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Long-Term Hydraulic Conductivity and Consolidation Behavior of Compacted Sludges Using Geotechnical Centrifuge

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Synopsis
In design of the landfill water interception structure, evaluation for hydraulic conductivity of barrier layer in cover and bottom liner is the most important task. In this study, in order to reuse paper sludge and construction sludge to landfill barrier materials, long-term hydraulic conductivity and consolidation characteristic of sludges were examined using geotechnical centrifuge. As the results, PS could retain the hydraulic conductivity of the order of 1.0×10^{-7} cm/s in the 60 G field for 24 hours. This result comprises that, when PS was used as barrier material in the field, the hydraulic conductivity of 1.0×10^{-7} cm/s will maintain for 10 years.

Keywords: centrifuge test, cover system, hydraulic conductivity, landfill, sludge

1. Introduction

A sound water interception structure, which prevents the leakage of toxic substances, is necessary for waste disposal site, and landfill cover and bottom liner systems play a major role to protect the surrounding environment. Generally, the water interception structure can be classified into cover system (installed on the upper part of waste in order to minimize the permeating rainfall water into the disposal site), and bottom liner system (installed below the waste layers in order to prevent the leakage of generated leachate due to wastes decomposition). The barrier layer composed of the material that can retain the low permeability fulfils the important role for water interception performance in landfill. Therefore, the evaluation of hydraulic conductivity of barrier layer in the cover and bottom liner systems becomes important in the design of water interception structure.

Until now, compacted clay that retained the low hydraulic conductivity was generally used as barrier layer material. Recently, trials have been carried out to construct barrier layer using suitable waste materials that retains low permeability due to the social request of reduction of the disposal site construction cost, and rational reduction of the waste materials landfill capacity. The applicability of paper sludge (PS), construction sludge (CS) and bentonite mixed sludge to the barrier layer in the cover system through the laboratory flexible wall permeability testing has been well established (Kamon et al. 1999 and 2000, Rajasekaran et al. 2000).

In the present study, the long-term consolidation characteristics, permeability performance, and the effect consolidation on the hydraulic conductivity of PS and CS have been investigated using geotechnical centrifugal model tests on PS and CS as barrier materials.

2. Centrifugal Model Test

In the centrifugal model experiments, geometric similar model of *1/N* is made in a test tank with identical soil composition of reality, and the relationship between prototype and model in centrifugal field of N G is considered. Scaling law shows the quantitative correspondence between the observed behavior of actual phenomenon and in the model experiment. By scaling law, it is possible to compare the behavior of centrifugal model experiment with the in-situ behavior. In addition, all dimensions and parameters such as hydraulic conductivity of the soil (i.e. model) can be decided. Table 1 shows the scaling law details for evaluating the hydraulic conductivity and compressibility of sludge material in the centrifugal model experiment. At first, theoretical research of the soil mechanics field on scaling law has been carried out by Rocha (1957). He examines the scaling law of physical quantity such as stress to satisfy the static problem. He has examined few cases, for example, a case in which the dead weight effect has to be included or not, and a case in which the water movement of soil has to be considered or not (Rocha 1957).

3. Test Programme

3.1 Experimental outline

In this study, permeability and settlement characteristics of the compacted sludge materials were measured in centrifugal force of 60 G loading environment in order to predict the long term behavior of sludges to be used as barrier material of cover system within short period. Tests were carried out for 24 hours to simulate the long-term behavior of barrier material that corresponds to 9.86 years as per scaling law (Table 1).

3.2 Measuring method

Figure 1 shows the cross sectional view of model used in the centrifugal experiment with the details of instruments layout. Stainless soil tank has been preferred in the experiment, which can resist the 60 G centrifugal field. In addition to that stainless steel filter had been installed at the base plate of the soil tank, and this part was considered as drainage layer. In the experiment, by providing the water level (20 cm) on surface of compacted sludge, with difference of water-level between sample side and reservoir side, the provided water was passed through the filter to the reservoir side from the sample side. In order to obtain the hydraulic conductivity of sludges, measurements of the change in the influent and effluent levels are necessary. Then, 3 pore pressure transducers (PPT) were set to the compacted sludge surface, and the draw down quantity (influent quantity) was measured at different time intervals during the test period. The rise of water level quantity (effluent quantity) in the reservoir side has been monitored similarly by setting three PPT to reservoir

Table 1 Scaling relationship for centrifugal loading test

Parameter	Dimension	Prototype	Centrifuge
Linear	L	L	L/N
Area	L^2	A	A/N^2
Volume	L^3	V	V/N^3
Stress	$ML^{-1}T^{-2}$	ρ	ρ
Strain		ε	ε
Force	MLT^{-2}	F	F/N^2
Mass	M	m	M/N^3
Mass density	ML^{-3}	ρ_m	ρ_m
Unit weight	$ML^{-2}T^{-2}$	γ	$N\gamma$
Time	T	T	T/N^2
Fluid viscosity	$ML^{-1}T^{-1}$	μ	μ
Fluid density	ML^{-3}	ρ_f	ρ_f

