INFLUENCE OF SAND FRACTION ON THE IMPERMEABILITY OF SEEPAGE CONTROL CLAYEY LAYER

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ABSTRACT
Since deformability and durability are required for seepage control of waste disposal site, it is ideal to use a natural material with non-deterioration. In this study, for a mixture of dredged clay and bentonite, the hydraulic conductivity was investigated. In addition, some influences of sand fraction on the hydraulic conductivity were examined. Mixing the bentonite into the clay improves the performance as seepage control, since the fine particles of the bentonite clog the pores in the clay fabric. If the sandy particles do not make a skeletal structure and each particle independents, increasing sand fraction contributes to decreasing consolidation settlement, but does not affect on the hydraulic conductivity under the same consolidation pressure.

RÉSUMÉ
L'article examine la conductivité hydraulique d'un mélange d'argile draguée et de bentonite. Le mélange est utilisé pour une barrière d'un site d'enfouissement des déchets à la zone côtière. De plus, quelques influences de la fraction de sable sur la conductivité hydraulique sont aussi exmaninées. La bentonite melangée à l'argile contribue à la performance de la barrière. Si chaque particule de sable est independente dans la matrice de l'argile, la fraction de sable n'influence pas la conductivité hyraulique sous la même pression de consolidation.

1. INTRODUCTION

The sediment found in a certain coastal area of Osaka City, Japan, is highly contaminated showing ORP (oxidation reduction potential) of –425 mV, ignition loss of 16.3%, deep black color, and extremely bad odor. For this contaminated sediment, aerobic biodegradation by aeration in laboratory was carried out and summarized in Table 1. The aeration in laboratory for a few days can change the color of contaminated sediments in a column from black to brown-green as shown in Figure 1 with SEM image, removing its offensive odor. By continuing the aeration for over 30 days, the oxidation has progressed up to the ORP of over +600 mV, but the ignition loss has not been changed, indicating that a longer time is required to gasify the organic substance by degradation. Accordingly, it can be said that the sediment is significantly contaminated, but it cannot be decontaminated efficiently by biotechnological methods. Therefore, the contaminated sediments have to be removed by dredging for the environmental recovery.

The contaminated soil dredged is dumped into a controlled type waste disposal site. Since Japan has confronted with the deficiency of the land, lately waste disposal sites are constructed along the coastal city area. Because the seepage control facility is constructed under the seawater, there are some difficulties on the construction from the unfavorable conditions, e.g. waves from the sea, settlement

Table 1. Aeration for the contaminated seabed.

Time (day)	w_L (%)	w_P (%)	I_P	Ignition loss (%)	ORP (mV)
0	162.0	54.9	107.1	16.34	–425
1	--	--	--	16.18	–28
2	--	--	--	16.39	31
4	--	--	--	16.31	193
8	--	--	--	16.32	423
17	--	--	--	15.89	511
30	149.7	57.1	92.6	16.73	652

