低レベル放射性廃棄物の処分に用いる隔離材料の新しいせん断透水同時試験方法に関する研究

張, 銘
九州大学工学建設デザイン

https://doi.org/10.11501/3110889

出版情報：Kyushu University, 1995, 博士（工学）, 課程博士
バージョン：published
権利関係：
Chapter 5 COUPLED SHEAR AND PERMEABILITY TEST ON KAOLIN-SAND MIXTURE

5.1 Objectives

As mentioned in the previous chapters, to simultaneously conduct the shear and permeability test on soil materials is very difficult. The coupled shear and permeability test on extremely low permeability materials is even more complicated because any existing permeability test methods have the limitations of themselves when testing impermeable materials. Although the promising methods and the correspondingly improved analysis theories for both shear and permeability tests have been derived in chapter 3 and chapter 4 respectively, it is necessary to firstly ascertain the practicability and the designed functions of the proposed methods.

In addition, the major purpose of the present study is to investigate the impact of shear strain on the permeability of barrier materials. In other words, the purpose should be the experimental verification of that the permeability of the barrier materials will not be significantly influenced by the shear strain owing to the presence of expansive component of soil that swells and fills the fissures which might occur in the barrier materials and thus maintains their permeability almost constant. To verify this expected function of the expansive soil, it is also necessary to conduct the coupled shear and permeability test on the mixtures only consisting of non-expansive soils for a comparison. Similar tests on non-expansive soils are also important for many engineering practices covering various kinds of engineering fields (as described in section 3.1).

This chapter develops a shear test system which enables to load a thick-walled hollow cylindrical specimen by means of the differential pressure between the pressures to be applied on the outer and inner side walls of the specimen (see section 3.4). This system for the shear test should be capable of monitoring the small changes in specimen volume so that the deformation status of the specimen during loading can be checked through the measurements. Also, the measurements are expected to be used to verify the feasibility of the theoretical analysis of the new shear test method by comparing those with theoretically computed values and/or to directly calculate the shear strain in the specimen. To easily confirm the functions of the manufactured shear test apparatus, the permeability test method to be utilized is the constant-head method, a technically maturated approach. This can be accomplished by selecting the testing materials with relatively high permeability. In addition, by practically conducting the coupled shear and permeability test on non-expansive soils, this chapter establishes the basic procedures for the
coupled shear and permeability test on soil materials, and illustrates whether and how the permeability of a general soil material varies with increasing shear strain in the specimen.

5.2 Testing Materials

The components coupled in the shear apparatus for the permeability measurement should be compatible with the permeability of the specimens to be tested. Passing hole or holes and pipe lines for the permeability measurement must be selected with appropriate dimensions. The narrowness of the passing way for permeating fluids should enable to

(1) extrude the bubbles in the pipe lines easily and completely when saturating the specimen before the permeability measurement;

(2) avoid forming bubbles in the pipe lines during the permeability test; and

(3) flow the permeating fluid with less resistance compared with that caused by the testing specimen.

Similarly, special care should be taken in designing the porosity of porous plates and filter paper. Their permeability should be greater than that of specimens to be tested. At the same time, however, they must be capable of preventing the specimen from piping and erosion during the permeability measurement.

The shear test apparatus in the present study is basically designed for testing low permeability barrier materials, passing way of permeating fluids will be relatively narrow. Consequently, the resistance of the pipe lines and porous plates to the flow will be relatively high. Therefore, the permeability of nonexpansive soil materials to be tested using the same shear apparatus for barrier materials should be carefully determined before tests. Two important aspects are considered in determining the permeability of the nonexpansive soil materials. They are:

(1) the permeability of the nonexpansive soil materials should be as low as possible to fit the ability of permeability measurement components coupled in the shear apparatus; and

(2) the permeability of the specimen can be measured by means of the constant-head permeability test method, which is technically mature, so that the functions of the newly developed shear test apparatus based on the new analysis theory can be easily confirmed.

5.2.1 Physical properties
The appropriate permeabilities on the order of $10^{-8}$ m/s of the specimens, which might be the lowest limit for the permeabilities to be measured by means of the constant-head method with an acceptable testing time, were obtained by mixing coarse-grained and fine-grained nonexpansive soils and compacting them with an appropriate water content. The coarse-grained soil used in this study is the so-called Standard sand made by Toyoura Industry (see appendix A-1). The fine-grained soil used here is kaolin made by Katayama Chemistry Industry (see appendix A-1). Both of the soils are commercially available materials and their physical properties are tabulated in Table 5-2-1. Necessarily, the more the fine-grained component in the mixture, the lower the permeability of the specimen. The weight ratio of the oven-dried Standard sand to the air-dried kaolin was determined to be 85:15 in the present study (see appendix A-1). This weight ratio was determined with consideration of the following two factors:

1. the weight ratio to be used for the bentonite-sand mixtures will be 85:15 (see Chapter 6);
2. a trial permeability test result of a compacted kaolin-sand mixture with the weight ratio of 85:15 showed that the mixture can produce the required permeability on the order of $10^{-8}$ m/s.

