water characteristic curve data, obtained from the soil-water retention tests, provide important unsaturated infiltration properties such as the unsaturated hydraulic conductivity. Therefore, it is necessary to identify the soil-water characteristic curve data according to the fitting models. The representative curve-fitting models are the van Genuchten model and the Brooks-Corey model. These models are usually intended for use with sand, silt, and agricultural soil (Meerndink et al., 1996). Examples of the models being applied to compacted clay are few (Tinjum et al., 1997). An application of the models is performed in this study on the soil-water characteristic curves of the compacted sludge materials.

The van Genuchten model can be expressed as Eq. (1):

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + (\alpha\phi)^n} \right)^m \quad (1)$$

where Se is the effective saturation ratio, α , n , and m are the fitting parameters, and m is frequently set at $1-n^{-1}$. The Brooks-Corey model is described by Eqs. (2a) and (2b):

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\phi_a}{\phi} \right)^\lambda \quad \phi \geq \phi_a \quad (2a)$$

$$Se = 1, \theta = \theta_s \quad \phi < \phi_a \quad (2b)$$

where λ is a fitting parameter that is called the pore-size-distribution index, which is a function of the distribution of pores in the soil. The fitting parameters define the shape of the soil-water characteristic curves for both models. Soils with steeper soil-water characteristic curves

are characterized by smaller λ or n . A higher level of air-entry suction is characterized by the greater ϕ_a seen in Eq. (2) or the smaller α seen in Eq. (1).

Estimation of Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity indicates the resistance during water migration through unsaturated soil. Hence, the unsaturated hydraulic conductivity depends on the viscosity of the water, the soil-pore structure, and the water content of the soil. The unsaturated hydraulic conductivity is generally expressed as a function of the water content of the soil, and it significantly decreases from an approximately saturated condition to the air-dried state. In addition, the unsaturated hydraulic conductivity can also be displayed as a function of the matric potential, because the volumetric water content can be functionally determined from the matric potential, as shown in the soil-water characteristic models. The function of the unsaturated hydraulic conductivity is frequently estimated using semi-empirical models, most of which are based on the saturated hydraulic conductivity, k_s , and the fitting parameters which describe the shape of the soil-water characteristic curves. van Genuchten (1980) indicated that the relative hydraulic conductivity function, $Kr = K_\phi/k_s$, can be estimated using the relationship between the matric potential and the unsaturated hydraulic conductivity proposed theoretically by Mualem (1978), if the soil-water characteristic curves can be identified by the van Genuchten model expressed by Eq. (1). This van Genuchten-Mualem model, which estimates the unsaturated hydraulic conductivity function from the fitting parameters, is shown in the following Eq. (3) (Meerndink et al., 1996):

$$Kr(\phi) = \frac{\{1 - (\alpha\phi)^{n-1} [1 + (\alpha\phi)^n]^{-m}\}^2}{[1 + (\alpha\phi)^n]^{m/2}} \quad (3)$$

Brooks and Corey have also suggested that the relative hydraulic conductivity function could be empirically estimated by Eq. (4) (Corey, 1994):

$$Kr(\phi) = \left(\frac{\phi_a}{\phi} \right) \quad \phi > \phi_a \quad (4a)$$

$$Kr(\phi) = 1 \quad \phi \leq \phi_a \quad (4b)$$

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

Kamon et al. (2000, 2001, 2002a, 2002b) and Rajasekaran et al. (2000a, 2000b) have been verifying the feasibility of paper sludge (PS), generated from the dehydration process of paper factory effluent treatment facilities using a belt press, and construction sludge (CS), generated from shield tunnel construction sites, as the barrier materials through laboratory experiments. The sludge materials used in this study are the same as those reported previously. The PS abundantly contains organic substances due to the origin of its production, and it maintains plasticity even when the water content is high at

Table 1. Basic properties of PS and CS used in the experiments (summarized from Kamon et al., 2000, 2001, 2002a, 2002b; Rajasekaran et al., 2000a, 2000b)

	PS	CS
Natural water content (%)	132.5	337.5
Particle density (g/cm ³)	1.79	2.68
Liquid limit (%)	330.0	46.5
Plastic limit (%)	111.5	28.0
Optimum water content (%)	74.0	18.2
Maximum dry density (g/cm ³)	1.637	0.553
Minimum saturated hydraulic conductivity, k_s (cm/s), and compaction water content (%)	3.5×10^{-7}	1.2×10^{-8} ,
Coefficient of consolidation*, C_v (cm ² /s)	133.6	26.7
Compression index*, C_c	1.87×10^{-3}	1.03×10^{-3}
Cohesion*, c' (kPa)	1.22	0.43
Internal friction* ϕ' (degrees)	3.9	3.6
Unconfined compressive strength* (kPa)	40.5	34.1
	65	100
Grain size distribution (%)		
gravel fraction (<2 mm)	—	0
sand fraction (0.075–2 mm)	—	32.5
silt fraction (0.005–0.075 mm)	—	53.3
clay fraction (<0.005 mm)	—	14.2
pH in sludge	7.57	7.34
Ignition loss (%)	63.7	6.2
Exchangeable cations (meq/100 g)		
Ca ²⁺	14.63	27.03
Na ⁺	12.80	5.89
K ⁺	0.89	6.61
Mg ²⁺	0.06	4.93
	0.88	9.60

*Sludge with the molding water content obtaining the minimum saturated hydraulic conductivity is compacted so that the dry density may agree with the one of standard compaction curve.

