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Permeability of lightweight treated soil mixed with air foam

Perméabilité d'un sol léger traité mélangé à de la mousse à air

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ABSTRACT
Lightweight treated soil mixed with air foam is proposed for application in waterfront construction. The permeability of the material is an important characteristic governing changes in the mechanical properties and the possibility of ground water pollution. In this paper, several kinds of permeability tests were conducted and the permeability mechanism was observed using X-ray CT scanner. We concluded that the permeability of lightweight treated soil mixed with air foam is governed by the clay mixed with cement and that the air voids are compressible, impermeable media.

RÉSUMÉ
Il est proposé d'utiliser un sol léger traité mélangé à de la mousse à air pour les constructions situées sur des rives. La perméabilité est un aspect important en ce qui concerne les changements de propriétés mécaniques du matériau et dans l'éventualité d' une pollution de la nappe souterraine. Pour ce document, plusieurs tests de perméabilité ont été effectués et le mécanisme de la perméance a été étudié au moyen d'un tomodensitomètre à rayons-X. Nous avons conclu que la perméabilité d'un sol léger traité mélangé à de la mousse à air est affectée par de l'argile mélangée à du ciment et que la porosité est un élément compressible et imperméable.

1 INTRODUCTION

Lightweight treated soil mixed with air foam(LWS) is geotechnical materials made of high-water-content clay mixed with air foam and cementing materials. It is characterized by light unit weight and strong shear strength. Such characteristics are favorable in backfill materials for reducing the earth pressures acting on retaining structures.

As LWS is intended for use under the water table in port areas, there is a risk that part of the air in LWS could be replaced with water over a long period. This kind of problem is caused not only by water pressure but also by the soil's permeability. Reduction in material strength through contact with seawater or groundwater pollution through the alkaline material can also occur. These kinds of phenomena are mainly related to the permeability of LWS.

Little information is available on the permeability of LWS, although the permeability of cement-mixed clay is known to decrease(Terashi et. al., 1983). LWS is a new material composed of saturated clay, cement, and air foam. The air in LWS is in the form of bubbles, and each bubble retains its position after the LWS is solidified. Because the unsaturated condition of LWS differs from natural unsaturated soils, its permeability mechanism may also differ from natural unsaturated soil.

The purpose of this study is to clarify the permeability characteristics of LWS. First, permeability tests with triaxial apparatus and constant rate of consolidation tests were conducted. From the results, a hypothesis of the permeability mechanism was proposed. Then, a seepage experiment with X-ray CT observation was conducted to determine the permeability mechanism in LWS. Finally, other permeability tests were conducted using an X-ray CT scanner. We conclude the permeability of LWS is governed by clay mixed with cement and that the air voids are compressible, impermeable media.

2 EXPERIMENTAL METHOD

2.1 *Permeability test*

Permeability tests with triaxial apparatus and constant rate of consolidation tests were conducted to clarify the macroscopic permeability of LWS.

2.1.1 *Specimen preparation*

Marine clay dredged from Kawasaki Port (ρ_s= 2.678 g/cm^3, w_L= 52.1%, w_P= 23.0%) was used in this test. The mixing conditions for making LWS are shown in Table 1. The target unconfined compression strength at 28 days cured q_{u28} was 200 kN/m^2.

Specimens were prepared as follows:

1) Liquefied clay of 2.5w_L was prepared.
2) Air foam made of surface-active agent and blast furnace cement B were mixed to the clay for three minutes.
3) Molds of 5cm in diameter and 12cm in height were filled up with the mixture.
4) The molds were placed in a pressure cell filled with water before being solidified for curing under pressure simulating underwater conditions. The pressures in the cell were 0, 50, and 100 kN/m^2. Curing durations were between 14 days and 28 days.

Table 1. Mixing conditions for LWS.

	Kawasaki clay		Ariake clay	
	Mass (kg/m^3)	Volumetric fraction (l/m^3)	Mass (kg/m^3)	Volumetric fraction (l/m^3)
Dry mass	442	164	367	136
Water	574	574	624	606
Cement	75	24	100	33
Air foam	9	238	9	225
Total	1100	1000	1100	1000

2.1.2 *Permeability test using triaxial apparatus*

The test procedure was as follows: First, the specimen cured at 0 kN/m^2 curing pressure was trimmed to 10 cm in height and 5 cm in diameter, after which it was placed in the triaxial cell. Then the cell pressure of 50 kN/m^2 was applied to start consolidation. No back pressure was applied. The consolidation duration was 3 days. Following consolidation, pressure of 20 kPa was applied to the volume change burette connected to the bottom of the specimen. Then the water was let into the specimen. Influent and effluent water volumes were measured using volume change burettes connected to both the bottom and top of the specimen during the water flow. Water flow continued for a week.