5.2.2 Compaction and preparation of specimens

1. Compaction test

To determine an appropriate water content for preparing the testing specimens, compaction test on the Standard sand and kaolin mixture was firstly conducted. For obtaining uniform distribution of the fine-grained kaolin particles in the mixture, the materials were sufficiently mixed with the assigned weight ratio before adding appropriate amounts of water to them. Compaction test was conducted with the routine Method of Test for Moisture-Density Relations of Soils Using Rammer (JIS A 1210 T-1979, JSSMFE 1980). The test results for the Standard Proctor Compaction were shown in Fig. 5-2-1. The water content was measured according to the Method of Test for Moisture Content of Soils (JIS A 1203-1978, JSSMFE 1980) from the residual materials prepared for each compaction test. From the diagram in the Fig. 5-2-1, we can find that the maximum dry density for the mixture is 1.78 Mg/m$^3$, and the corresponding optimum water content is 11.5%.

2. Preparation of specimens
Table 5-2-1 Properties of Toyoura standard sand and kaolin

<table>
<thead>
<tr>
<th>Type</th>
<th>Toyoura standard sand</th>
<th>Kaolin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Mg/m³)</td>
<td>2.650</td>
<td>2.70</td>
</tr>
<tr>
<td>Mean particle size (mm)</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Uniformity coefficient</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Max. void ratio</td>
<td>0.977</td>
<td></td>
</tr>
<tr>
<td>Min. void ratio</td>
<td>0.597</td>
<td></td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td></td>
<td>51.6</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td></td>
<td>28.0</td>
</tr>
<tr>
<td>Plastic index</td>
<td></td>
<td>23.6</td>
</tr>
</tbody>
</table>

Zero-air-void curve

\[ S_r = 100\% \quad \rho_s = 2.649 \text{ Mg/m}^3 \]

Fig. 5-2-1 Compaction test result of kaolin standard-sand mixture
Specimens for the triaxial test and for the coupled shear and permeability test were prepared with the obtained optimum water content. However, in order to investigate the impact of compaction method on the permeability of specimens, both specimens for the triaxial test and for the coupled shear and permeability test were compacted with two different conditions:

1. to bring the mixture to a specified density; and
2. to apply to the mixture a known compactive effort.

The first condition was achieved by setting a split former (two segments) for triaxial test specimen of 50 mm diameter by 100 mm in length on the pedestal of the base of triaxial cell and compacting the mixture gradually filled in the former dynamically by means of a circular platen and a hammer to make the density of the specimen as high as possible. Before filling the mixture into the former, the surface of the previously compacted layer was slightly notched by means of a spatula so that the interface of the neighboring layers can be well combined. The actual density of the compacted specimen can be calculated from the mass used and the volume of the former. The wet density obtained by means of this method was 2.08 Mg/m³. Specimens to be prepared with the same condition were then easily controlled by compacting the required mass of mixture in the former or a mould with a known volume.

Specimen for triaxial test was prepared with the same former and compacted in the same way. Specimen for the coupled shear and permeability test was also prepared directly on the pedestal of shear apparatus in the similar way. In this case, a split former with 100 mm in inner diameter and a solid cylinder with 40 mm in diameter were used to prepare the thick-walled hollow cylindrical specimen. Mixture filled in the annular space between the split former and the cylinder was compacted by means of a fan-shaped platen (see the following paragraph) and a hammer to the specified density.

The second condition for preparing triaxial test specimen is easily obtainable in a standard compaction mould, by using recognized standard compaction procedures such as the Standard Proctor Compaction which has been used for determining the optimum water content. The compacted sample is removed from the compaction mould by means of a hydraulic or screw jack extruder. The sample is then set onto a soil lathe and trimmed to the diameter of 50 mm using a wire saw against vertical guide plates. The cylindrical specimen is finally trimmed to 100 mm in length by means of a split pipe and the wire saw.