330.0%. Low saturated hydraulic conductivity in the order of 10^{-7} cm/s can be maintained. The CS with a high natural water content (337.2%) can ensure a sufficiently low saturated hydraulic conductivity, when used as barrier material, by dehydrating up to the liquid limit (about 40%) through natural desiccation. The basic properties of these sludge materials are shown in Table 1. The physico-chemical properties of these sludge materials and their applicability to barriers have been reported in detail by Kamon et al. (2000, 2001, 2002a, 2002b), and Rajasekaran et al. (2000a, 2000b).

Soil-Water Retention Test

Two different methods, referred to as Procedure-A and Procedure-B, were applied for conducting soil-water retention tests. Both methods are categorized as pressure-plate methods, which are considered to be the most suitable for clayey soils. A schematic diagram of the soil-water retention test equipment used for the Procedure-A is shown in Fig. 2. The equipment was originally developed by Tinjum et al. (1997), and realizes perfect contact by two o-rings between the ceramic disk and the suction ring to maintain the hydraulic contact between the ceramic disk and the soil specimen. The equipment has been modified for use inside the triaxial compression test apparatus in this study. The suction ring has a diameter of 4 cm and a height of 2 cm. Procedure-A was conducted as follows. (1) The PS and CS with different levels of molding

Fig. 2. Schematic diagram of equipment for the soil-water retention tests (Procedure-A)

water content were compacted directly in the suction rings, respectively, to achieve the same compaction conditions as their compaction curves obtained from the test method for soil compaction using a rammer (JGS 0711) at each molding water content. (2) Compaction using a wooden hammer with a weight of 0.12 kg, was carried out so that the divided three layers have equal density with each other. (3) Porous stones were placed at the top

Fig. 3. Soil-water characteristic curves for compacted (a) PS and (b) CS

and the bottom of the specimen in the suction ring, and the degree of saturation of the specimen was increased by a vacuum. (4) The mass of the specimen plus the suction ring was periodically measured until there were no more increases in the mass; then, the saturation step was terminated (the degree of saturation can be determined by the final mass of the specimen). (5) The two porous stones were removed, a ceramic disk with an air-entry pressure of 1500 kPa was placed on the bottom of the specimen, and the suction ring was fixed with bolts in the pressure chamber. (6) Various levels of pressure were applied in steps to the pressure chamber. (7) The water expelled from the soil specimen through the ceramic disk was collected in a graduated cylinder. The graduated cylinder was placed on an electric balance with a sensitivity of 0.01 g to periodically measure the mass of the expelled water. Each pressure level was maintained until there were no more increases in mass of the expelled water (thus, the degree of saturation for each pressure can be calculated using the mass of expelled water). (8) After the final pressure level, the total mass of the soil specimen was directly measured. In addition, the mass of the oven-dried specimen was measured to obtain the final water content, which can be checked with the amount of expelled water.

For Procedure-B, four to five compacted and saturated specimens with suction rings were placed on a ceramic disk with an air-entry pressure of 1500 kPa in a suction chamber. Various levels of pressure were applied until an equilibrium for the expelled water was achieved. For each pressure level, one specimen was removed to directly measure the water content. Thus, the same number of specimens is required as the number of pressure stages. Another difference of Procedure-B from Procedure-A is that the suction ring is not fixed on the ceramic disk and perfect contact between the soil specimen and the ceramic disk is not necessarily assumed. However, one advantage of Procedure-B is that as many as twelve specimens under specified pressure levels can be measured simultaneously.

SOIL-WATER CHARACTERISTIC CURVES FOR COMPACTED SLUDGE

Results of Soil-Water Retention Test

Soil-water retention tests using the above-mentioned pressure plate methods (Procedures-A and -B) were carried out on paper sludge (PS) and construction sludge (CS) with several levels of initial water content. Both materials were compacted in the suction ring to achieve the same conditions of water content and dry density as those in the standard compaction curves. Figure 3 shows the soil-water characteristic curves for the compacted PS and CS obtained by the soil-water retention tests, in comparing with that for Toyoura sand from studies of Committee on Permeability Assessment of Unsaturated Ground (1997). The degree of saturation for each specimen tends to decrease gradually with an increase in the matric suction. The data for each initial water content from Procedure-A provide smoother curves for the degree of saturation and the matric suction than from Procedure-B. This is because, Procedure-A requires one specimen with an initial water content for continuously obtaining the data of the degree of saturation and the matric suction. However, only one plot for the degree of saturation and the matric suction is obtained from one specimen in Procedure-B. It is difficult to provide exactly the same conditions for each specimen. However, there is no great difference between Procedure-A and -B in regard to trends of the data obtained.

For all of the compacted PS specimens, an asymptotic tendency is observed at matric suction levels higher than 200 kPa. Thus, the residual volumetric water content can be obtained using the fitting equations. In addition, the residual volumetric water content and the matric suction which provides the residual volumetric water content for the compacted PS is larger than that for typical sandy soil such as the Toyoura sand. This fact is thought to demonstrate that the pore water in the organic substances contained in the PS can be retained even at a high level of matric suction. Consequently, most of the water existing in the pores of the organic substances of PS can be re-

garded as strongly retained adsorption water. Unlike the compacted PS, the asymptotic tendency is not observed for a high range of matric suction, and the residual volumetric water content cannot be obtained from this experiment for the compacted CS.