The permeability of a specimen made of the same amount of cement and clay, but without air foam, was also examined in order to check the effect of air foam.

2.1.3 *Constant rate consolidation test*

We also performed constant rate consolidation tests through which the coefficient of permeability of the geotechnical material could be estimated.

The mixing conditions of LWS were the same as those of the specimen used in the permeability test in the triaxial apparatus. The LWS was used to fill a consolidation ring 2cm in height and 6cm in diameter. The specimen used in this test was cured at 0, 50, and 100 kPa for 28 days. After curing, both ends of the specimen were trimmed to 2cm in height, and then the specimen was placed in the consolidation apparatus. Back pressure of 100 kPa was applied for measuring the pore water pressure change. The consolidation rate was 0.05%/min.

2.2 *Seepage test and permeability test with X-ray CT observation*

2.2.1 *Seepage test*

The sample used in this test was in-situ LWS that was sampled at the trial construction site at Kumamoto Port. The dredged slurry used for the LWS was Ariake clay(ρ_s= 2.619 g/cm^3, w_L= 119%). Table 1 shows the mixing conditions. The LWS was mixed using the mixing plant at the construction site. The air foam was made with surface-active agent. The sampling depth was 0.9 to 1.0 m. The target of the density after 28 days of curing was 1.1 t/m^3. The density after 28 days of curing was 1.17 t/m^3, a slightly higher value than expected.

The sample was trimmed to 100 mm in height, and 50 mm in diameter. The specimen was kept in water at a constant temperature of 20 °*C* . Therefore, water could seep into the specimen from not only from the sides but also from the bottom and top ends. In this test, the weight of the specimen and its volume were measured over a long period. Additionally, the specimen was scanned using X-ray CT every 1mm of the thickness from the bottom to the top each time measurement were taken. This test was continued for 19 months.

2.2.2 *Permeability test with X-ray CT observation*

Ariake clay was used for making LWS in this test. The mixing conditions of LWS were the same as those in the tests in 2.2.1(Table 1).

Figure 1 shows the apparatus used in this study. The dimensions of the specimen were 50 mm in diameter and 60 mm in length. The specimen was placed in the pressure cell and sealed at the side using a rubber membrane. To confirm the sealing and minimize the void between the specimen and the membrane, the silicon type glue was used. The end where the water flowed out was covered with porous stone and a cap with a pipe to direct the flow to the outside of the cell. The other end was open for free influent of water to the specimen.

Cell pressure of 100 kPa and 300 kPa was used. In this test, the water was expected to flow one dimensionally from the open end to the capped end. To observe the flow of water, an X-ray CT scanner was used.

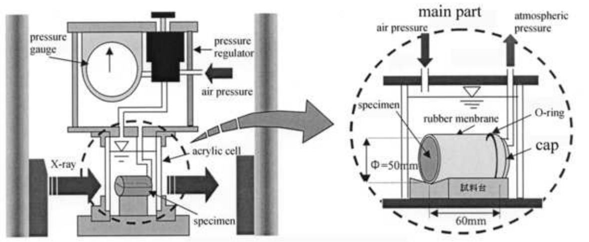

Figure 1. Outline of the permeability test apparatus in X-ray CT scanner.

3 RESULTS

3.1 *Permeability test*

3.1.1 *Permeability test using triaxial apparatus*

Figure 2 shows the relation between duration and water influent and effluent. The difference between the two specimen conditions was whether or not air foam was included. The water content ratio of both specimens was almost the same. The specimen included air foam in Case A-4 and did not include air foam in Case A-6. Water pressure gradients of both tests were about 20.

Figure 2 shows that when the specimen did not include air foam, the amount of water influent and effluent was almost the same, and influent and effluent velocities were almost constant. On the other hand, when the specimen included air foam, the velocity of water influent was very fast and the water content increased at the beginning, but became constant later. The water effluent rate of the specimen with air foam was smaller than that without air foam. These two test results showed that the permeability determined from the water influent and effluent — 'apparent' permeability — in the case without air foam was larger than that in the case with air foam. This result shows that the air foam is a less permeable media.