The thick-walled hollow cylindrical specimen satisfying the second condition for the coupled shear and permeability test was prepared with the equivalent compaction effort to the Standard
Proctor compaction test by means of a specialized mould and a fan-shaped rammer (Fig. 5-2-2). Specifically, preparation of the specimen was performed by compacting the mixture in three equal layers in the specialized mould, measuring 40 mm in outer diameter of a movable core cylinder and 100 mm in inner diameter of the outside ring by 100 mm in length, by dropping a 1.25 kg hammer through a distance of 37.5 cm, each layer being subjected to 21 blows. The compacted mixture was finally trimmed to be 40 mm in length by means of a wire saw and an apparatus for removing the compacted mixture from the mould. Dry density of the specimen was checked to be 98% of that obtained from the Standard Proctor compaction test. A prepared thick-walled hollow cylindrical specimen is shown in appendix A-2.

5.2.3 Mechanical properties

The values of the mechanical parameters of testing specimen are necessary for appropriately evaluating the shear strain distribution in the specimen during the coupled shear and permeability test. To obtain these mechanical properties, undrained triaxial tests were conducted on the cylindrical specimens prepared with the two kinds of method previously described. The undrained triaxial test has been improved so that the small volume change during the test can be monitored (see Fig. 3-3-1, section 3.3). The cylindrical specimen is set between the pedestal and cap, and encased by the membrane. The space between the specimen and pressurized water-tight triaxial cell can be completely filled with water. The confining pressure to the specimen is provided through a pair of parallely set burettes. The volume change of the specimen during test is transformed to the small head differences between two of the parallely set burettes and measured by means of a Differential Pressure Transducer (DPT). This confining pressure supplying system is a part of the shear and volume change measuring system which will be described in the next section. At first, a relatively low confining pressure is applied to the specimen when saturating the specimen with deaired water. A specified confining pressure is then applied and let the specimen consolidate in drainage condition until the volume change of the specimen ceases. In these two procedures, axial deformation of the specimen is restrained. Axially loading the specimen with strain rate controlled at $2.00 \times 10^{-2}$/min is performed under undrained condition. An example of the stress-strain and volumetric strain curves for kaolin-sand mixture has been plotted in Fig. 3-4-1 (see Chapter 3). For simplicity, hereafter, the specimens prepared with the first and second compaction conditions are referred to as Type 1 and Type 2 respectively.
Fig. 5-2-2 Schematic of specialized rammer and mould
The mechanical properties of the two kinds of specimen are summarized in Table 5-2-2. Herein, the stress-strain path is divided into the elastic section and plastic section by means of the point that converts compressive volume change to dilatancy. Consequently, the piecewise-linear sections are used to illustrate the stress-strain characteristics of the specimen, as shown in the Fig. 3-4-1 in dashed lines. Because the volume changes during elastic deformation are very small, the Possion's ratios of the specimens are given to be 0.5. The value of the remaining parameters is the average value of those obtained from different confining pressure conditions.

5.3 Experimental Systems

Based on the theory of thick-walled hollow cylinder shear test proposed in Chapter 3, the coupled shear and permeability testing system for kaolin-sand mixture is then practically developed (Fig. 5-3-1). Its structural components and functions can be described as follows:

1. Shear and volume change measuring system

Shear strain in the specimen is produced by the differential pressure between the internal pressure and the external pressure, same high as that applied to pressurized chamber, to the cylindrical specimen in plane strain state. Each of the pressures are provided through a pair of parallelly set burettes to exert pressures on the internal and external surfaces of the hollow cylindrical specimen. By using the inner cell in the pressurized chamber, both internal and external sides of the specimen become enclosed and they can be fully filled with deaired water to measure the small volumetric changes of the testing specimen for checking the deformation status of, and calculating the shear strain in the testing specimen. The volumetric changes are transformed to the small head differences between two of the parallelly set burettes and measured by means of the Differential Pressure Transducers (DPT). This system is the same as that used in the improved triaxial test equipment developed in section 3.3. The narrower of the parallel burettes, the higher of the measuring precision. However, the initially filled water level in these small capacity narrow buretttes may decrease greatly due to the compressibility of the deaired water and the equipment compliance when back pressure is applied and makes the measurement become impossible. This problem has been solved by adding a hand-operated pump into the deaired water supply system which enables to adjust water level in the burettes under pressurized condition. Besides, errors arising from water evaporation can also be compensated in these same
<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion (kPa)</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>Elastic modulus (MPa)</td>
<td>71</td>
<td>35</td>
</tr>
<tr>
<td>Plastic modulus (MPa)</td>
<td>-0.5</td>
<td>-0.9</td>
</tr>
<tr>
<td>Possion's ratio</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Plastic Possion's ratio</td>
<td>0.9</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Fig. 5-3-1 Schematic drawing of coupled shear and constant head permeability test apparatus
sized parallel burettes measuring system. A burette for saturating the specimen is also attached to
the panel setting these burettes. A two days' leakage check of the pressurized system, calibration
test for compressibility of the deaired water and the equipment compliance for volume change
measurement have been carried out by substituting a stiff metal hollow cylindrical cylinder with
the same size as the specimen prior to the test on compacted soil mixtures. The result of leakage
check showed that there was no measurable leakage happened during the two days' check at the
highest pressure level of 6 MPa to be applied for the coupled shear and permeability test (see next
section and section 6.4). An example of the compressibility of the deaired water including the
equipment compliance is shown in Fig. 5-3-2 for measuring the volume change inside of the
hollow cylindrical specimen. This compressibility can be considered in calculating the actual
specimen volume changes from the experimental output.