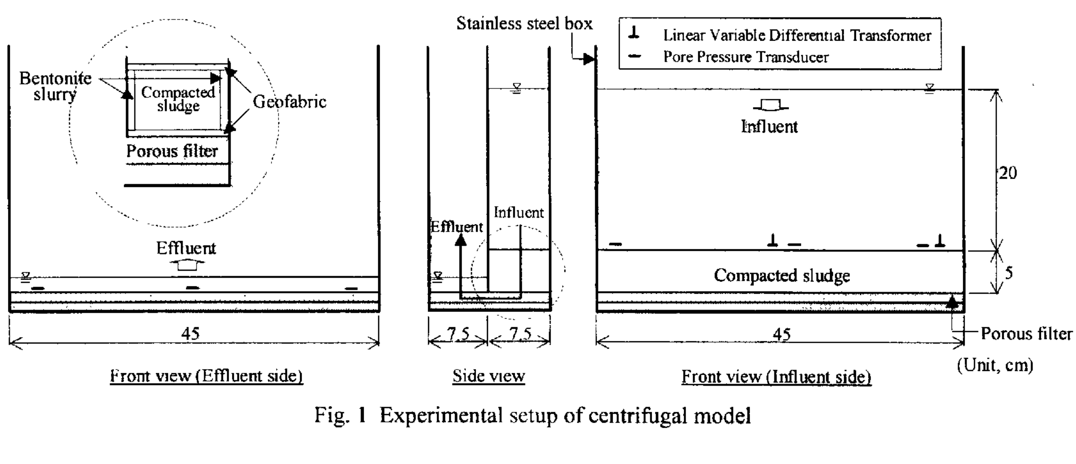

Fig. 1 Experimental setup of centrifugal model

side basal plane, and it was measured at various time intervals. It is possible to measure the variation of water-level difference between influent and effluent sides during the centrifugal loading period. In the meantime, linear variable differential transformer (LVDT) was set at the sludge surface of 2 places, and the settlement of sludges during the centrifugal loading period was measured.

3.3 Estimation of hydraulic conductivity

In the centrifugal experiment, fluctuations of water levels of influent side to the sludge and effluent side from the sludge are measured at various time intervals (Δt). Using the measured values, hydraulic conductivity of sludges was calculated as following Fig. 2. As shown in Fig. 2, though the effluent level is stable for falling head permeability test that regulated at JGS 0311-2000, influent and effluent level together fluctuate in the permeability cross section set by this experiment. Therefore, it is not possible to apply the formula of the permeability shown in JGS 0311-2000 to the evaluation of the permeability in this experiment. Then, Equation (1) is established for the evaluation of the permeability in this experiment. Further, the permeability test of such type is generally regulated in ASTM D 5084 as *Test with Increasing Tailwater level (Method C)*.

$$k = \frac{La_{in}a_{ef}}{At(a_{in} + a_{ef})}\ln\left(\frac{h_{it1}}{h_{it2}}\right) \quad (1)$$

where, a_{in} is cross-sectional area of the containing the influent liquid, a_{ef} is the cross-sectional area of the containing the effluent liquid, L is the thickness of the

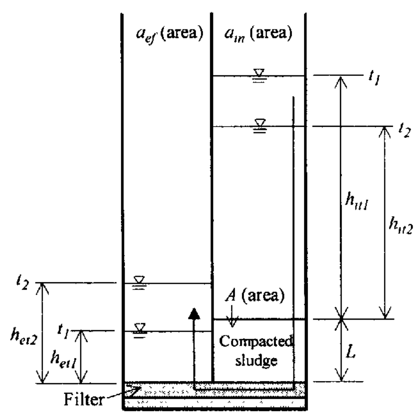

Fig. 2 Schematic diagram for the calculation of Hydraulic conductivity

specimen, A is the cross-sectional area of the specimen, t is the elapsed time between determination of h_{it1} and h_{it2}, h_1 is the head loss across the specimen at time t_1, and h_2 is the head loss across the specimen at time t_2.

For evaluating the hydraulic conductivity in centrifugal force loading field, k value of the model material required in the centrifugal field of N G is equal to k value (actual hydraulic conductivity) of 1 G in the field. That is to say, hydraulic gradient affects the sludge in the model equivalent to the size of N twice. In short, it consists like Equation (2), if Equation (1) has to be evaluated in the centrifugal field.

$$k = \frac{La_{in}a_{ef}}{NAt(a_{in} + a_{ef})}\ln\left(\frac{h_{it1}}{h_{it2}}\right) \quad (2)$$

3.4 Estimation of consolidation

As shown in Table 1, the stress that affects the centrifugal model and prototype are equal. Therefore, settlement S measured in the model becomes $1/N$ of prototype. That is to say, generating excess pore water pressure becomes equal prototype.

3.5 Materials

The sludges used in the centrifugal test are paper sludge (PS) and construction sludge (CS) in applicability test to a series of barrier material. The basic properties of sludge materials are shown in Table 2. Sludge compaction was carried out so that the sludge density can be adjusted at fixed water content that agree with the standard compaction curve. The initial conditions of each sludges compacted at centrifugal soil tank is shown in Table

Table 2 Basic properties of PS and CS

Properties	PS	CS
Water content (%)	132.5	337.2
Organic content (%)	63.7	6.2
Particle density (g/cm^3)	1.79	2.68
Liquid limit (%)	325 - 335	46.5
Plastic limit (%)	106 - 117	28
Opt. moisture content (%)	74	18.2
Heavy metals leachte (mg/L)		
Pb	≤ 0.01	≤ 0.01
Cd	≤ 0.01	≤ 0.01
Cr	≤ 0.01	≤ 0.01
Zn	≤ 0.01	≤ 0.01

Table 3 Initial conditions of PS and CS in Centrifugal loading test

Index	PS	CS
Water content (%)	145.2	25.3
Wet density (g/cm^3)	1.179	1.857
Dry density (g/cm^3)	0.481	1.482
Void ratio	2.726	0.808
Porosity (%)	0.732	0.447
Degree of saturation (%)	95.5	83.9

3. For centrifugal test with 60 G field, the layer thickness of compacted sludge corresponds to the field barrier layer is 60 cm or less, which corresponds to the layer thickness in the model 1 cm or less under centrifugal field (60 G). In this layer thickness, the uniform compaction becomes difficult and the danger of water leakage under centrifugal loading is more occurred. Then, the layer thickness of compacted sludge in the model was made to 5 cm, and in prototype, 300 cm should be assumed. There is no layer thickness effect caused the hydraulic conductivity for the evaluation long-term hydraulic conductivity of sludges. A thin layer of bentonite slurry was applied between compacted sludge layer and sidewall of tank in order to prevent the sidewall leakage during the test.