The shape of the obtained soil-water characteristic curves is considered to depend on the pore properties of the materials. The compacted PS contains a large amount of water, and the water retained in the compacted PS exists in inter-particle pores or in pores of the organic substances. Pores in organic substances are generally very small, and the pore water in organic substances exhibits higher viscosity than inter-particle pore water (Adams, 1963; De Jong, 1968; Fredlund and Rahardjo, 1993). Thus, the effect of pore water in organic substances on the soil-water characteristic curves should be considered, especially in the case of the compacted PS. In contrast, the soil-pore structures in the compacted CS specimen are categorized into pores formed in the inter-particles and those formed in the intra-particles, such as those in organic substances. As the CS particles are practically aggregated during water adjustment and compaction, the CS particles form clod structures, and the soil pores of the compacted CS exist in inter-clods or intra-clods. This is discussed in detail in a later section using the fitting equations.

Fitting for Soil-Water Characteristic Curves

The fitting for the data on the soil-water characteristic curves obtained from the experiments is conducted using the van Genuchten model (Eq. (1)) and the Brooks-Corey model (Eq. (2)). The inverse analysis, which is an indirect method recommended by Daniel and Wood (1971), is applied as a fitting technique (Hollenbeck et al., 2000; Miller et al., 2000). The technique calculates parameter vector b , which minimizes the residual sum of squares $O(b)$, defined in Eq. (5). Thus, the non-linear least-squares method is applied for Eq. (5) as the objective function:

$$O(b) = \sum_{i=1}^N \{w_i [\theta_i - \theta_{ci}(b)]\}^2 \quad (5)$$

where N is the number of data points, θ_i is the observed water content, $\theta_{ci}(b)$ is the fitted water content, and w_i refers to the weighting coefficients. An equivalent error is assumed for each measured value, and weighting coefficient w_i is assumed to be 1. For soils which have too high a level of matric suction to be measured by the residual volumetric water content, Tinjum et al. (1997) recommended that the residual volumetric water content θ_r should be assumed to be 0 to improve the fitting accuracy. In the present study, this assumption is applied to the curve fitting for the compacted CS, because the soil-water characteristic data of the compacted CS for matric suction levels higher than 1500 kPa cannot be obtained.

Typical fitting results are shown in Fig. 4, and the obtained parameters are summarized in Table 2. The data fitted by the van Genuchten model can exhibit a slightly better correlation than the data fitted by the Brooks-Corey model, which is indicated by the r -square, r^2 , in Table 2. The equation form of the van Genuchten model, as shown in Eq. (1), gives more flexibility than that of the

Fig. 4. Representative examples of the fitting results for compacted PS and CS

Table 2. Fitting results of applying the van Genuchten and the Brooks-Corey models

Soil	w (%)	ρ_d (g/cm ³)	k_s^* (cm/s)	θ_s (cm ³ /cm ³)	van Genuchten model				Brooks-Corey model				Test procedure
					θ_f (cm ³ /cm ³)	n (—)	α (kPa ⁻¹)	r^2 (—)	θ_f (cm ³ /cm ³)	λ (—)	ϕ_a (kPa)	r^2 (—)	
PS	52.3	0.530	7.8×10^{-7}	0.727	0.323	1.610	0.130	0.998	0.310	0.480	0.512	0.998	A
PS	75.7	0.599	9.0×10^{-7}	0.673	0.353	1.409	0.103	0.998	0.305	0.022	5.274	0.994	A
PS	133.6	0.526	3.5×10^{-7}	0.732	0.476	1.378	0.115	0.990	0.432	0.231	4.558	0.984	A
PS	135.0	0.522	3.5×10^{-7}	0.711	0.459	1.394	0.111	0.964	0.452	0.347	6.963	0.968	B
PS	175.4	0.501	3.8×10^{-7}	0.785	0.570	1.350	0.058	0.092	0.359	0.096	6.143	0.978	A
CS	12.3	1.361	6.5×10^{-8}	0.492	0.000	1.172	0.021	0.859	0.000	0.116	13.770	0.792	B
CS	20.8	1.577	1.6×10^{-8}	0.423	0.000	1.107	0.036	0.976	0.000	0.088	14.026	0.964	B
CS	21.5	1.568	1.6×10^{-8}	0.417	0.000	1.097	0.019	0.972	0.000	0.074	22.332	0.918	A
CS	26.7	1.506	1.2×10^{-8}	0.439	0.000	1.097	0.029	0.966	0.000	0.075	14.106	0.933	B
CS	32.2	1.391	4.0×10^{-8}	0.479	0.000	1.093	0.013	0.937	0.000	0.069	31.935	0.887	B
CS	37.1	1.317	6.0×10^{-8}	0.507	0.000	1.057	0.042	0.964	0.000	0.047	13.037	0.943	B

*Saturated hydraulic conductivity, k_s , obtained by flexible-wall hydraulic conductivity tests.

Fig. 5. Relationship between van Genuchten and Brooks-Corey parameters represented by (a) α versus ϕ_a and (b) n versus λ

Fig. 6. Water content in compaction versus van Genuchten parameters for compacted (a) PS and (b) CS

Brooks-Corey model, as shown in Eq. (2). The correspondence between the van Genuchten and the Brooks-Corey fitting parameters is shown in Fig. 5. Parameter α by the van Genuchten model and ϕ_a by the Brooks-Corey model are related to the level of air-entry suction. Parameters n and λ , which are obtained by the van Genuchten and the Brooks-Corey models, respectively, reflect the degree of steeper slope of curve for the degree of saturation and the matric suction. The parameter α generally decreases with an increase in the ϕ_a for both types of the compacted sludge. This inverse relationship is more apparent in the case of the compacted CS than in the case of the compacted PS (see Fig. 5(a)). The comparatively low correlation between α and ϕ_a for the compacted PS is probably because the lowest level of matric suction applied in the experiment is still higher than the true value of air-entry suction of the compacted PS. The lowest level of matric suction, 10 kPa, is applied in this experiment. In contrast, the correlation between n and λ for the compacted CS is stronger than that for the compacted PS, as shown in Fig. 5(b). This means that the slope of the soil-water characteristic curves using n and λ is better determined for the compacted CS than for the compacted PS. This is because the compacted CS has a higher level of air-entry suction compared with the lowest

level of suction applied in these experiments (10 kPa), unlike the compacted PS. As a result, a high accuracy in the estimation of ϕ_a and α is obtained.