The internal and external pressures required for shear and the permeating pressure required
for saturating the specimen are obtained from a servo-controlled air compressor. The pressure is
directed to three branches through a system of regulators on the pressure regulating panel. Gauges
on the panel display the values of the regulated pressures, and the low permeating pressure for
saturating is finely checked by the electrical pressure gauge through the data-acquisition and
monitoring system to be described later.

2. Constant-head permeability test apparatus

Apparatus providing water with constant-head is connected to the base of the permeameter. A
pressure transducer connected to the permeameter base plate is used to monitor the hydraulic
gradient during the test. Flow rate of water is measured by means of an electronic balance. For
compensating the evaporation effect on flow rate measurement, time-dependent weight loss of
water in the vessel that is the same as that used for flow rate measurement is monitored during the
permeability test, and then considered in permeability calculation.

3. Data-acquisition and monitoring system

The computer-based data-acquisition and monitoring system permits automatically recording
of all the physical parameters to be measured with a given interval. Run by a specialized program,
the system can simultaneously display the plots and the current digital values of the measuring
parameters, by which we can judge the experimental status and take any necessary measurements
immediately during the test.
Fig. 5-3-2 The compressibility of the deaired water including the equipment compliance

Fig. 5-4-1 The flowchart of coupled shear and permeability test on kaolin-sand mixture
In addition, the permeability test is conducted in a temperature controlled room. However, temperatures of circumstances, permeating water and inside of the permeameter cell are still checked or monitored during the whole permeability test. They can be used in permeability correction if necessary.

5.4 Testing Procedures and Conditions

The coupled shear and permeability tests on the prepared specimens of compacted kaolin-sand mixture were conducted with the procedures and conditions as follows:

1. Setting the specimen

When the specimen was compacted directly on the pedestal of the coupled shear and permeability test apparatus, lower ends of the membranes inside and outside of the specimen were previously set. Membranes outside of the specimen was sucked by vacuum to fit evenly onto the inside surface of the former during preparation of the specimen. The split former and the solid core cylinder for compacting the thick-walled hollow cylindrical specimen were dismantled after the cap had been set onto the top of the specimen and the specimen had been stabilized by sucking the inside of the soil specimen to the vacuum state. When the specimen was prepared with the specialized rammer and mould, special care should be taken to prevent the thick-walled hollow cylindrical specimen from failure when setting it onto the testing apparatus. Any potential damage in this kind of weak specimen caused by localized force or other reasons might result in errors of the test. The inside of the soil specimen was also sucked to the vacuum state after the specimen had been encased by the membranes between the pedestal and the cap. The vacuum state was remained until all the setting work had been completely finished.

To prevent the specimen from piping and erosion during saturation and the permeability test, filter paper was placed between the specimen ends and porous metals on both of the pedestal and cap. Furthermore, sealing faces and O-rings were spread with a thin layer of water-resistant silicone grease for ensuring the tightness of seal.

2. Applying confining pressure

Fill the cells and pipes with deaired water, then apply a lower confining pressure of 0.03 MPa (internal and external pressures) to the specimen. To minimize the error of volumetric
measurement, air in the inner cell and pipes should be completely discharged. The water level in
the burettes for volumetric change measurement should also be adjusted to the proper positions,
same as those for the calibration test, by means of the hand-operated pump. Considering the
compressibility of the water is dependent on the deairing degree and the water quality, the water
compressibility calibration test should be conducted just before each of the tests using the same
water for the tests.

3. Saturating the specimen

Saturating the specimen with deaired water was performed by means of the pressurized burette
attached to the confining pressure supply and regulating panel in the way of upward flow of
saturating water through the specimen. Then the saturation condition of the specimen was judged
by the outflow of full water, other than the water-gas blend, from the flooding pipe connected to
the upper end of the specimen.

4. Consolidation

Simultaneously increase the internal and external pressures slowly to the setting level of 0.6
MPa for consolidation, and monitor the volume change during consolidation.