3.6 Stress distribution

It is clear that stress affected the sludge in centrifugal model is equal to the prototype for scaling law as shown in Table 1. Then, it is necessary to clarify the corresponding relationship between the sludge stress condition, which reappeared in the model, and the stress condition that affects the actual barrier material. In past investigation, the stress, which affects the barrier layer of the landfill cover system, is almost 20 - 50 kPa (Zimmie et al. 1995, Quiroz et al. 1998). The acting stress of the test-piece was also set to about 30 kPa in flexible wall permeability test of each sludge tests carried out. Figure 3 shows the initial stress distribution that affects the sludge in the centrifugal model. It can be seen that the initial stress affects the sludge in the model is 120 kPa, and the stress of about 4 times will affect than acting stress in the actual barrier layer. However, there is a research report on the hydraulic conductivity of the sludge material for different stress conditions. Under 10 kPa or less, the hydraulic conductivity of sludge is remarkably dependent on the acting stress. However, the stress over it does not

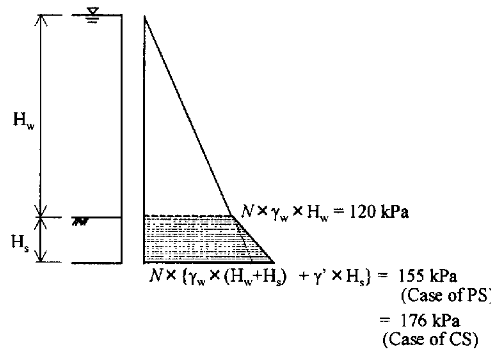

Fig. 3 Stress distribution in the centrifugal model

significantly affects the hydraulic conductivity of sludge (Kraus et al. 1997). Therefore, it was not greatly influenced in measuring the hydraulic conductivity, though there is a difference in the stress between centrifugal model and prototype. In the meantime, the compressibility under stress action was compared with the standard consolidation test of each sludges. By converting the consolidation behavior from centrifugal model to the general barrier layer thickness, the variation of settlement and consolidation can be evaluated.

4. Long-term Consolidation Behavior

4.1 Paper sludge (PS)

The consolidation behavior of sludges are unlike usual cohesive soil especially in the case of PS since it contains high organic content that has to be applied as landfill cover material under over burden pressure. One-dimensional consolidation tests were carried out, and the consolidation characteristic for paper sludge at different water contents was evaluated in the laboratory. The relationship between void ratio and consolidation pressure (e-log p curve) of PS is shown in Fig. 4. There are many examples of reports that the linearity of e-log p relation is not well established in high organic soil. However, the linearity has been comparatively established in case of PS. When it tries to obtain compression index in the normally consolidated region, Cc = 0.97 for paper sludge at 102.8% water content, and Cc = 1.22 at 144.3% since PS is a highly compressible material. In the case for which paper sludge was applied to the low permeability cover material and case in which the vacant lot reusing of landfill was not operated, anticipating loading pressure on the upper layer is estimated as about 30 kPa. Under such loading stress,

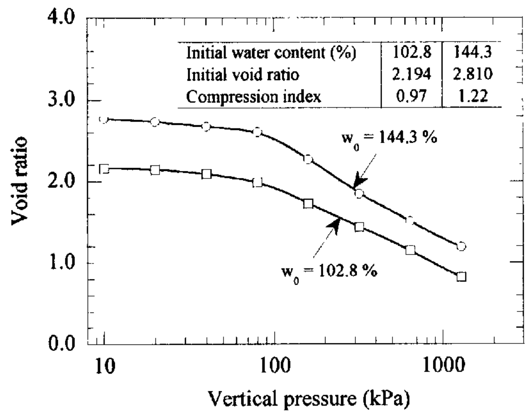

Fig. 4 e-log p curves of PS

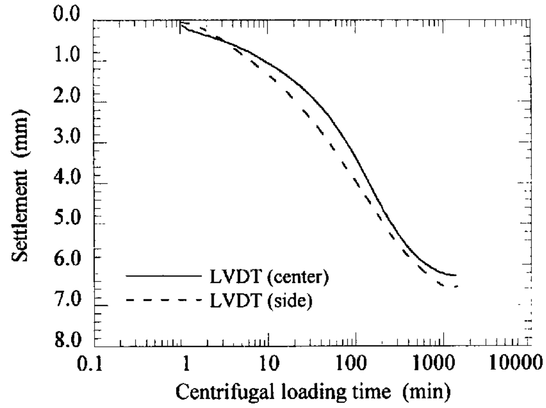

Fig. 6 Settlement versus time at 60 G (case of PS)

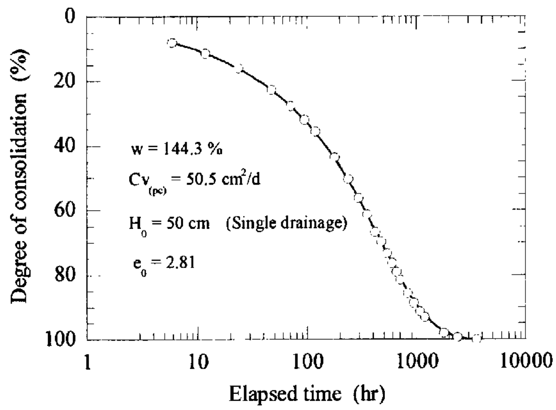

Fig. 5 Change of degree of consolidation for elapsed time (case of PS)

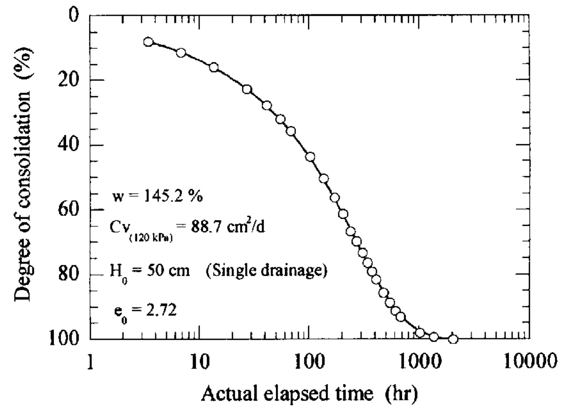

Fig. 7 Consolidation behavior of the barrier material using the centrifugal model result (case of PS)

paper sludge reaches the over consolidation region, and large settlement is not generated. In the meantime, paper sludge of the barrier layer comes to the normally consolidated region, if the case in which the external force with vacant lot reusing of landfill worked is considered, and the settlement in proportion to coefficient of consolidation will be generated. Figure 5 shows that the degree of consolidation with the progress in time under the consolidation yield stress in case of using paper sludge as the barrier layer of cover system. That the consolidation behavior follows Terzaghi's theory is assumed. If the consolidation yield stress is affected to compacted paper sludge The consolidation of paper sludge progresses, further the time duration of 1000 hours (about 42 days) is required at least to reach 90% degree of consolidation.