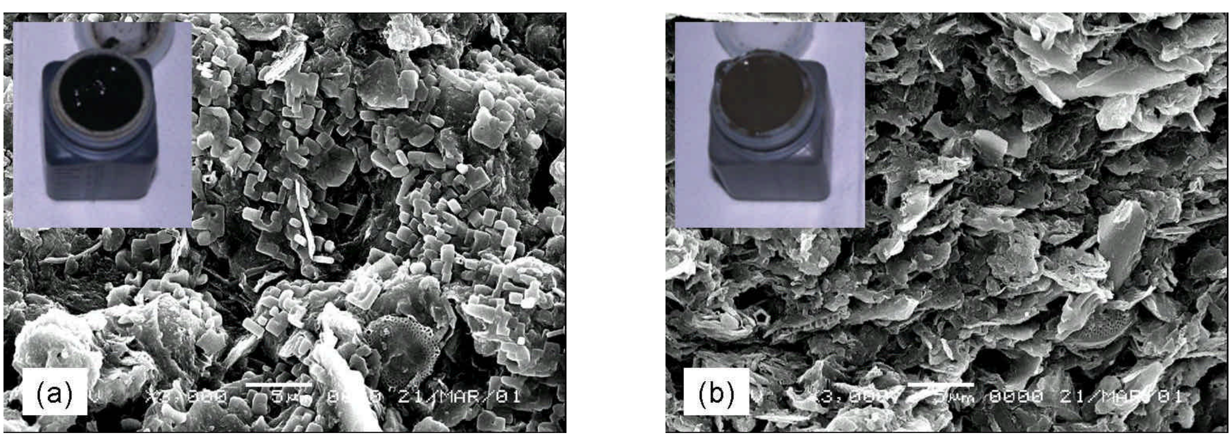


Figure 1. SEM image and color of the sediment (a) before aeration, and (b) after aeration for 30 days

Table 2. List of tested samples.

Sample	Mixture (dry mass ratio) Nagoya clay : Niigata sand	Bentonite Kg/m^3
S0(NC)	10 : 0	0
NB	10 : 0	75
S1	10 : 1	0
S2	10 : 2	0
S3	10 : 3	0
S4	10 : 4	0
S5	10 : 5	0
S10	10 : 10	0
S20	10 : 20	0
S40	10 : 40	0

and lateral displacement of the soft ground, etc. Therefore, it is necessary for the seepage control system both to be simple and reliable.

Considering the above background, a utilization of natural clay is ideally profitable, since the clay is both deformable and non-deteriorating. Recently, a new mixture of dredged clay with bentonite has been proposed as a seepage control layer. In a design procedure to evaluate the material properties, the relation of hydraulic conductivity with sand content is important in order to ensure the seepage controlling performance.

In this study, the mechanism improving the impermeability with bentonite mixing was investigated by oedometer test, SEM (scanning electron microscope) observation, and mercury intrusion porosimetry test. In addition, the effect by the variation of the sand content on the impermeability was also examined and discussed.

2. SAMPLES

The clay used in this study is Nagoya clay (NC), which has passed a sieve of 2 mm. The water content was adjusted to twice of liquid limit $2w_L$ as 130%. In addition, clay mixtures with i) bentonite, and ii) Niigata sand, were prepared as shown in Table 2. Where the bentonite is able to swell in salty water.

In NB, the bentonite of 75 kg was mixed in NC at $2w_L$ of 1 m^3. S0, S1, S2, S3, S4, S5, S10, S20 and S40 are mixtures of both NC and Niigata sand in dry mass percentage of 10:0, 10:1, 10:2, 10:3, 10:4, 10:5, 10:10, 10:20 and 10:40, respectively. Grain size distribution curves for S0–S40, are shown in Figure 2. The flow value of NB is adjusted in a range of 105–110 mm. Here, the flow value is defined as the specimen diameter after lifting up a hollow cylinder, with 80 mm in inner diameter and 80 mm in height, filled by slurry specimen, following JHS (Japan Highway Public Corporation Standard) A 313. The specimens for the oedometer tests were prepared in a mold by preliminary consolidation under a pressure of 49 kPa, and trimmed into size of 60 mm in diameter and 20 mm in height.

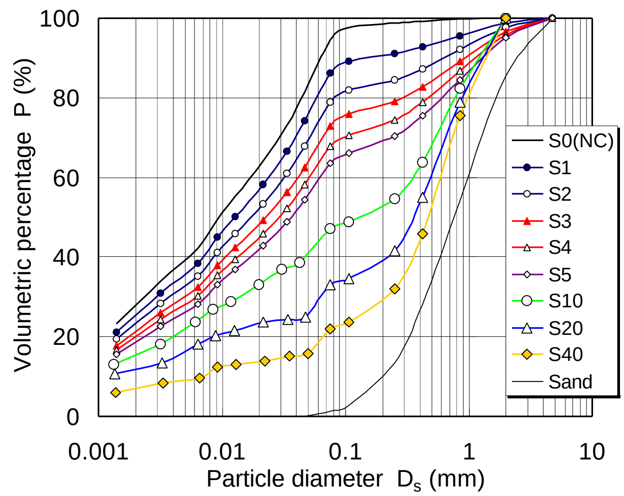


Figure 2. Grain size distribution curves.