5. Shear and permeability test

When the volume change of the specimen during the consolidation ceased, the shear and
permeability test were conducted by keeping the external pressure to be constant and decreasing
the internal pressure step by step. Then the permeability of the sheared specimen was measured at
each of shear steps with the constant-head method. The setting levels of the internal pressure used
for shear test were 0.1 MPa and 0.01 MPa for type 1 specimen, and 0.2 MPa, 0.1 MPa and 0.05
MPa for the type 2 specimen. To decrease the seepage-induced effects on the permeability of the
specimen to the minimum, the imposed hydraulic gradients were very small (less than 10). The
validity of the permeability test components (for testing low permeability materials) to test the
relatively high permeability materials was also verified by measuring the permeability with
different hydraulic gradients, and there was no evidence of deviation from the Darcy's Law. The
permeability was calculated by means of Eq. 4-2-1 using the data obtained from the steady state of
flow. Also, the effect of evaporation on the measurement of flow rate was considered in
calculating the permeability.
6. End the test

End the test and check the deformed conditions of the specimen.

The procedures for conducting the coupled shear and permeability test using the differential pressure between the pressures applied on the outside and inside walls of the thick-walled hollow cylindrical specimen to shear is then summarized in Fig. 5-4-1.

5.5 Test Results and Analysis

1. Permeability test results

The permeability of the type 1 and type 2 specimens measured at each of the differential pressure steps for shearing the specimen are summarized in Table 5-5-1. It can be seen from the table that when the internal pressure decreased, the permeability of both type 1 and type 2 specimens increased.

2. Deformation of the specimen

By substituting the mechanical properties of the compacted kaolin-sand mixtures obtained in section 5.2.3 (Table 5-2-2) and the differential pressure conditions for shearing the specimens (Table 5-5-1) as well as the specimen dimensions into Eq. (3-4-15), displacement of the inner surface of the hollow cylindrical specimen at each shearing condition can be calculated, and the volume change inside the hollow cylindrical specimen can also be estimated. The inner volume changes with the decrease in the internal pressure for type 1 and type 2 specimens obtained from the theoretical analysis are drawn in solid and dashed lines respectively in Fig. 5-5-1. The experimental values measured at different pressure conditions are plotted in the same figure for a comparison. The calculated values fit quite well with volumetric measurements. This fact proved that the proposed mechanical model and the values of the parameters used for the analysis are feasible. Since the relationship between displacement and strain is independent on mechanical properties of the materials (see Eq. (3-4-4)), the theoretical analysis of shear strain, which will be described later, can also be properly evaluated. Moreover, it is obvious that the density of type 1 specimen is relatively high and consequently has a relative high strength. Conversely, the deformation of the type 1 specimen is smaller than that of type 2 specimen at each of the differential pressure conditions for shear test.
Table 5-5-1 The differential pressure conditions and results of permeability test

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
</tr>
<tr>
<td>External</td>
<td>Internal</td>
</tr>
<tr>
<td>0.60</td>
<td>4.89 x 10^-8</td>
</tr>
<tr>
<td>0.20</td>
<td>—</td>
</tr>
<tr>
<td>0.06</td>
<td>8.89 x 10^-8</td>
</tr>
<tr>
<td>0.05</td>
<td>—</td>
</tr>
<tr>
<td>0.01</td>
<td>1.10 x 10^-7</td>
</tr>
</tbody>
</table>

Fig. 5-5-1 The comparison between the calculated and measured inner volume changes of specimen
3. Relationship between shear strain and permeability

Substitute the values of mechanical parameters obtained in the section 5.2.3 and other values corresponding to the test conditions and specimen dimensions into Eq.(3-4-13) and Eq.(3-4-17), the maximum shear strain distribution across the thickness of the hollow cylindrical specimen at each differential pressure state can be evaluated (Fig. 5-5-2). As the internal pressure decreased, the maximum shear strain in the specimen increased. However, the magnitude of the maximum shear strain varies with the distance from the center line of the specimen. Herein, the relationship between the maximum shear strain at inner wall of the hollow cylindrical specimen and the permeability at each of the shear conditions (differential pressure conditions) are plotted in Fig. 5-5-3.

For simplicity, shear strain in the specimen can also be evaluated by their average values through the measured inside wall displacement $u_i$ and outside wall displacement $u_o$ of the hollow cylindrical specimen. The average radial strain $\varepsilon_r$ and tangential strain $\varepsilon_\theta$ are based on a linear variation of radial displacement across the wall and can be expressed as follows (e.g., Ampadu and Tatsuoka 1993; Saada 1988):

\[
\varepsilon_r = -\frac{u_o - u_i}{R_o - R_i}, \quad (5-5-1)
\]

\[
\varepsilon_\theta = -\frac{u_o + u_i}{R_o + R_i}, \quad (5-5-2)
\]

Where $R_o$ and $R_i$ are the radii of the thick-walled hollow cylindrical specimen respectively.