Two LVDT were set on the compacted sludge surface of centrifugal soil tank to evaluate the long-term compressibility of paper sludge, and then settlement with elapsed time on the sludge surface was measured. During the consolidation stage, the initial void ratio of compacted paper sludge is 2.73, and the consolidation load in the centrifugal field is about 120 kPa. From Fig. 4, the compacted paper sludge becomes the normally consolidated region. Figure 6 shows the settlement with centrifugal force loading time, and it is proven that the settlement tendency shows the shape of the Terzaghi type. When the result of standard consolidation test was compared with centrifugal model experiment, the void ratio at end of consolidation is about 2.27 in the case of standard consolidation test under the loading pressure of 120 - 150 kPa has been worked. In addition, settlement of about 10 mm was measured for the initial height of 7 cm under acting load of 160 kPa. In short, the compression of 14.3% occurred for the test-piece. In the meantime, paper sludge compacted for layer thickness of 5 cm in the centrifugal model experiment, settlement of about 7 mm was finally generated. That is to say compression of 14.0% is occurred. The consolidation behavior of paper sludge from centrifugal model experiment indicate void ratio after the centrifugal force loading was 2.28, and agree well with the result of standard consolidation test. Figure 7 is simulated the consolidation behavior of compacted paper sludge used as the barrier layer in cover system applying the results of centrifugal model experiment. The coefficient of consolidation (88.7 cm^2/d) of paper sludge obtained from centrifugal model experiment is equivalent with the actual ground from scaling law (Table 1). The estimation cross-section details are similar with case in Fig. 5. From Fig. 8, when pressure of 120 kPa is acted to compacted paper sludge with layer thickness of 50 cm, during about 600 hours (about 25 days) is needed to reach the degree of consolidation of 90%.

4.2 Construction sludge (CS)

The construction sludge as well as paper sludge evaluation of the consolidation characteristic is same as from the normal consolidation test and centrifugal model. Adjustment of water content of the construction sludge for each experiment is 27.0%, which is 10% wet side of the optimum water content in normal consolidation test and is 25.2% in centrifugal model experiment. The test-piece has been made in such a way that it agree well with the compaction curve. Figure 8 is shown the e-log p curves of the construction sludge by the normal consolidation test, and Fig. 9 indicate the settlement tendency with the progress of centrifugal loading time. As the results of normal consolidation test, the stress level of construction sludge reaches the over consolidation condition in 120 kPa surcharge load, therefore the decreased amount of the void is less. That is to say, void ratio of construction sludge decreased a little from 0.81 (initial void ratio) to 0.76 under the acting stress of 120 kPa. The settlement that occurred at that time is about 1.5 mm, it is the compression of 2.1% for the test-piece height. In the meantime, settlement of about 3.0 mm under the acting load of 120 kPa is measured in the centrifugal model experiment, and the compression of 6.0% occurred for the layer thickness. The void ratio of compacted construction sludge after the centrifugal loading is 0.70. When compared with both tests, more large compressibility appeared in the centrifugal model experiment. In short, applying the centrifugal force of 60 G to sludge during 24 hours is equivalent with that the pressure of about 120 kPa is acted to the construction sludge for 9.6 years. Under such stress condition, secondary consolidation with the rearrangement of soil particle seems to progress, after the first consolidation by the dissipation of excess pore water pressure. Therefore, the case in which applied the construction sludge to the cover

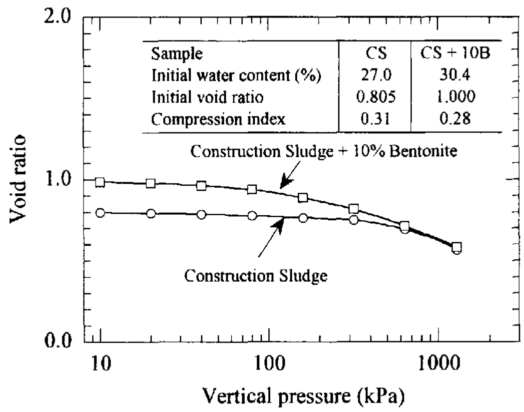

Fig. 8 e-log p curves of CS

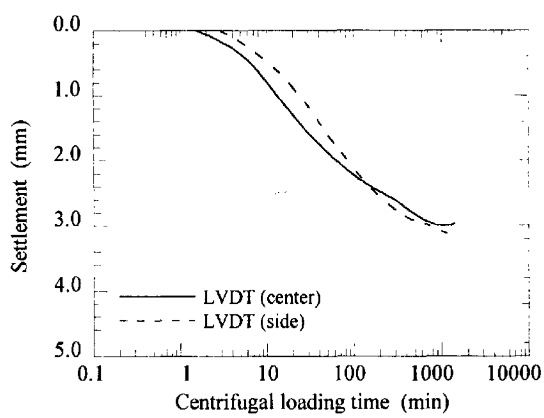

Fig. 9 Settlement versus time at 60g (case of CS)