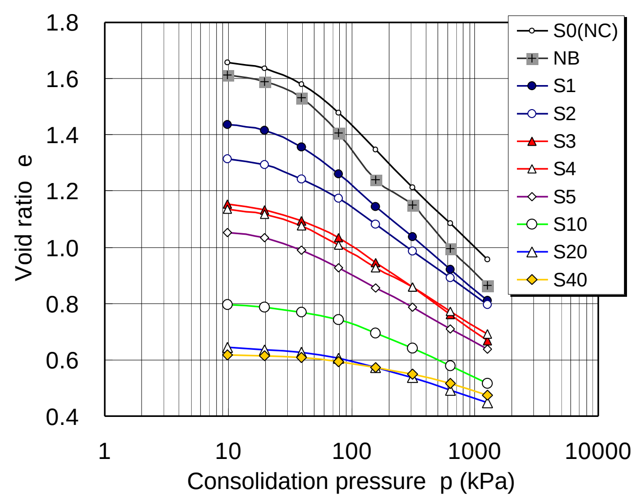


Figure 3. e – log p relationships.

3. TEST PROCEDURE

3.1 Oedomenter Test

In a case using the proposed material as a bottom seepage control layer, the layer is consolidated incrementally by waste dumping. In this study, the 24 hours incremental loading oedometer test was carried out to investigate the variation of hydraulic conductivity during consolidation, with an incremental loading ratio $\Delta p/p$ of 1. The pressure applied to the specimen was from 9.8 kPa to 1256 kPa, in total 8 stages.

The hydraulic conductivity k of clayey soil is obtained from both the coefficient of consolidation c_v and the coefficient of volume compressibility m_v. In this study, k is calculated from both c_v and m_v, but not considering the primary consolidation ratio.

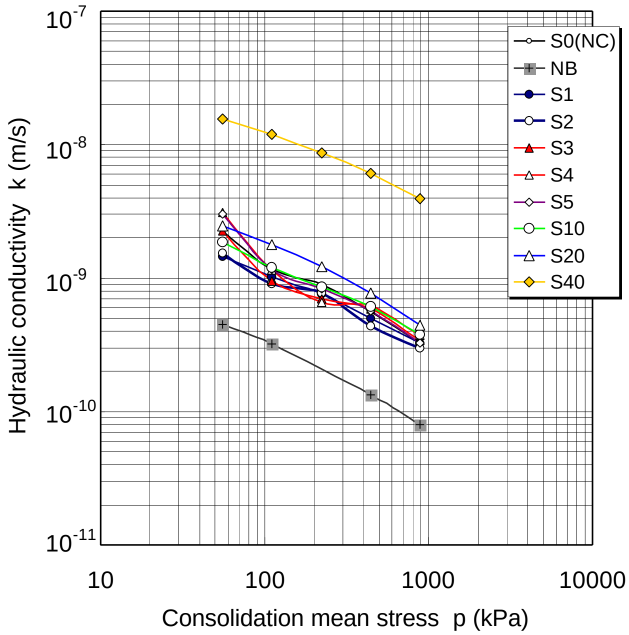


Figure 4. Relationships between hydraulic conductivity and consolidation stress.

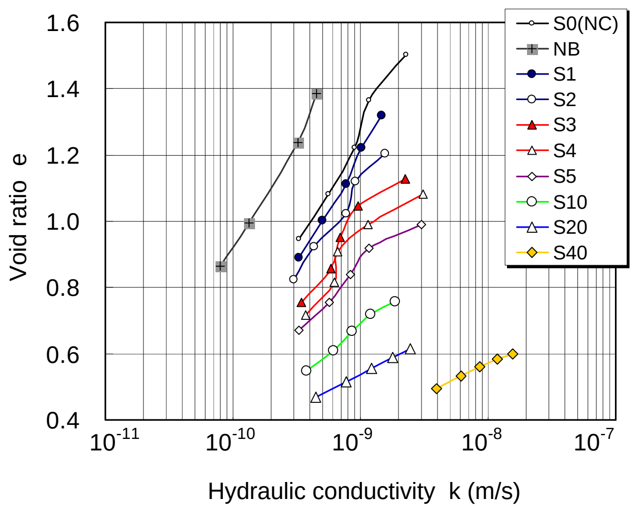


Figure 5. e – log p relationships.