If we define the average maximum shear strain $\gamma_{\text{max}}$ as the difference between the tangential strain $\varepsilon_\theta$ and the average radial strain $\varepsilon_r$, we get:

\[
\gamma_{\text{max}} = -\frac{u_o + u_i}{R_o + R_i} + \frac{u_o - u_i}{R_o - R_i}, \quad (5-5-3)
\]
Fig. 5-5-2 Shear strain distribution in the specimen corresponding to various loading conditions
Fig. 5-5-3 The relationship between the permeability and the maximum shear strain
The displacements of the inside wall and outside wall of the specimen can be calculated from the volume change measurements of inside and outside of the specimen by assuming that the deformation is uniform along the vertical direction. By substituting the calculated displacements into the above Eq.(5-5-3), shear strains based on experimental measurements can be correspondingly evaluated. The relationship between the average shear strain and the permeability of specimen is shown in Fig. 5-5-4.

From both Fig. 5-5-3 and Fig. 5-5-4, it can be seen that the permeability of the specimen increased linearly with the increment of the maximum shear strain or the average shear strain in the specimen. The initial permeability of type 1 specimen with relatively high density (or small porosity) is lower than that of type 2 specimen with relatively small density (or large porosity). As the maximum shear strain increased to about 10% or the average shear strain increased to about 4%, the permeability of the specimens increased to about two fold.

5.6 Conclusions

The coupled shear and permeability tests on kaolin-sand mixtures were conducted using the newly developed apparatus for the coupled shear and permeability test on soil materials. The apparatus permits measuring permeability of the progressively sheared thick-walled hollow cylindrical specimen until post-failure region in the direction perpendicular to the plane in which the maximum shear strain occurs. Conclusions drawn from the study are as follows:

1. An appropriate permeability of a specimen can be obtained by mixing the coarse-grained soil with fine-grained soil with a proper weight ratio.

2. The density of the thick-walled hollow cylindrical specimen prepared by means of the specialized rammer and mould was almost the same as that obtained from the Standard Proctor compaction. Therefore, the specialized rammer and mould designed in this study can be used to apply to the mixture a known compactive effort. The compaction effect is almost the same as that obtained by means of the standard method for compaction test.

3. The thick-walled hollow cylindrical specimen can be sheared by means of the differential pressure between the external and internal pressures applied on the outside and inside walls of the specimen. The volume change of the specimen can be monitored during the consolidation. Also, the small volume change of the specimen during shear can be precisely measured by means of the parallelly set pressurized narrow burettes and the Differential Pressure Transducers.
Fig. 5-5-4 The relationship between the average shear strain and the permeability of kaolin-sand mixture

a) Type 1

b) Type 2
4. The volume change measurements obtained during shear tests fit well with those obtained from the theoretical analysis. Therefore, the proposed mechanical model and the elasto-plastic analysis in this study are feasible for properly evaluating the mechanical behavior of the compacted mixture. Also, the values of the mechanical parameters obtained from the improved triaxial test can represent those of the hollow cylindrical specimens used in the coupled shear and permeability test.

5. No deviation from Darcy's law was observed during the permeability measurements with different hydraulic gradients. Therefore, the components coupled in the shear test apparatus are valid for testing the specimens with the permeability on the order of $10^{-8}$ m/s.

6. The testing procedures established in this chapter for nonexpansive soil materials can provide a basis for establishing the testing procedures for testing expansive soil materials with low permeabilities.

7. When the maximum shear strain or the average shear strain increases in the specimen of nonexpansive soils accompanying volume dilatancy, the permeability of the testing specimen increases linearly. In the cases of the specimens used in the present study, the permeability of the specimens increased to about two fold as the maximum shear strain increased to about 10% or the average shear strain increased to about 4%. Therefore, quantitative study on the impact of shear strain on the permeability of the soil materials can be performed with the coupled shear and permeability method developed in the present study.

REFERENCES


Chapter 6 COUPLED SHEAR AND PERMEABILITY TEST ON BENTONITE-SAND MIXTURES

6.1 Introduction

Bentonite-sand mixtures are comprised of two truly contrasting soils in regards to grain size, permeability, chemical activity, and strength which, when combined in optimum proportion, can form an excellent seepage barrier that is dimensionally stable and possesses a low value of permeability. When the mixtures are well mixed and well compacted, they possess strong load-supporting frameworks of sand particles that resist macroscopic shrinkage due to desiccation or osmotic consolidation. Bentonite is contained within voids between sand particles and, in the presence of water, hydrates and swells. When the void ratio of a bentonite mixture is less than the free-swell capacity (i.e., volumetric expanding capacity upon wetting at zero effective stress) of the comprised bentonite, bentonite completely fills the spaces and presses lightly against the sand particles, thereby acting as a minor part of the load-bearing structure of the mixture, meanwhile, the permeability of the bentonite-sand mixture is controlled by the permeability properties of bentonite, and the sand particles are imperious inclusion in the matrix of hydrated bentonite.