Since the van Genuchten model provides fitting with a higher accuracy than the Brooks-Corey model, which is clear in the r-square, r^2 , in Table 2, a later section discusses using the parameters regulated in the van Genuchten model.

Effects of Molding Water Content and Dry Density on the Soil-Water Characteristic Curves

The compacted PS and CS exhibit different shapes of soil-water characteristic curves according to their levels of molding water content, respectively, as shown in Fig. 3. The relationship between the molding water content and the van Genuchten parameters such as α and n for the compacted PS and CS is shown in Fig. 6. Both α and n for the compacted PS decrease with an increase in the molding water content, as shown in Fig. 6(a). A decrease in α indicates an increase in the air-entry suction, and a decrease in n reflects the steeper slope of soil-water characteristic curve. Thus, the compacted PS at a higher molding water content retains more soil-water. The pore formations of the compacted PS are divided into inter-particle pores and pores in the organic sub-

Fig. 7. Dry density in compaction versus van Genuchten parameter n for compacted (a) PS and (b) CS

stances. In the compacted PS with a higher molding water content, the microscopic pores of the organic substances may possess a larger amount of water than the inter-particle pores. The PS compacted at a higher molding water content indicates a higher level of air-entry suction and water retentiveness than the PS compacted at a lower molding water content even at a higher level of suction.

Although the parameters n and α of the compacted CS decrease with an increase in the molding water content (see Fig. 6(b)), and this tendency is the same as that for the compacted PS, the state of the soil-water in the pores is considered to not be the same as that for the compacted PS. The molding water content of CS affects the shapes of their soil-water characteristic curves because it affects the micro- and macro-scopic pore formations of the compacted CS. The CS prepared at a low water content contains clods of soil particles developing during the soil-water processing, and these clods are maintained during the compaction effort of CS. Such phenomenon is observed through the experiment. Thus, macroscopic pores as well as microscopic pores are formed in the inter-clods of the compacted CS with a low water content. In contrast, the CS with a high water content can be compacted without the formation of macroscopic pores in it, and only microscopic pores exist in the compacted CS. Benson and Daniel (1990) discussed the influence of the clods formed during soil processing and compaction with the standard Proctor effort on the soil-pore structures, and concluded that soils compacted under drier than optimum conditions have large clods and visible inter-clod pores in them, while soils compacted under wetter than optimum conditions have homogeneous small clods in them. These results seem to be similar to the compaction property of CS observed in this study. Due to changes in the soil-pore structure depending on the molding water content of the compacted CS, the parameters n and α are considered to be decreasing with an increase in the molding water content of the compacted CS.

Figure 7 shows the relationship between the van Genuchten parameter, n , and the dry density of the compacted PS and CS. It is obvious that the dry density of the compacted PS and CS is a factor which governs fitting

parameters such as n and α . But besides dry density, the molding water content also influences n . This can be found from the fact that the sludge compacted at a higher molding water content provides smaller n than that compacted at a lower molding water content, even when both compacted sludge have the same level of dry density (see Fig. 7). The dry density governs the total amount of soil pores, while molding water content controls the pore-size distribution. The water retentiveness of the compacted PS and CS is controlled more greatly by the pore-size distribution than by the amount of soil pores. Tinjum et al. (1997) reported experimentally the effect of pore size distribution in different types of clay compacted with the standard Proctor effort on the shape of the soil-water characteristic curve. They concluded that the clay specimens compacted to the same dry density under the compaction water contents with dry and wet of the optimum water content have radically different pore-size distributions. Therefore, significantly different α and n should be obtained for the same dry density, depending on the compaction water content. They also explained the effect of pore size distribution on the shape of the soil-water characteristic curve as the following: the compacted clays with dry of optimum water content contain stiff clods that are not remolded during the standard Proctor effort. As a result, large macroscopic pores exist, which result in a lower air-entry suction. The compacted clays with wet of optimum water content, however, are devoid of macroscopic pores, which results in higher air-entry suction. Furthermore, Tinjum et al. (1997) succeeded in observing the microscopic pore distributions of the clay specimens by photograph, and they showed that the steeper slopes of the soil-water characteristic curve of the compacted clays with the wet of optimum water content suggest the broader distribution of microscopic pores.

The PS and CS specimens used for the soil-water retention test are prepared according to the conditions of their standard compaction curves. Under such compaction conditions of specimen, the shape of soil-water characteristic curve depends on an increase in the molding water content. However, if the standard compaction effort is not achieved due to the field conditions, it is expected that

Fig. 8. Estimation of the unsaturated hydraulic conductivity of compacted (a) PS and (b) CS

the PS and CS compacted with lower dry density exhibit larger α and n than that of PS and CS compacted with the standard compaction effort, under the same level of molding water content. This is because, as Benson and Daniel (1990) reported, the parameters n and α of the clay compacted using different compaction energy under the same level of compaction water content are increased with a decrease in the compaction energy. This proves that the water retentiveness of the clay is dependent on the dry density in compaction, if the clay has the same molding water content. In this experiment, the relationships between different levels of molding water content and the shapes of soil-water characteristic curve are clarified in the PS and CS compaction according to their standard compaction curves. It should be noted that these relationships are discussed based on the conditions of PS and CS, in which the compaction is performed in accordance with the standard compaction effort. The effects of the dry density in compaction on the water retentiveness of the PS and CS compacted at different compaction efforts should be investigated in the future.