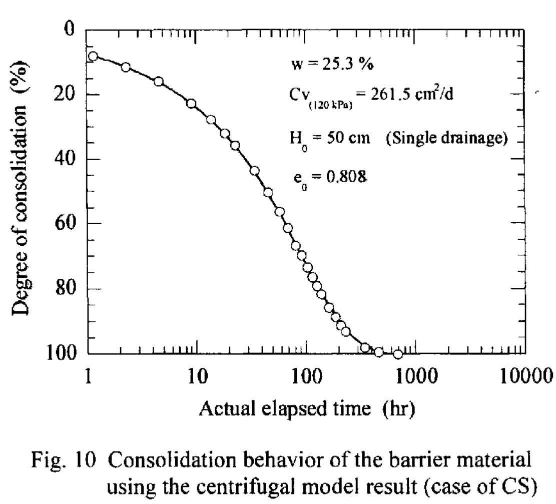

Fig. 10 Consolidation behavior of the barrier material using the centrifugal model result (case of CS)

material is assumed using compression behavior based on the centrifugal model experiment. It can be assumed that the settlement of about 6% of layer thickness is generated throughout the 10 years with considering the secondary consolidation. In addition, coefficient of consolidation of measured construction sludge is 261.5 cm^2/d in centrifugal model experiment. The relationship between consolidation and elapsed time shown in Fig. 10 is obtained, and consolidation behavior of the construction sludge follows the consolidation theory of Terzaghi is assumed. For cases of 120 kPa acting load worked to construction sludge compacted at layer thickness 50 cm, it is necessary about 206 hours (about 8.6 days) for the degree of consolidation to reach 90%.

5. Permeability performance

5.1 Flexible wall permeameter

The hydraulic conductivity performance function is important when paper sludge and construction sludge are applied as barrier layer in the landfill over system. Generally, the performance of barrier material is shown by the hydraulic conductivity in the application standard. Then, authors have examined the hydraulic conductivity performance of each sludges using the flexible wall type permeameter (Rajasekaran et al. 2000). The results are as follows. Figure 11 shows the relationship between initial water content and saturated hydraulic conductivity of paper sludge. From this, the water content of paper sludge that showed the smallest hydraulic conductivity (3.8×10^{-7} cm/s) is 136.1% (about 60% wet side from the optimum water content), which is equal to initial water content. However, there is no remarkable difference over 50% - 150% wide water content region in the hydraulic conductivity, and it is 3.8×10^{-7} cm/s - 9.0×10^{-7} cm/s. As a result of the flexible wall permeability test for paper sludge, there is a report in which the hydraulic conductivity of paper sludge is also minimized to 50% - 100% wet side of the optimum water content to be used (Moo-Young et al. 1996, Quiroz et al. 1998). In the meantime, Fig. 12 is indicated the relation of the hydraulic conductivity and initial water content, and compaction curve in case of the construction sludge. The compacted construction sludge can be retained more low hydraulic conductivity of 1.2×10^{-8} cm/s - 6.5×10^{-8} cm/s comparing with paper sludge. In addition, application standard ($k \leq 1.0\times10^{-7}$ cm/s) of U.S.A. is satisfied, when construction sludge is applied to the low hydraulic conductivity cover material.

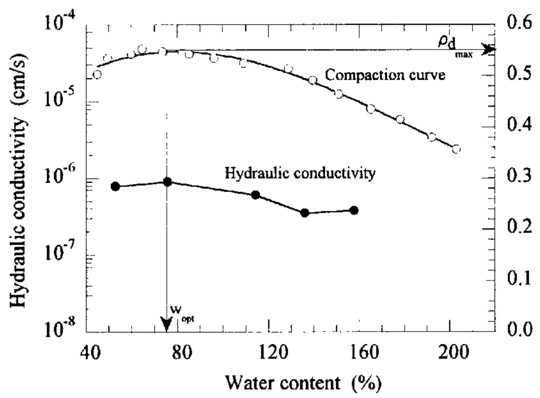

Fig. 11 Hydraulic conductivity of PS (Flexible wall permeability test)

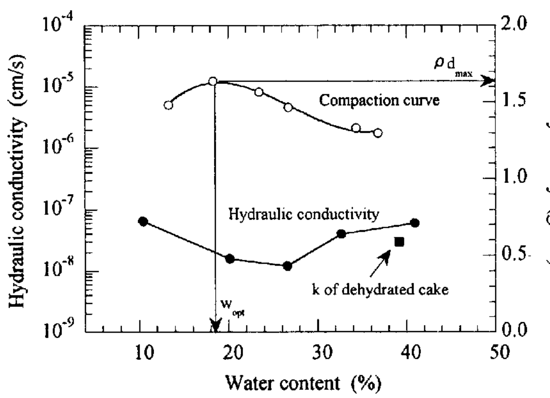

Fig. 12 Hydraulic conductivity of CS (Flexible wall permeability test)

By the flexible wall permeability testing of the sludge, the hydraulic conductivity of each sludges retained was confirmed and the effect that the water content gave for hydraulic conductivity was clarified. However, based on periods of testing using flexible wall permeability testing was the longest of about 2 months, and it did not come to in order to confirm the fluctuation of the long-term hydraulic conductivity. Design service life of the cover material constructed in disposal site is about 30 years (Koerner et al. 1997), and it is necessary to grasp the fluctuation of the long-term in order to confirm the applicability of the barrier material.