3.2 SEM Observation

A plane for SEM observation is better to be cut by tension crack in frozen condition to prevent sample disturbance. This technique is so called freeze drying method. In this study, the specimens for SEM observation were prepared as follows. A trimmed sample of 5×5×30 mm was dropped into the liquid nitrogen (boiling point at -196^{o}C) in order to freeze instantly without crystallized ice, and divided into two pieces by tension crack to make a flat observation plane, which is a vertical section. The ice is sublimed under the vacuum. The dried sample is trimmed, except for the observation plane, into size of 5×5×5 mm, and put it on an aluminum specimen mount with electrical conducting adhesive. The specimen surface was coated by gold.

The scanning electron microscope (SEM) used in this study is JEOL JSM-5900LV. The observation was carried out with acceleration voltage of 22 keV, working distance of 20 mm and magnification of 1,500 times, under the high vacuum mode.

3.3 Mercury Intrusion Porosimetry Test

The specimen preparation for mercury intrusion porosimetry test is the same as that for SEM observation by using the freeze drying technique, but the size is 5×5×5 mm and observation plane is not necessary. The porosimeter used in this study is Micro-Meritics Autopore III-9400.

Because of a large surface tension, the mercury cannot enter into the pores in the specimen without a certain value of intrusion pressure. In the mercury intrusion porosimetry test, the relationship between intrusion pressure p and pore entrance diameter is expressed as the following equation,

$$D_p = \frac{-4T\cos\theta}{p} \quad [1]$$

where, T is the surface tension of mercury, and θ is the mercurial contact angle. In this study, T = 0.484 N/m and θ = 147 degree are used. The absolute intrusion pressure in a range of 0.007–228 MPa available for the porosimeter corresponds to the pore entrance diameter of 235–0.007 μm.

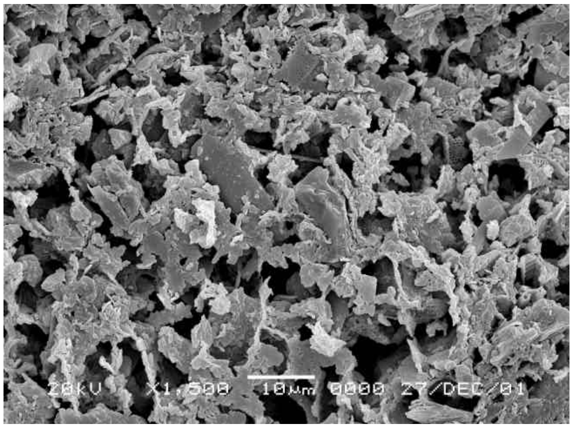
4. TEST RESULTS

4.1 Oedometer Test

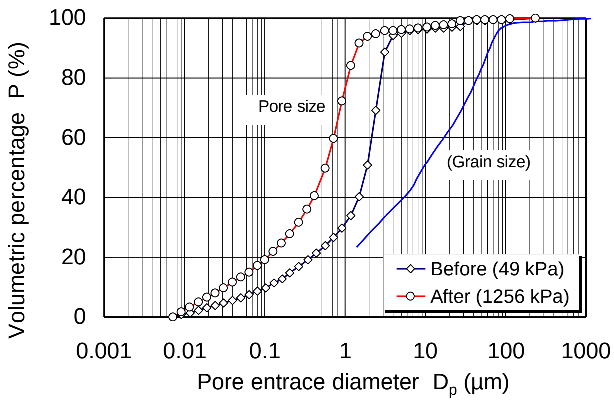
Relationships between void ratio e and logarithmic consolidation pressure p are shown in Figure 3. The value of e does not change so much, even though the bentonite is mixed into NC. Void ratio e decreases by mixing the Niigata sand, e.g., e of S5 is 30% smaller than that of S0.