Unsaturated Hydraulic Conductivity of the Compacted Sludge

The soil-water retention properties of compacted clay material for landfill barriers affect the unsaturated hydraulic conductivity of the compacted clay (Fredlund and Rahardjo, 1993; Meerdink et al., 1996). Hence, the unsaturated hydraulic conductivities of the two types of the compacted sludge are estimated by Eqs. (3) or (4) using saturated hydraulic conductivity k_s , measured with flexible-wall permeameters, and soil-water characteristic curves, measured by the pressure plate extractor. The relationship between the unsaturated hydraulic conductivity and the degree of saturation for both types of the compacted sludge is shown in Fig. 8. For both types of the compacted sludge, the unsaturated hydraulic conductivity significantly decreases in orders of magnitude with a decrease in the degree of saturation from the fully saturated condition to the drying state. Such a significant decrease in the unsaturated hydraulic conductivity for variations in the water content is firstly due to the re-

moved water from the largest soil pores. According to the law of Hagen-Poiseuille, fluid flux f_w flowing in a tube with a radius r and a length Δx is expressed as follows:

$$f_w = (r^2/8\nu)(\Delta P/\Delta x) \quad (6)$$

where ν is the coefficient of the kinematic viscosity (m^2/s) and Δp is the pressure difference across Δx . Equation (6) implies that the passage of water through the smaller soil pores is more difficult than that through the larger pores. If the degree of saturation decreases, the refraction of the flow increases, and the waterway is lengthened. The unsaturated hydraulic conductivity of the compacted PS and CS, adjusted at higher levels of water content, is significantly decreased by a decrease in the degree of saturation, compared with that at lower levels of water content. Since the sludge materials with higher levels of water content can be compacted without the formation of clod structures, as discussed in the preceding section, the inside of the compacted specimen is composed of microscopic soil pores rather than macroscopic soil pores. Thus, the unsaturated hydraulic conductivity, which is greatly influenced by the distribution of soil pore size, decreases with an increase in the molding water content. Consequently, the compacted sludge at higher levels of molding water content has significant water retentiveness, which contributes to a significant decrease in the unsaturated hydraulic conductivity with a decrease in the degree of saturation.

However, there is a difference between the van Genuchten and the Brooks-Corey models in terms of estimating the unsaturated hydraulic conductivity, as shown in Fig. 8. The accuracy of estimating the unsaturated hydraulic conductivity from fitting parameters for the soil-water characteristic curves depends on several factors, in particular, the following two major ones. Firstly, the data available for defining the shape of the soil-water characteristic curves at lower levels of water content (at higher levels of matric suction) are insufficient. This may affect the estimation of θ_r and the gradient of each curve, which will in turn affect the predicted unsaturated hydraulic conductivity. Secondly, the van Genuchten-Mualem model is based on the

Fig. 9. Simulation outline for the UNSAT-H model and the initial boundary conditions used in the analysis (modified from Khire et al., 1995)

statistical models of flow through a set of capillary tubes (Mualem, 1978), described by the law of Hagen-Poiseuille, which are unlikely to capture the complexities of the unsaturated flow through compacted clay where the flows occur through inter-clod and intra-clod pores. In addition, mineral surface forces increasingly affect the flows through those pores as they desaturate (Meerdink et al., 1996).

WATER INTERCEPTION PERFORMANCE OF LANDFILL COVER SYSTEMS

Method for Evaluating Simulation Model

The most important function of landfill cover systems is to prevent water from percolating into waste layers. The amount of water percolating from cover systems depends on the hydrological conditions of the construction site, the components of the cover systems, the surface gradients of the landfill site, and the existence of vegetation. Some hydrological water balance simulation models are used to predict the amount of rainfall and snowfall percolating from the cover systems. The Hydrologic Evaluation of Landfill Performance (HELP) model is one of these representative models. The HELP model is based on a quasi-two-dimensional analysis, and the constituent layers of the cover systems are categorized into the vertical infiltration layer, the lateral drainage layer, and the barrier layer. The water which has percolated from the vertical infiltration layer is calculated using the given soil water retentiveness of the vertical infiltration layer. The percolated water from the lateral drainage and the barrier layers is then calculated applying Darcy's law to the drainage and the vertical directions, respectively (Schroeder et al., 1994). Thus, the drainage and the barrier layers are assumed to be in the saturated condition in the HELP model. The HELP model tends to overestimate the quantity of percolated water in the pluvial region in comparison to the value observed in the field (Khire et al., 1997), because the condition of the barrier

layer is only assumed to be in a saturated condition rather than in an unsaturated condition.

Recently, an unsaturated water balance model has been developed as an alternative evaluation technique for the pluvial region. For example, the water interception performance of cover systems has been evaluated with the Unsaturated Soil Water and Heat Flow (UNSAT-H) model which considers the unsaturated condition of cover systems. In this paper, the UNSAT-H model is used to predict the water interception performance of cover systems using the compacted PS or CS as the barrier material, because cover systems are subjected to unsaturated condition which are affected by the weather and the compaction conditions.