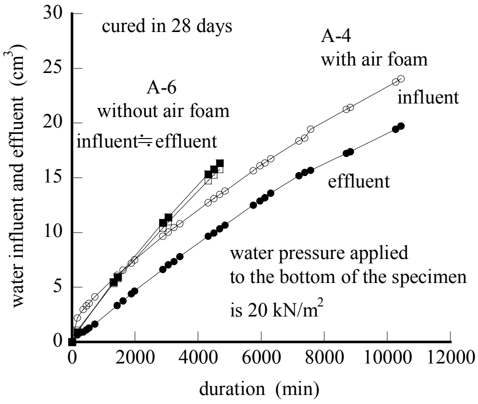

Figure 2. Difference in water influent and effluent due to existence of air foam.

3.1.2 *Permeability in constant rate consolidation test*

Coefficient of permeability was also measured using the constant rate consolidation test with pore pressure measurements. The coefficient of permeability can be calculated in accordance with (1) if the specimen is saturated.

$$k = \frac{\Delta H \cdot \overline{H}}{2 \cdot \overline{u} \cdot \Delta t} \times \gamma_w \tag{1}$$

where, Δt: measuring interval, ΔH: compression of specimen during Δt, $\overline{H}$:average specimen height during Δt, $\overline{u}$:average of the pore water pressure measured at the bottom during Δt.

Figure 3 shows the relation between the coefficient of permeability k calculated by (1) and the void ratio. Because of the compressibility of pore fluid in LWS, the coefficient of permeability shown in Fig.3 has some error. The coefficient of permeability calculated in accordance with (1) gives too high a coefficient when the void ratio is large; because the compressibility of pore fluid was higher, the consolidation pressure was lower.

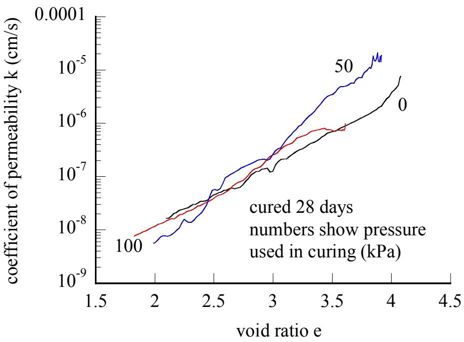

Figure 3. Relation between void ratio and coefficient of permeability derived from constant rate of consolidation test. Calculation of k assumed a saturated specimen.

3.2 *Seepage test and permeability test with X-ray CT observation*

3.2.1 *Seepage test*

During the seepage test, the wet density of the specimen was increased with the increase of elapsed time. The initial wet density of it was 1.17 g/cm^3, and it changed to 1.32 g/cm^3 after 19 months period. But the velocity of the change of the density gradually decreased.

Figure 4 shows X-ray CT images of the specimen at mid height at several different elapsed times, from the beginning to 19 months. The light parts of the image show relatively high CT values with high density. Meanwhile, the dark parts show relatively low CT values with low density. Thus, it was observed that the seepage of water at the front, gradually extended to the center of the specimen axi-symmetrically. Here, there was a large black region in the X-ray CT image and it was considered to be a relatively large air void. The shape of the air void did not change over the 6 month period from the time the seepage test started. However, water seeped into the air foam after 6 months because the CT values changed from about -1000 to 0 (also see Fig.5).

Figure 5 shows the change in CT values around the large air void indicated by the arrows in Fig.4. Up to 6 months, the CT values of the central part of the air void was less than -1000. After 9 months, the CT values were suddenly changed to around 0. The CT value of water is defined as 0 in this case. This change means that the void was filled with air up to 6 months, but was filled with water after 9 months. It can be seen from Fig.4 that color of the area surrounding the air void had already changed at 6 month. Then the void was filled with water. This means that first the water seeped in around the air void.

3.2.2 *Permeability test with X-ray CT observation*

Figure 6 shows the X-ray scanned image of a cross section of the center of the cylinder axis of the specimen. The specimen used was prepared in the laboratory and the pressure of the cell was 100 kPa. Figure 6 (a) shows the original scanned image. Figure 6 (b) shows the locally smoothed image. In these images, the light part shows the area with high CT values and the dark part shows the area, with low CT values.