5.2 Hydraulic conductivity of PS in centrifuge

In the centrifugal model experiment, for estimating the long-term hydraulic conductivity of sludge, each sludges was compacted in 5 cm layer thickness to centrifugal soil tank. The initial conditions of compacted paper sludge are shown in Table 3. The water level was measured at 3 places of both inflow and runoff side during centrifugal loading period. This is to clarify the formation of the meniscus water surface by the centrifugal force loading. Calculation method of the hydraulic conductivity from the measured value was described at the subsection 4.3. Figure 13 shows the time fluctuation of the influent and effluent level of paper sludge adjusted at water content of 145.2% under centrifugal loading. In the figure, it is not possible to confirm the meniscus surface because there is no difference in fluctuation of water levels measured at 3 places in each both influent and effluent side. Then, in the calculations of influent and effluent rate, the average water level measured at 3 places should be used respectively. Figure 14 is shown the fluctuation of influent and effluent rate of paper sludge with the progress in the loading time. The flow rate fluctuates within 0.010 cm^3/s - 0.045 cm^3/s during loading period very small, and the flow rate gradually decreases with the progress in the time. One of the causes is due to the decrease of the water head difference between influent and effluent inflows. There is not large difference at influent and effluent rates, and the effect of sidewall leakage during the centrifugal loading period on the hydraulic conductivity seems to be less. Figure 15 shows the time variation of hydraulic conductivity of paper sludge in the centrifugal model. Where the scaling relationship between hydraulic conductivity in the centrifugal model and actual hydraulic conductivity is 1. In short, hydraulic conductivity of sludge obtained by the centrifugal model experiment can be directly evaluated as hydraulic conductivity as barrier material. From Fig. 15, the hydraulic conductivity calculated using the influent and effluent flow rate has ensured the 10^{-7} cm/s order over the centrifugal loading of 24 hours. When centrifugal model experimental results converted to the prototype, compacted paper sludge (layer thickness 300 cm) as a cover material retains hydraulic conductivity of 4.0×10^{-7} cm/s just after the installation. However, the hydraulic conductivity decreases to about 1.0 - 2.0×10^{-7} cm/s in post 600 days installed with progress of the consolidation and decomposition of the organic substance, and it can be assumed that hydraulic conductivity has been almost stabilized within the 10 years. Comparison of the hydraulic conductivity of the centrifugal model experiment with flexible wall permeability testing verified that the hydraulic conductivity that is almost equivalent under similar compaction condition of paper sludge. Therefore, the hydraulic conductivity measured by the flexible wall permeability testing can able to confirm that it could

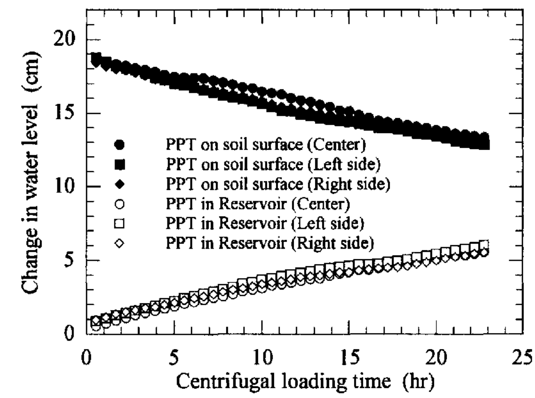

Fig. 13 Change in water level for the centrifugal loading time (case of PS)

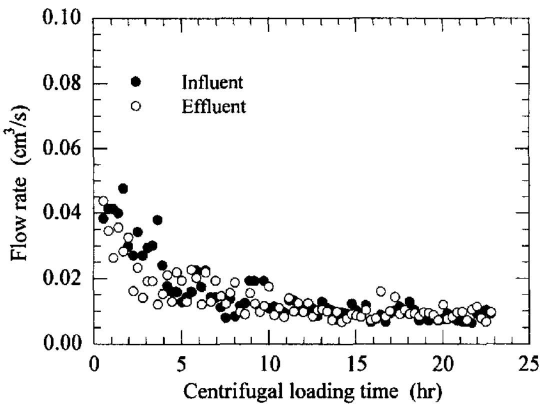

Fig. 14 Change of flow rate for the centrifugal loading time (case of PS)

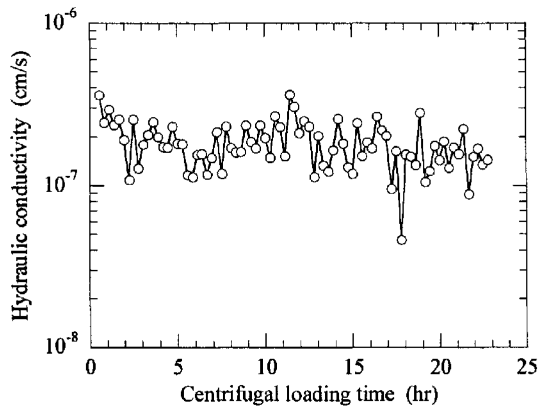

Fig. 15 Change of hydraulic conductivity for the centrifugal loading time (case of PS)

be maintained throughout the long term from the centrifugal model load testing.

5.3 Hydraulic conductivity of CS using centrifuge

From the centrifugal model experiment, the result of long term hydraulic conductivity of construction sludge that has been adjusted to water content of 25.3% (Table 3) are Figs. 16, 17, and 18. In Fig. 16, there is no difference at 3 water levels measured value in the fluctuation of influent and effluent water levels respectively. Although the fluctuation of the water level is very dull, decreasing ratio of influent water level for elapsed time and increasing rate of effluent water level for elapsed time matched well. Therefore, the effect of sidewall leakage can be disregarded, and the influent passes through the construction sludge and effluent is clear. Figure 17 shows influent and effluent flow rate required from the fluctuation of water levels, which can be guessed because influent and effluent flow rate agree well. Figure 18 shows the change of hydraulic conductivity for the centrifugal loading time of the construction sludge. In end time point of centrifugal loading, the hydraulic conductivity decrease to 2.0 - 5.0×10^{-8} cm/s. This tendency is due to the consolidation of construction sludge. That is to say, the construction sludge in the centrifugal model slightly occur settlement, and the settlement has finally ended after the centrifugal loading in about 7 hours (Fig. 9). The void of compacted sludge decreases gradually during the consolidation period. In short, the water flow in the void becomes gradually difficult by the void narrowing. It becomes necessary that the hydraulic conductivity was also comparatively stabilized when the void is constant at the end of consolidation. The hydraulic conductivity of construction sludge (Fig. 12) is 1.4×10^{-8} cm/s in the condition of 26% water content from the flexible wall permeability test, and it is lower than the hydraulic conductivity measured in the centrifugal model experiment. Under this difference, the evaporation of the water in the centrifugal model can be considered. Decreasing of influent level can be divided into due to infiltration and evaporation during centrifugal loading period. It is similar in the effluent side. In present experiment, the effect of the evaporation is not considered. That is to say, the indoor temperature of the centrifugal loading is low temperature under centrifugal loading, and moreover, it is fixed. Therefore, it was regarded as disregarding the decreasing of the water level by the evaporation. However, rate of inflow is very small in case of the construction sludge; therefore the effect of the evaporation appears comparatively well for the flow rate. As the result, they tend to seem to superfluously evaluate the hydraulic conductivity. When the