The UNSAT-H model developed by Fayer and Jones (1990), solves the modified Richard's equation using a one-dimensional finite difference approximation and predicts the water seepage through cover systems using the governing equation as expressed in Eq. (7) (Khire et al., 1997, 2000):

$$\frac{\partial \theta}{\partial \phi} \frac{\partial \phi}{\partial t} = \frac{-\partial}{\partial z} \left\{ (K_{\phi} + K_{v\phi}) \frac{\partial \phi}{\partial z} + K_{\phi} + q_{vt} \right\} - S(z, t) \quad (7)$$

where ϕ is the matric potential head (negative) due to the capillary suction forces, t is the time, z is the vertical coordinate (positive downward), θ is the soil volumetric water content, K_{ϕ} is the unsaturated hydraulic conductivity, $K_{v\phi}$ is the isothermal vapor conductivity, q_{vt} is the thermal vapor flux density obtained by applying Fick's law to the vapor flux, and $S(z, t)$ is the sink term representing the water uptake by vegetation, although this factor is not considered in the present study.

Figure 9 shows a simulation outline for the UNSAT-H model and the initial boundary conditions used in the analysis (Khire et al., 1995). The initial conditions for UNSAT-H are specified by assigning an initial head to each node in the finite difference nodal grid. The matric suction corresponding to the water content of each compacted sludge material is used to determine the initial

head in this analysis. The simulation is conducted using the lower boundary as the unit gradient and the upper boundary as the specified infiltration or the evaporation flux boundary. Khire et al. (1997) used similar boundary conditions for analyzing the water balance at various existing landfill sites. Fayer et al. (1992) also simulated the hydrology of drainage lysimeters constructed at the Hanford site by applying boundary conditions similar to those of the UNSAT-H model. UNSAT-H separates the precipitated rainfall on a landfill cover into infiltration and runoff. Runoff occurs when water applied to the soil surface exceeds the infiltration capacity of the cover systems during a rainfall. Thus, the runoff of rainfall depends on the saturated and the unsaturated hydraulic conductivities of each constituent soil layer. Water that infiltrates into the cover systems moves upward due to evaporation or downward as a consequence of gravity and the matric potential. When the upper boundary is set as a flux boundary, infiltration and evaporation from the surface are the specified flux. Evaporation is computed using Fick's law. Water removed by the transpiration of plants is treated as a sink term in Eq. (7). The potential evapotranspiration (the upper limit on actual evapotranspiration) is computed from the daily relative humidity, the net solar radiation, the wind speed, and the daily minimum and maximum air temperatures using a modified form of Penman's equation given by Doorenbos and Pruitt (1997). The soil water storage is computed by the infiltrated water content profile. Flux from the lower boundary (the bottom of the cover system) is defined as percolation. UNSAT-H does not consider the absorption or the interception of water by a plant canopy or the effect of the slope and the slope length.

Soil Properties under the Unsaturated State

A water balance analysis using the UNSAT-H model requires the unsaturated infiltration characteristics of each constituent layer of the cover systems. Infiltration parameters such as the θ - ϕ relation, the unsaturated hydraulic conductivity function, and the saturated hydraulic conductivity are necessary for predicting the water interception of the cover systems. In this analysis, the fitting results by the van Genuchten model (Eq. (1)), as shown in Table 2, for the soil-water characteristic curves are used for the θ - ϕ relations of the compacted PS and CS as barrier materials. This is because the van Genuchten model resulted in a better fitting than the Brooks-Corey model. The unsaturated hydraulic conductivity has been estimated using the van Genuchten-Mualem model (Eq. (3)). These unsaturated infiltration parameters of the compacted sludge are obtained in the drying process, and the effects of the hysteresis are not considered in this analysis. Since the soil undergoing drying has a higher volumetric water content, it also has a larger cross-sectional area for flow, less tortuous flow paths, and consequently, a higher level of unsaturated hydraulic conductivity at the same suction level (Meerdink et al., 1996). Therefore, the drying process can provide more serious evaluation results for the analysis

Table 3. Assumed values for each composed layer in the cover system

	Surface layer	Barrier layer
Soil	Silty loam	Compacted sludge
Thickness, D (cm)	10	10, 20, 30, 40, and 50
Infiltration parameters		see Table 2
θ_s (cm ³ /cm ³)	0.388	
θ_r (cm ³ /cm ³)	0.173	
n	0.047	
α (1/cm)	1.461	
k_s (cm/s)	1.5×10^{-3}	

than the wetting process.

Cross-Section of the Simulated Cover Systems and the Meteorological Data Input

The assumed structural profile for the analysis is shown in Table 3. A cover system composed of a surface layer of silty loam and a barrier layer of the compacted sludge is assumed. The unsaturated infiltration parameters of the silty loam are in accordance with the results by Fayer (2000). The parameters used in the water balance calculation are also shown in Table 3. The effects of the hydrological weather conditions and the unsaturated infiltration characteristics of the barrier layer with the compacted sludge on the water interception performance are quantitatively evaluated.

The meteorological input for UNSAT-H includes the daily precipitation, the daily maximum and minimum air temperatures, the daily solar radiation, the average daily dew point, and the average daily wind speed. Weather databases in 1998, 1999, and 2000 obtained from the Japan Weather Association are used as input data.