Relationships between logarithmic hydraulic conductivity k and logarithmic mean consolidation pressure p in normal consolidation; where p is larger than 55.5 kPa, are shown in Figure 4. The k for NB becomes about 1/4 of that for S0–S10. The k for S20 is slightly larger than S0–S10. The k for S40 is larger by one order of magnitude than that for S0–S10. Since log k decreases linearly with log p, the hydraulic conductivity at p of 10 kPa can be extrapolated, and the value is less than 1×10^{-8} m/s, except S40, indicating that the material can be placed as a part of seepage control if its thickness is larger than 0.5 m, according to the Japanese standard.

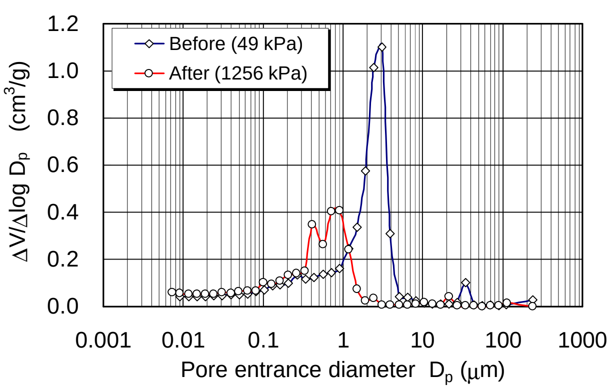
Relationships between void ratio e and logarithmic hydraulic conductivity k are shown in Figure 5. The k value for NB is about 1/3 of that for S0 at the same e. The e – log p relationships for NB is close to that for S0 (Figure 3); however, the bentonite mixtures improve the performance



(a) SEM image



(b) Pore size distribution



(c) Pore size frequency

Figure 6. Microscopic observations for S0.

as a seepage control. The value of k varies against e; however, all of log k – log p relationships for S0–S10 with various sand fractions are coincident. This fact indicates that clay matrix governs the hydraulic conductivity for these specimens.

4.2 Observation of Microstructure

For S0, NB and S4, SEM images before the oedometer test, and volumetric pore size distribution and volumetric pore size frequency before and after the oedometer tests, are shown in Figures 6, 7, and 8, respectively. Where, before and after the oedometer tests correspond to consolidation pressure of 49 kPa and 1256 kPa, respectively. The scale bar shown in the SEM images indicates 10 μm. The pore size frequency is expressed as ΔV / $\Delta \log D_p$ per soil particles of 1 g. The area below the frequency curve corresponds to the pore volume.

In Figure 6(a) showing SEM image for S0, it is seen macro-pores between aggregations of fine particles with inter bridges connecting these aggregations. The pore entrance diameters in the SEM image are in a range of 1–5 μm corresponding to the pore-entrance size frequency shown in Figure 6(c). In the same manner, in Figures 7 and 8 for NB and S4, respectively, the pore entrance diameters in the SEM images correspond to the pore-entrance frequencies.

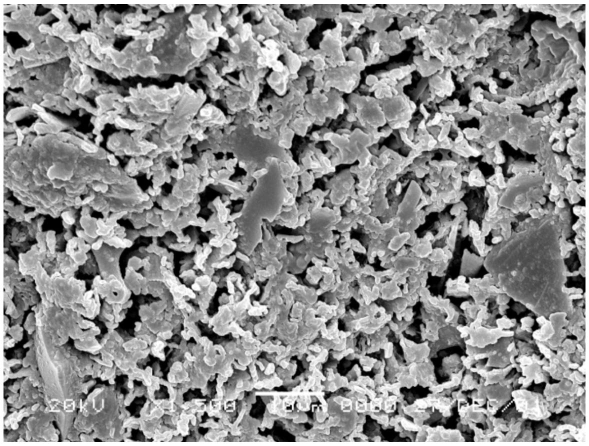
In comparison with S0 and NB, the macro-pores in NB are clogged by fine bentonite particles, resulting in a smaller hydraulic conductivity. From this fact, it can be concluded that the proposed material that is a mixture of both natural clay with a low hydraulic conductivity, and fine particle bentnite, for a seepage control layer is highly reliable.