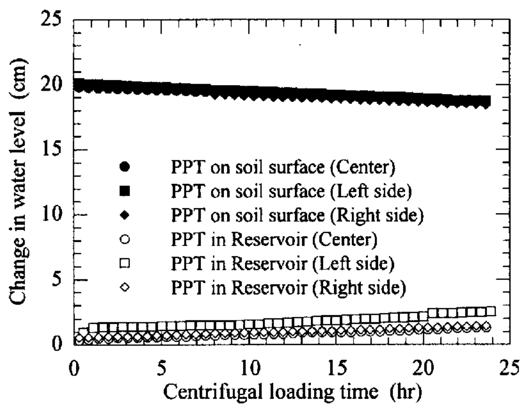

Fig. 16 Change in water level for the centrifugal loading time (case of CS)

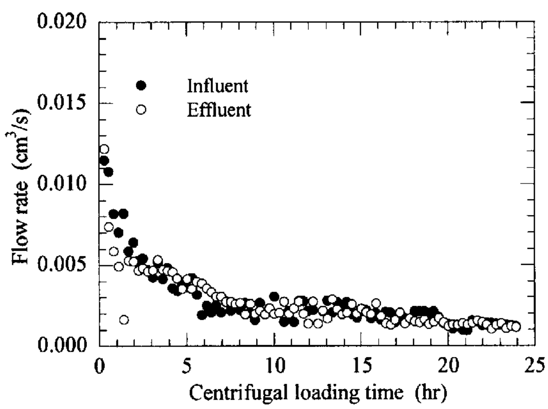

Fig. 17 Change of flow rate for the centrifugal loading time (case of CS)

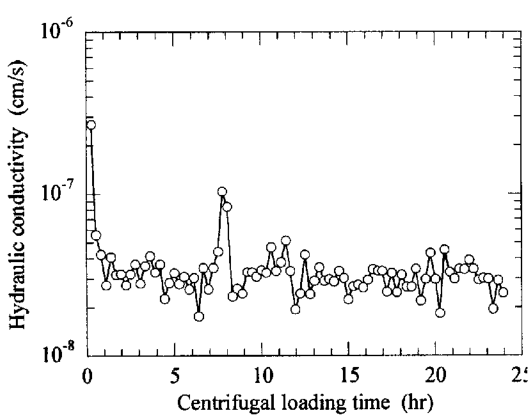

Fig. 18 Change of hydraulic conductivity for the centrifugal loading time (case of CS)

hydraulic conductivity of construction sludge based on centrifugal model experiment is converted to disposal site cover material (barrier layer), the construction sludge demonstrates the hydraulic conductivity that falls below application standard (k ≤ 1×10^{-7} cm/s) from the right after installation with barrier material. In addition, according to the consolidation effect, the hydraulic conductivity decreased to 10^{-8} cm/s, and it was proven to maintain the low hydraulic conductivity after 10 years can be possible.

5.4 Consolidation effect

As a means of performance evaluation of disposal site cover material using paper sludge, and construction sludge, long term consolidation characteristic and hydraulic conductivity performance of each material has to be clarified by centrifugal experiment.

By accompanying progress in the hydraulic conductivity progress of the centrifugal load testing and consolidation of either sludge, the hydraulic conductivity gradually decreased. The hydraulic conductivity of sludge gradually decreased with centrifugal loading time and progress in consolidation, and it was comparatively stabilized throughout the long term from point of time in which the consolidation ended was obtained. It is necessary to evaluate the low hydraulic conductivity required in the cover material from the right after installation of course. Therefore, the change tendency of the hydraulic conductivity for the progress of consolidation must be clarified.

Figure 19 shows the change of degree of consolidation and hydraulic conductivity for the centrifugal loading time of compacted paper sludge in the centrifugal model. In addition, the relationship between consolidation and hydraulic conductivity of paper sludge is shown in Fig. 20 Though the paper sludge shows the high compressibility, the hydraulic conductivity seems to be not depend on the degree of

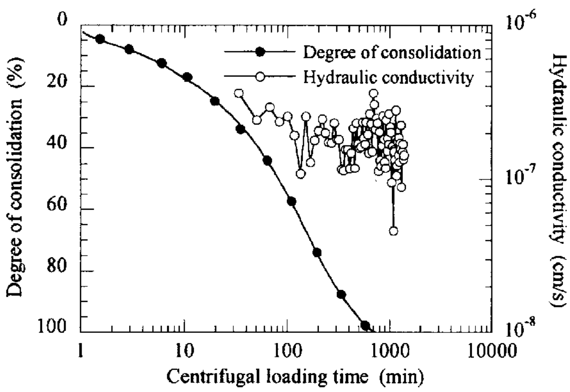

Fig. 19 Change tendency of consolidation and hydraulic conductivity (case of PS)

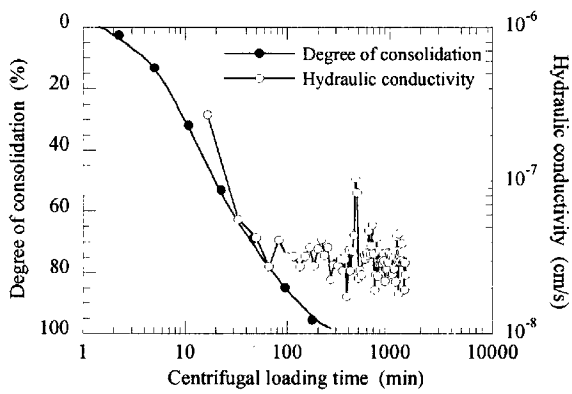

Fig. 21 Change tendency of consolidation and hydraulic conductivity (case of CS)