Owing to their long term physico-chemical stability and low permeability, bentonite-sand mixtures have been increasingly used as barriers to retard or control fluid permeation in many cases in geotechnical engineering, especially with respect to environmental control (e.g., Chapuis 1990; Chapuis et al. 1992; Lajudie et al. 1995). In recent years, bentonite-sand mixtures have also been proposed as candidate materials to be used in final geotechnical disposal facilities of hazard wastes, including radioactive nuclear wastes (e.g., Chan et al. 1989; Nakashima et al. 1995). A conceptional design of the geotechnical disposal facility for low level radioactive nuclear wastes is illustrated in Fig. 6-1-1 (DST). The essence of this kind of disposal method is to bury the radioactive nuclear waste contained in corrosion-resistant vessels into underground, the space around the facility is then filled with impermeable bentonite-sand mixture to absorb the radionuclide emitting from the vessels and to simultaneously retard the migration of radionuclide accompanying permeation of underground water to prevent the surrounding environment from being polluted.

Fluids and dissolved materials permeate through soil-based barriers by processes of seepage
Fig. 6-1-1 A conceptional design of final land disposal of low level radioactive nuclear wastes
and diffusion. Seepage is the movement of fluid through soil caused by a hydraulic gradient. Diffusion, or osmosis, is the movement of dissolved matter through the pore fluid of the barrier caused by chemical, electrical and thermal gradients. If seepage velocity is large, seepage transport will dominate, but if seepage velocity is small, diffusion transport might dominate (Kenney et al., 1992). The first requirement of a soil-based barrier is low permeability, and the focus of the present research is on the hydraulic conductivity behavior of bentonite-sand mixtures. Regarding the subject of diffusion through soil-based barriers, valuable references are Quigley et al. (1987), Rowe (1987) and Tsukamoto (1995). However, the permeability of the packed bentonite mixtures might be quite influenced by the following factors and can no more keep the expected water flow retardation property.

1. Design and construction factors

Bentonite-sand mixture, when it do not contain sufficient bentonite to fill all the voids in the sand framework and/or the bentonite is inadequately distributed, its permeability is increased by water-filled defects in the bentonite matrix, might reach a value closer to that of sand than that of bentonite (Kenney 1992). This problem can be easily solved by adding sufficient bentonite into and making it well mixed in the mixture through proper design and strictly controlled construction management. The dry weight ratio of bentonite to sand to be used in the laboratory study of the present research is determined to be 15% with reference to the published literatures (e.g., Kenney 1992; Komine and Ogata et al. 1991) and, the specimen will be prepared with sufficient mixing of the two materials to ensure a uniform distribution of bentonite in the specimen.

2. Chemical factors

Chemical factors influencing the permeability of bentonite-sand mixtures are the types of bentonite used, chemical composition of the mixing fluid and changes of chemical composition of the pore fluid after construction. Comprehensive investigation of the effect of these factors on the permeability of bentonite-sand mixtures can be performed only by changing the type of bentonite, mixing fluid and permeating fluid to be used in experimental tests (see section 2.1) and the present research will not discuss further on this matter.

3. Mechanical factors
The permeability is a porosity-related property of soil materials, hence it is evident that any factor which may cause variation in porosity must necessarily result in changes in permeability of a soil-based barrier. In the cases of final land disposal of radioactive nuclear waste, the permeability of back-filled bentonite or bentonite-sand mixture might increase due to shear strain accompanying dilatancy induced by nonuniform deformation and/or strong earthquake during its long term performance over several hundred years for low level radioactive nuclear waste disposal, and several thousand years for high level radioactive nuclear waste disposal. In sections that follow, the stress is emphasized on investigating the effects of shear strain on the permeability variation of bentonite-sand mixtures.

6.2 Testing Specimen

6.2.1 Materials

1. Bentonite

The permeability of a bentonite-sand mixture is dependent on the fabric of bentonite in the mixture. Conditions at the time of mixing determine the fabric of bentonite in, and controls the permeability of, the mixture. Because they are natural materials, bentonites vary considerably from one source to another in regards to mineral composition, chemical state, and grain-size distribution. The bentonite used in the present research is an example of high-swell bentonite (named Kunigeru V1) containing sodium montmorillonite, produced by Kunimine Industry (see appendix A-3), and its properties are listed in Table 6-2-1.