In S4, there are some large particles, but these do not make a skeletal structure and independent each other in the clay matrix. The number of the visual pores decreases with increasing sandy particles; however, the pore entrance diameter remains in a rage of 1–5 μm. Considering a fact that both void ratio e and compression index C_c decrease with increasing the sand fraction in Figure 3, following conclusions are derived:

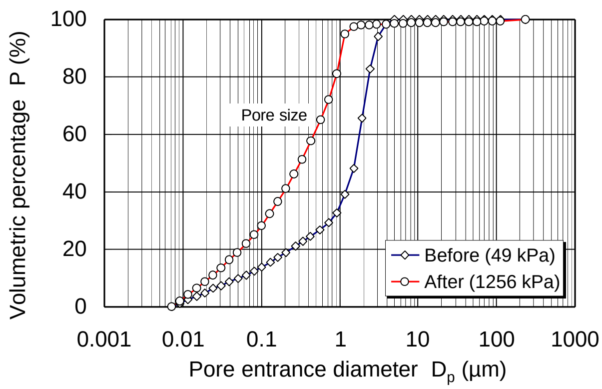
Mixing sandy particles in clay contributes to decrease the consolidation settlement by minimizing the void ratio, and does not influence the hydraulic conductivity under the same overburden stress, if each sandy particle independents in the clay matrix. In this study, some evidence of sandy skeletal structure was observed for the specimen S20 and S40. For S20, clay fraction (less than 0.005mm) and sand fraction (larger than 0.075mm) are 16% and 70%, respectively. Therefore, the variation of sand fraction in the dredged clayey soil is not very important in practice. In addition, since increasing the sand fraction at the same water content improves the fluidity for pumping, mixing sand is possibly an effective method.

5. MICROSTRUCTURE AND HYDRAULIC CONDUCTIVITY

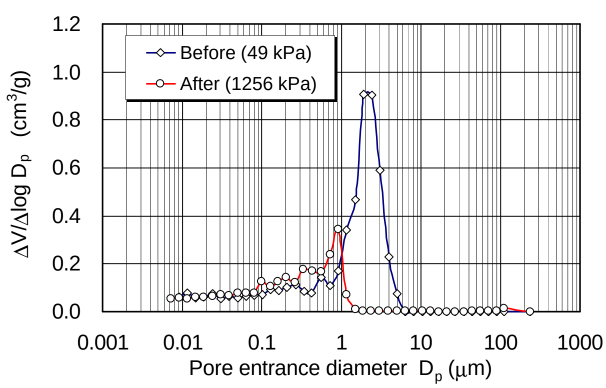
For sandy soils, the hydraulic conductivity has been often evaluated by using a representative grain size (e.g. D_{10}). However, for a clayey soil, the hydraulic conductivity has to be evaluated taking account of the complicated tortuous channel in the fabric. Among many previous researches correlating the microscopic fabric with the hydraulic conductivity, a probabilistic approach proposed by Childs and Collis-George (1950) and Marshall (1958) are often used (e.g. Garcia-Bengochea et al., 1979; Lapierre et al., 1990; Watabe et al., 2000).