Performance of the Cover Systems

Geographical Effects on Water Interception

The water interception performance of the cover systems is greatly affected not only by the (unsaturated) infiltration characteristics of each constituent layer, but also by the weather conditions of the sites where the landfills are constructed. Hence, the water balance under various climatic environments is estimated for a cover system in which the compacted PS with a compaction water content of 133.6% and a layer thickness of 30 cm is assumed to be used for the barrier layer. Figure 10 shows the results of the water balance analysis for the cover system subjected to the weather conditions of Owase City, Mie Prefecture, Japan, from January of 1998 to December of 2000. Owase City has the most precipitation in Japan. If the cover system is established in Owase, approximately 90% of the rainfall would be removed from the cover system as surface runoff or evaporation, and 10% would be infiltrated into the cover system. If the rainfall flux exceeds the infiltration capacity defined by the saturated and the unsaturated hydraulic conductivity of the cover system, the accumulated water quantity on the surface would be removed as surface runoff. Although the quantity of evaporated water, which depends on air tempera-

Fig. 10. Input data and results of the water balance analysis for a cover system with a PS barrier (water content of 133.6%, thickness of 30 cm) in Owase, Japan

ture, solar radiation, and wind speed, tends to be actively generated in the rainy season, the absolute value of the quantity of water evaporated from the surface of the cover system is less than 10% of the rainfall. Consequently, most of the rainfall that is removed is caused by effects of the surface runoff. A quantity of water percolated from the cover system can be especially observed from May to September of each year, during which there is comparatively heavy rainfall.

Figure 11 indicates the results of a water balance analysis represented by the cumulative flux in Owase, Kyoto, and Tokyo, Japan. The quantity of surface runoff in Owase (see Fig. 11(a)) is more dominant than that in Kyoto (see Fig. 11(b)) or in Tokyo (see Fig. 11(c)). This is because the rainfall flux in Owase frequently surpasses the infiltration capacity of the cover system. The quantity of cumulative water percolated from the cover system is less than 15 cm, equaling approximately 1% of the total rainfall throughout the three-year period used for the analysis, even though the time at which the percolation begins depends on the weather conditions at each site. More than 99% of the rainfall was intercepted by the installation of the cover system in Owase, Kyoto, and Tokyo throughout the three-year period used for the analysis.

Fig. 11. Influence of weather conditions at each site on the results of the water balance analysis for cover systems with a PS barrier (water content of 133.6%, thickness of 30 cm)

Effects of the Barrier Layer on Water Interception

The effects of the compaction properties of PS and CS as the barrier layer on the performance of cover system are evaluated for that constructed in Owase. The PS and CS as barrier layers in cover system are assumed to be compacted at molding water contents of 133.6% and 21.5%, respectively, which provide the lowest saturated hydraulic conductivities of the compacted PS and CS. Figure 12(a) indicates the quantity of cumulative water percolated from the cover system. The quantity of water percolating from the barrier layer with the compacted PS increases during the period of relatively heavy rainfall (for example, from May to July of 1998). Namely, the compacted PS under unsaturated condition reaches the saturated condition during the period of heavy rainfall immediately after the installation. In addition, it can be assumed that the infiltration characteristics of the compacted PS, after the saturated condition is once reached, depend mainly on the saturated hydraulic conductivity.

This is because the barrier layer of the compacted PS, which reached the saturated condition, cannot recover to the unsaturated condition due to the weather conditions of heavy rainfall and the components of the cover system. The quantity of water percolated from the barrier layer of the compacted PS with different compaction water contents is shown in Fig. 12(b). The degree of saturation of the PS in the compaction greatly affects the water interception tendency of the cover system. Since the compacted PS with the highest molding water content (175.4%) in this study reaches saturated condition after compaction, the percolation from the compacted PS barrier layer, due to rainfall immediately after the installation, occurred at the earliest time. In contrast, when the PS is compacted

under unsaturated condition, such as at the compaction water contents of 133.6% and 75.7%, the infiltrated rainfall is retained in the compacted PS barrier layers for several months after the installation. The water percolated from the barrier layer is not noticed until the barrier layer reaches the fully saturated condition. Furthermore, although the evaporation of soil moisture is considered in this analysis, the barrier layer does not recover the unsaturated condition once the saturated condition is reached. This is probably because the surface layer prevents significant evaporation, and the infiltrated rainfall is strongly retained by the compacted PS layer. In a simulation case for which the barrier layer is constructed using the compacted CS, the quantity of water percolated from the compacted CS barrier equals almost 0 cm throughout the three-year period used for the analysis (see Fig. 12(a)). This tendency clearly indicates that the compacted CS does not reach the saturated condition even under such weather conditions as those in Owase.

With the above explanation, it is estimated that fluctuations in the moisture profile of the cover system affect the rainwater interception performance of the cover system. Figure 13 shows the distribution of volumetric water content in the cover system when the quantity of water percolated from the compacted PS has significantly increased (for the period of May to July, 1998). The water content increases throughout the layer during this period and reaches a saturated volumetric water content of the barrier layer in July, if the compacted PS is assumed to be installed as a barrier layer in the cover system. When the barrier layer is constructed with the compacted CS, the rainfall infiltrating into the cover system also accumulates at the interface of the surface layer and the barrier layer. However, the infiltrated water cannot reach the bottom of the compacted CS barrier layer. As a result, the bottom of the compacted CS barrier layer maintains its initial compaction water content. Other calculated results indicate that it takes at least about five years for the compacted CS barrier layer to be fully saturated under the weather conditions that exist at Owase. This is clarified in Fig. 14, which predicts the quantity of water percolated from the CS barrier having a water content of 21.5% and

Fig. 12. Effects of sludge type and molding water content of the PS barrier on the quantity of percolation water

Fig. 13. Distribution of the volumetric water content in a cover system with (a) PS and (b) CS barriers

Fig. 14. Quantity of percolated water from the cover system with a CS barrier (water content of 21.5%, thickness of 30 cm) located in Owase

a thickness of 30 cm for eight years using the meteorological data of 1998 at Owase repetitiously. Consequently, the cover system using the compacted CS as barrier layer shows a significant rainwater interception performance, because infiltration of the rainfall does not reach the bottom of the cover system in periods of heavy rainfall throughout the five years. In addition, the quantity of water percolated is significantly low in the five-year durations, because the compacted CS maintains a relatively low saturated hydraulic conductivity as 10^{-8} cm/s even after it reaches the saturated condition.