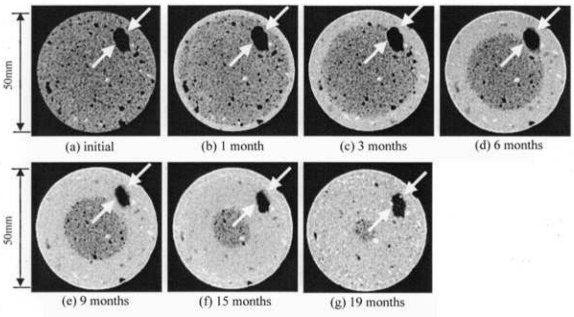

Figure 4. Change in X-ray image according to seepage duration.

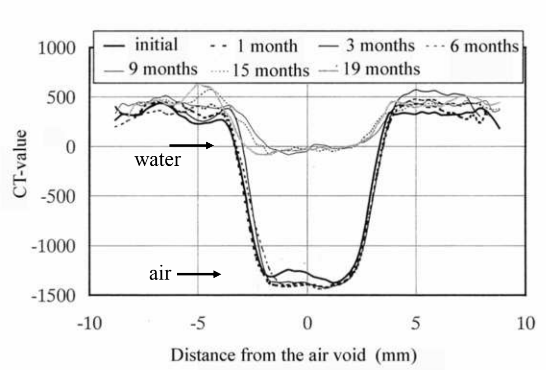

Figure 5. Change in CT values around the air void shown in Fig.4.

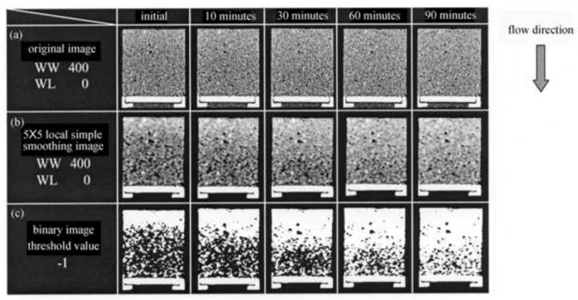

Figure 6. Images of X-ray CT during the permeability test.

4 DISCUSSION

4.1 *Macroscopic image of permeability*

Figure 2 shows that the volume of air in LWS was changed during the test, and the flow of the water in the specimen was affected by the compressibility of the pore fluid. The consolidation of soil including compressive fluid is expressed as follows:

$$\alpha \frac{\partial u}{\partial t} = \frac{k}{m_v \rho g} \frac{\partial^2 u}{\partial z^2} \qquad (2)$$

where $\alpha = 1 + n\left(C'_w / m_v\right)$, ρ: density of the pore fluid, z: distance, t: time, , n: porosity(=e/(1+e)), k: coefficient of permeability, u: absolute pressure of the pore fluid, g: gravity acceleration, C'_w: volumetric compressibility of pore fluid, m_v: coefficient of volume change for saturated soil.

Verruijt(1969) showed thatC'_w is expressed as follows if the compressible fluid can be modeled as a mixture of water and air.

$$C'_w = (1 - S_r)/u + S_r C_w \qquad (3)$$

where C_w: compressibility of water, S_r: rate of saturation.

This assumption is valid if the entrapped air is in a bubble state in pore water and the coefficient of permeability is approximately the same as that of the saturated clay (Zen, 1993). The air in LWS exists separately and never run through the specimen in considering the specimen preparation. It is reasonable that LWS can be treated as the material with compressible fluid in considering the permeability of LWS.

Simulation of influent volume using (2) showed air in the foam was pressurized even the foam was produced under atmospheric pressure. It is reasonable that the diameter of each bubble was less than 0.1mm and such a small bubble can be pressurized because of surface tension(Kikuchi and Yoshino, 1998). Change in influent volume during flow testing was also simulated using (2).

Air foam in LWS was less permeable as mentioned in 3.1.1. Figure 7 shows the corrected relation between permeability and void ratio. The volume of air foam was excluded for the plotted void ratio in the figure. The permeability of LWS shown in Fig.7 was calculated using (2) and considering that the cross sectional area of air foam was excluded for calculating the effective cross sectional area for water flow. Here, we define this permeability as 'true' permeability. Figure 7 shows that the relations between the coefficient of true permeability and void ratio of LWS with air foam, and of LWS without air foam estimated by triaxial apparatus agree well. The result shows that this kind of correction can represent the permeability of LWS with air foam from macro point of view.