(a) SEM image

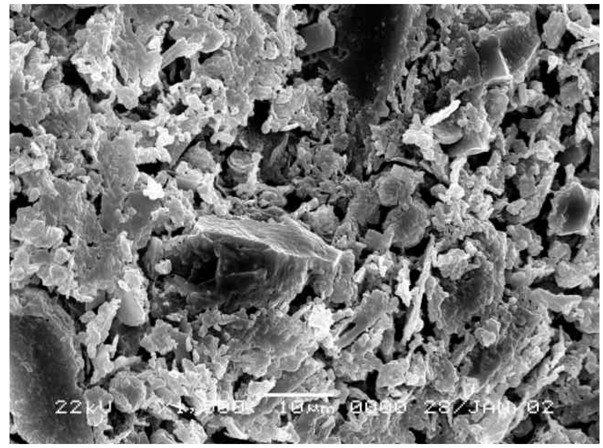


(b) Pore size distribution

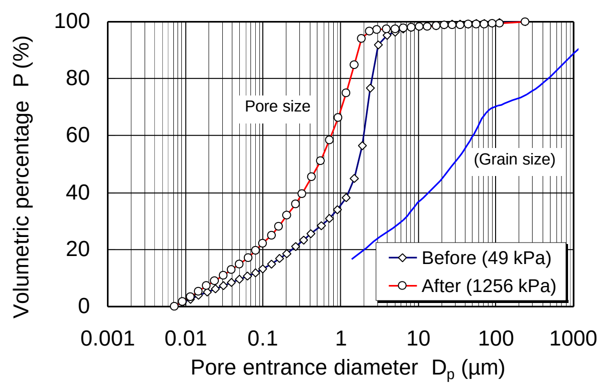


(c) Pore size frequency

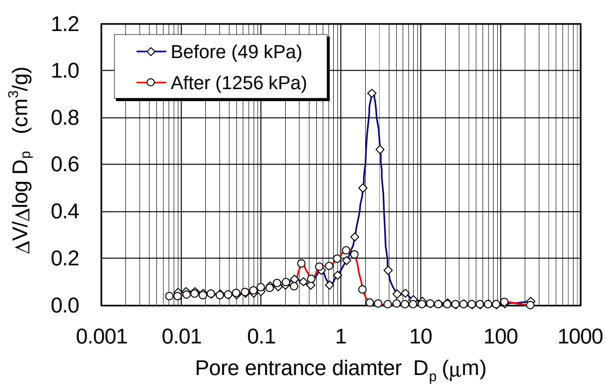
Figure 7. Microscopic observations for NB.



(a) SEM image



(b) Pore size distribution



(c) Pore size frequency

Figure 8. Microscopic observations for S4.

The detail of the model is as follows: if two sections of the porous material having a porosity n are brought into contact, the probability that a pore of diameter D_{pi} from one section is joined with a pore of diameter D_{pj} of the other section is [n $P(D_{pi})$] [n $P(D_{pj})$]. In these circumstances and for circular capillaries, Garcia-Bengochea et al. (1979) derived the following equation for hydraulic conductivity:

$$k = \frac{\rho_w g n^2}{32\mu} \sum_{i=1}^{m} \sum_{j=1}^{m} \left[D_s^2 P(D_{pi}) P(D_{pj}) \right] \qquad [2]$$

Where, ρ_w is the water density; g is the gravitational acceleration; μ is the absolute viscosity; m is the total number of intervals on probability of pore diameter between 0 to 1; i, j are counters from 1 to m; and D_s is the smallest diameter between D_{pi} and D_{pj}. Eq.2 is based on the idea that the smallest pore diameter between upstream and

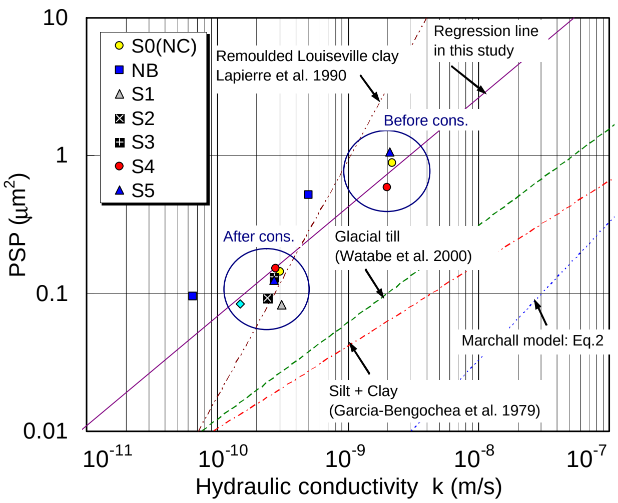


Figure 9. Relationships between pore size parameter PSP and hydraulic conductivity k.