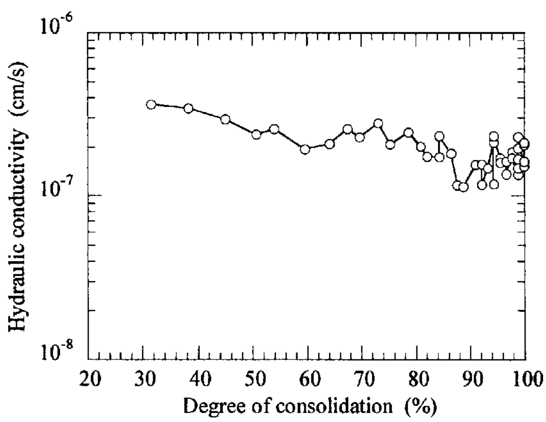

Fig. 20 Relationship between hydraulic conductivity and degree of consolidation (case of PS)

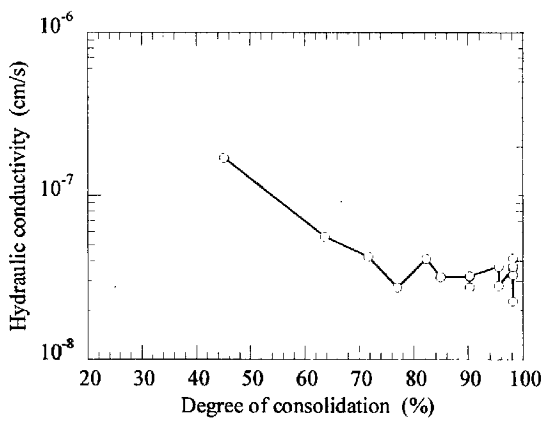

Fig. 22 Relationship between hydraulic conductivity and degree of consolidation (case of CS)

consolidation, and the hydraulic conductivity of PS can be maintained the 10^{-7} cm/s order throughout the initial to final consolidation step. It is considered that rather trend of variation of the hydraulic conductivity of the paper sludge will be more dependent on degree of decomposition of organic substance than the consolidation effect. Figures 21 and 22 showed the relationship between the centrifugal loading time, degree of consolidation and hydraulic conductivity for the construction sludge. In the construction sludge, the hydraulic conductivity decreases in proportion to the progress of the consolidation, and the hydraulic conductivity in about 80% degree of consolidation will be kept throughout the long term. The hydraulic conductivity also decreases for both sludges (in especially construction sludge) according to the consolidation effect from the just after compaction, and the hydraulic conductivity at the end of the consolidation continues throughout the long term afterwards. Therefore, it seems to be desirable that the hydraulic conductivity is handled as the variable, which depends on the consolidation degree, when the hydraulic conductivity for the time course is evaluated.

6. Conclusions

In order to reuse paper sludge and construction sludge, the application of these industrial wastes to disposal site cover material (barrier material) has been examined. In this study, centrifugal model experiment was carried out in 60 G centrifugal field, and the long term hydraulic conductivity performance and consolidation characteristic of sludge behavior has been examined.

1) Centrifugal model experiment is an effective method for measuring the long-term hydraulic conductivity of barrier material in short period. The hydraulic conductivity of sludge materials can be converted to the long-term behavior by centrifugal model experiment as per the scaling laws.
2) Under the centrifugal force loading, settlement of 14% observed compacted paper sludge in the centrifugal model at layer thickness 5 cm for the layer thickness has been observed, which is consistent with normal consolidation test results.
3) Since the degree of consolidation reaches 90% at 120 kPa acting load, the case in which the consolidation behavior of paper sludge in centrifugal model experiment was converted to the real field conditions needs about 25 days.
4) The settlement of the construction sludge is less throughout 60 G centrifugal force loading period, and it is estimated as 6% settlement of the layer thickness.
5) The case in which constructing barrier layer thickness of 50 cm in making the construction sludge, about 8.6 days are needed for the end of the consolidation under 120 kPa surcharge load.
6) Paper sludge can maintain the hydraulic conductivity of 10^{-7} cm/s under 60 G field throughout 24 hours, and test results indicated that about 10 years can maintain the hydraulic conductivity when it has been used as a barrier material.
7) The hydraulic conductivity of construction sludge in the centrifugal model experiment was converted to the disposal site barrier material, and maintaining low hydraulic conductivity is demonstrated sufficiently as a barrier material from the right after installation. In addition, the hydraulic conductivity decreases to 10^{-8} cm/s order by the effect of consolidation, it can be maintained after 10 years.
8) Variation trend of the hydraulic conductivity of the paper sludge will be more depended on degree of decomposition of organic substance than the consolidation effect.
9) Hydraulic conductivity of the construction sludge decreases in proportion to the progress of the consolidation, and the hydraulic conductivity in degree of consolidation of 80% is kept throughout the long term.

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要　旨

処分場遮水構造において重要な機能を発揮するのは，低透水性が保持できる材料で構成するバリア層である。よって，遮水工の設計では底部ライナー，およびカバーシステム内バリア層の透水性の評価が重要となる。本研究では，廃棄物である製紙汚泥および掘削汚泥を処分場バリア材へ有効利用するため，遠心模型実験を実施し，汚泥の有する透水性能，および圧密特性の 10 年間に及ぶ長期挙動を検討した。結果の一例として，製紙汚泥は，60 G 場において 10^{-7} cm/s オーダーの透水係数を 24 時間にわたって維持でき，実際にバリア材として用いた場合，約 10 年間はその透水性を維持できる結果を得た。

キーワード：遠心載荷試験，汚泥，カバーシステム，処分場，透水係数