Figure 15 shows the effects of the thickness of the barrier layer on the water interception performance for a case in which the compacted CS with a water content of 21.5% is applied to the barrier layer. The quantity of cumulative water percolating from the barrier layer decreases with an increase in the layer thickness. For instance, the cumulative quantity from the compacted CS barrier layer with a thickness of 30 cm is over three orders of magnitude less than that from the barrier layer with a thickness of 10 cm, throughout the three years in the analysis. This is because the unsaturated zone increases with an increase in the barrier layer thickness. The quantity of percolating water is strongly controlled by the time it takes to reach a fully saturated condition.

The time it takes for the barrier layer to reach saturation depends on the weather conditions, and the unsaturated infiltration characteristics which are affected by the compaction conditions and the types of sludge. In the design of cover systems which use the compacted sludge, in terms of the water interception performance, a concern should be focused on whether or not the compacted sludge can retain the unsaturated condition over a long term. Evaluations of the water interception performance of cover systems, which consider the unsaturated and the saturated infiltration characteristics of the constituent layers, reproduces those in the field better than conventional evaluation techniques which depend on the saturated hydraulic conductivity represented by the HELP model. This is because the UNSAT-H model considers the changes in the water distribution within the cover sys-

Fig. 15. Effects of barrier thickness on the results of the water balance analysis for a cover system with a CS barrier (water content of 21.5%)

tems. The UNSAT-H model also clearly indicates the beneficial effects of the cover systems, showing the unsaturated condition, on the water interception performance.

SUMMARY AND CONCLUSIONS

The generation of leachate containing toxic matters and the leakage of leachate from bottom liners is normally caused by the accumulation of rainwater in the waste layers. Landfill cover systems can significantly cut off infiltration of rainfall. This study clarifies the application of two types of sludge such as the PS and CS for barrier materials in landfill cover systems from the viewpoint of

unsaturated infiltration characteristics. Soil-water characteristic curves for two types of compacted sludge are obtained experimentally using the proposed soil-water retention tests. The experimental results are identified using the van Genuchten and the Brooks-Corey models, which are representative fitting models. It is possible for these models to fit the soil-water characteristic curves of the compacted sludge. The feasibility of the two types of compacted sludge as barrier materials is verified from the viewpoint of water retentiveness. While the unsaturated infiltration characteristics of the compacted PS and CS are evaluated experimentally, a water balance analysis which considered the unsaturated infiltration behavior of the constituent layers is carried out to predict the performance of the rainwater interception of landfill cover systems by the compacted PS and CS. From this analysis, the cover systems which apply the compacted PS and CS as barrier layers can maintain the unsaturated condition over several months and several years, respectively, even in the very humid weather conditions that exist in Japan; and, the performance of the rainwater interception by the cover systems exhibiting the unsaturated condition is significant. The conclusive results of this study are as follows:

- 1) The van Genuchten and the Brooks-Corey models are available for soil-water characteristic curves of the compacted PS and CS. In addition, the van Genuchten model provides more flexible nonlinearity and has a higher adaptability for the compacted PS and CS than the Brooks-Corey model.
- 2) The PS, compacted at a higher level of water content, exhibits the microscopic pores of organic substances which may possess larger amounts of water than the inter-particle pores. The PS compacted at a higher level of water content can indicate a higher air-entry suction and water retentiveness than the PS compacted at a lower level of water content even at a higher level of suction.
- 3) When the CS is compacted at a lower level of water content, the macroscopic pores are formed in the inter-clods. In contrast, the CS compacted at a higher level of water content does not form the clod structures, and then microscopic pores are produced. The compacted CS with microscopic pores can strongly retain the pore water. A higher level of molding water content of CS is considered to contribute to the water retentiveness of CS.
- 4) The unsaturated hydraulic conductivity of both PS and CS, compacted at higher levels of water content, significantly decreased with a decrease in the degree of saturation, compared with that compacted at a lower level of water content. This is because the unsaturated hydraulic conductivity of the compacted PS and CS is significantly affected by the soil-pore size distribution.
- 5) As a result of the evaluation of the water interception performance using the UNSAT-H model, the quantity of the cumulative water percolating from cover systems is less than 15 cm, which equals approximately 1% of the total rainfall throughout the three years in the analysis. More than 99% of the rainfall could be intercepted by the installation of cover systems in Owase, Kyoto, and Tokyo, Japan throughout the three-year analyzing period.
- 6) The time it takes for the barrier layer to reach saturation depends on the weather conditions and the unsaturated infiltration characteristics. In the design of cover systems using the compacted sludge, in terms of the water interception performance, it is most important whether the compacted sludge is under unsaturated condition or not.
- 7) The UNSAT-H model clearly indicates the beneficial effects of cover systems, under the unsaturated condition, on water interception performance.

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