downstream governs the hydraulic conductivity. Garcia-Bengochea et al. (1979) defined a pore-size parameter (PSP), as follows:

$$k = C_s PSP \qquad [3]$$

where C_s is a shape factor with,

$$C_s = \frac{\rho_w g}{32\mu} \qquad [4]$$

and, for Marshall's model:

$$PSP = n^2 \sum_{i=1}^{m} \sum_{j=1}^{m} \left[D_s^2 P(D_{pi}) P(D_{pj}) \right] \qquad [5]$$

The relationships between PSP and hydraulic conductivity both before and after the oedometer tests are plotted in Figure 9. S1, S2 and S3 before the oedometer tests are not shown here, because a not negligible shrinkage had happen during the specimen preparation. The hydraulic conductivity measured are plotted around 1/100 of that calculated from Eq.2; however; the PSP can explain the fact that the hydraulic conductivity of NB is the smallest, before the oedometer test. However, the data for NB is plotted around 1/3–1/4 of the data family for sand mixtures, indicating that the tortuous channel of NB is much more complicated than that of sand mixtures.

In order to correlate the PSP from pore size distribution with the hydraulic conductivity, Garcia-Bengochea et al. (1979) proposed the following equation:

$$k = C_s^*(PSP)^b \qquad [6]$$

where, C_s^* and b are fitting parameters, and C_s^* and C_s in Eq.4 are not necessary to coincide.

The C_s* and b obtained from this study, and the relationship expressed by Eq.6 using these values, are shown in Table 3 and Figure 9, respectively, with some previous data. In Figure 9, the position of the line shifts rightward with increasing the C_s^*, and the gradient becomes smaller with the b. The b value except Lapierre et al. (1990) is greater than 1. All b values for this study, Garcia-Bengochea et al. (1979) and Watabe et al. (2000) are not so different, but that for this study is the smallest among them.

The values of C_s^* and b are influenced by test method, e.g. suction test, mercury porosimetry, etc., specimen preparation, e.g. consolidation, compaction, etc., and soil material, e.g. grain size, shape, minerals, etc. Applicability of proposed model has to be examined more, using C_s^* and b values for various materials.

6. CONCLUSIONS

In this study, for the mixture of the dredged clay and the bentonite, the hydraulic conductivity was investigated by carrying out the oedometer test and microscopic observations. In addition, some influence of sand fraction on the hydraulic conductivity was also examined. The followings are derived as conclusions:

1) Mixing the bentonite into the clay improves the performance as seepage control, since the fine particles of the bentonite clogs the voids in the clay fabric.
2) If the sandy particles do not make a skeletal structure and each particle independents in the clay matrix, increasing sand fraction contribute to decrease consolidation settlement, but does not affect on the hydraulic conductivity. In this study, some evidence of sandy skeletal structure was observed for the specimen S20 and S40. For S20, clay fraction (less than 0.005mm) and sand fraction (larger than 0.075mm) are 16% and 70%, respectively.
3) In order to correlate pore size distribution and hydraulic conductivity, the pore size parameter PSP is introduced following some previous researches. The PSP can evaluate variation of the hydraulic conductivity by consolidation, and the effect of mixing bentonite.

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Table 3. List of tested samples.

Reference	Remarks	C_s^*	b
Marshall, 1958	Marshall model, Eq.2	3.07×10^{-5}	1.0
Garcia-Bengochea et al. 1979	Clay + Silt Permeability test	2.06×10^{-5}	1.67
Lapierre et al. 1990	Clay Oedometer test	1.05×10^{-7}	0.58
Watabe et al. 2000	Gracial till Permeability test	5.34×10^{-6}	1.42
This study	Clay + Sand Oedometer test	2.96×10^{-7}	1.26