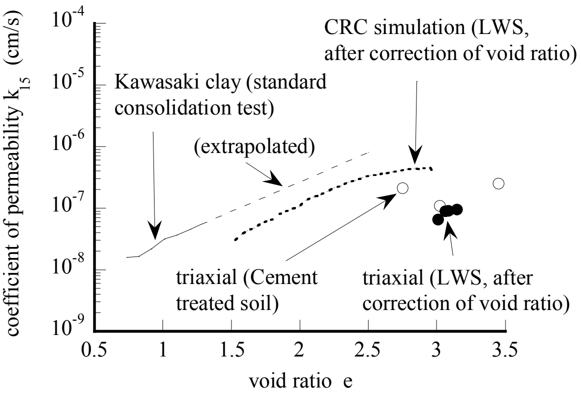

Figure 7. Coefficient of permeability of LWS.

Figure 7 also shows the relation between the permeability and void ratio of the Kawasaki clay used in LWS and the corrected relation estimated by the constant rate consolidation test. The permeability of Kawasaki clay is extrapolated in the figure because of a linear relation between the logarithm of permeability and void ratio(Kobayashi et al., 1990). The relation estimated by the constant rate consolidation test is almost parallel to the relation in Kawasaki clay. And, from the relation in LWS shown in Fig.2, the permeability of LWS is rather small due to the mixing of cement. Terashi et al. (1983) showed that the reduction of permeability is affected not only by grain distribution but also by void ratio: the addition of 75 kg/m^3 cement to clay produces one- or two- order magnitude reduction of permeability. The result in this study showed that the reduction of permeability ranges from 1/30 to 1/4.

4.2 *Permeability mechanism in accordance with the observation of X-ray CT scanner*

Here, we summarize the mechanism of the seepage(Otani et. al., 2001). Figure 8 shows an image of the mechanism. (1) Seepage moves in a concentric circle. Water seeps to the area without air at first. (2) The air void will be filled with water after it is surrounded by the water absorbed area.

From the smoothed CT-value distribution in accordance with Fig. 6 (b), the intensity of CT values smaller than 0 decreases with time and those larger than 0 increases. And, average CT value increase with time, because the density will increase in accordance with compression of air voids and water seepage. This is because voids in air foam will be compressed and saturated by water with water influent.

The threshold value was selected where the intensity of the CT value started to increase. Figure 8(c) shows the binary image according to the threshold. From Fig.8(c), we can separate the area where water entered and visualize front line of the water entrance. Figure 8(c) shows that the area of the white part increased with time and the front of the white part moved to the capped end with time.

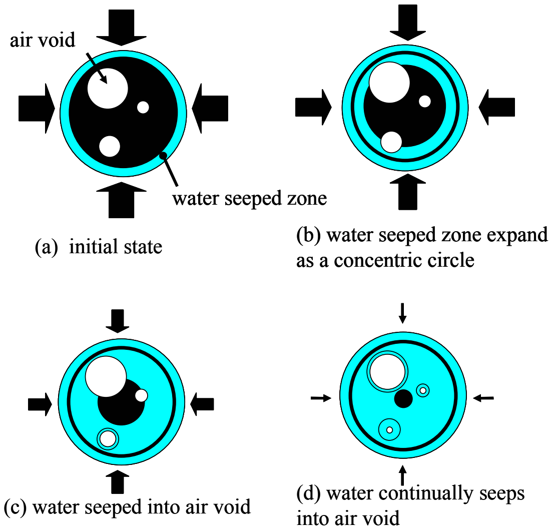

Figure 8. Image of mechanism of seepage to LWS.

Here we define the ratio of seepage as the ratio of the white area to the cross sectional area of the specimen for each distance from the entrance. We attempt to calculate the seepage velocity from the ratio of seepage. In this calculation, the white areas are considered to be water seeped area and the volume of water in the specimen was estimated from the cross section of the white area. The influent velocity of the water was calculated by the change of included water with time. The coefficient of permeability was estimated from the final influent velocity and the water pressure component. The coefficient of permeability calculated by the assumption was about 10^{-6} cm/s. The range matched that measured by the permeability experiment mentioned in 4.1.

5 CONCLUSION

In this paper, we discussed the permeability characteristics of LWS. We considered the hypothesis that the air voids in the material are impermeable compressible media, and the coefficient of permeability of the cement treated clay part of LWS is the same as that of cement treated clay. Using X-ray CT scanner, we visualized the permeability mechanism, and confirmed that the hypothesis is almost correct.

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