The primary ingredient of bentonite is montmorillonite. In the dry state a particle of montmorillonite resembles a closed book composed of many thin crystalline sheets held together by weak van der Waal forces and by cations. Each sheet has charge deficiencies within its crystal structure, and neutrality exists through the presence of cations held loosely to the surfaces of the sheets. When dry bentonite and water are mixed, as in the case of bentonite-sand mixtures, water is drawn into the montmorillonite particles to hydrate the surfaces of the elemental sheets and the cations. For the combination of sodium montmorillonite and freshwater, the fluid that enters the particles forms thick, viscous diffuse ionic layers around the sheets, causing the montmorillonite particles to swell, possibly to the extent of complete separation of the sheets. This results in that
Table 6-2-1 Properties of bentonite

<table>
<thead>
<tr>
<th>Type</th>
<th>Sodium bentonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( Mg/m³ )</td>
<td>2.79</td>
</tr>
<tr>
<td>Liquid limit ( % )</td>
<td>473.9</td>
</tr>
<tr>
<td>Plastic limit ( % )</td>
<td>26.61</td>
</tr>
<tr>
<td>Plastic index</td>
<td>447.3</td>
</tr>
<tr>
<td>Shrinkage limit ( % )</td>
<td>10.6</td>
</tr>
<tr>
<td>Activity ( % )</td>
<td>6.9</td>
</tr>
<tr>
<td>Plastic ratio</td>
<td>16.8</td>
</tr>
<tr>
<td>Clay (&lt; 2mm) content ( % )</td>
<td>64.5</td>
</tr>
<tr>
<td>Specific surface * ( m²/g )</td>
<td>46 ~ 51</td>
</tr>
<tr>
<td>Cation exchange capacity ( mequiv./g )</td>
<td>0.76</td>
</tr>
</tbody>
</table>

(* By BET method using nitrogen gas)

Before water uptake

![Before water uptake diagram](image1)

After water uptake

![After water uptake diagram](image2)

**Fig. 6-2-1 A model of bentonite-sand mixture swelling in a confined state**

*Nonswelling clay mineral*  
*Swelling clay mineral*  
(for example montmorillonite)
the fabric of freshwater and sodium bentonite resembles a pile of crumpled paper (Nakano 1994). A model to describe the bentonite-sand mixture in a confined state can be found similar to that modeling the swelling pressure of compacted bentonite established by Komine et al. (1994) as shown in Fig. 6-2-1. The water absorbed bentonite in visco-plastic state swells and fills the voids exist in the mixture, as well as cracks which might occur in the mixture due to external factors, e.g., dilatancy during deformation, so that the entire space between the non-swelling particles is entirely taken by swelled bentonite and the permeability of the mixture remains constant in principle. However, few reports on experimental verification of this effect can be found, and the sections that follow mainly contribute to this interest.

2. Sand

Two kinds of sand are used for preparing the specimen to be used in the coupled shear and permeability test on bentonite-sand mixtures. One kind of sand is the Toyoura standard-sand, the same as that described and used in Chapter 5 for the coupled shear and permeability test on kaolin-sand mixture. Another kind of sand called Dankyu-sand is taken from a site where final land disposal of low level radioactive nuclear waste has been planed in Japan. The physical properties of Dankyu-sand are tabulated in Table 6-2-2 and, its particle size distribution is plotted in Fig. 6-2-2. (see also appendix A-5)

6.2.2 Compaction test and specimen preparation

1. Compaction test

Compaction test on bentonite sand mixtures are conducted in accordance with the following procedures:

(1) Weigh the bentonite and sand according to the dry weight ratio of 15:85 and, mix them sufficiently to insure uniform distribution of bentonite in the mixture.

(2) Add proper amount of water into the mixture little by little and, at the same time, mix them sufficiently for obtaining homogeneous distribution of water and, then, put it into a sealing vessel for over 24 hours to have the bentonite in the mixture got sufficient hydrated.

(3) Conduct compaction test by means of the Method of Test for Moisture-Density Relations
Table 6-2-2 The physical properties of Dankyu-sand

<table>
<thead>
<tr>
<th>Type</th>
<th>Dankyu sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Mg/m³)</td>
<td>2.673</td>
</tr>
<tr>
<td>Max. particle size (mm)</td>
<td>4.75</td>
</tr>
<tr>
<td>Uniformity coefficient</td>
<td>1.57</td>
</tr>
<tr>
<td>Coarse-grained particle (%)</td>
<td>89</td>
</tr>
<tr>
<td>Fine-grained particle (%)</td>
<td>7</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>2</td>
</tr>
<tr>
<td>Fine gravel (%)</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 6-2-2 Grain size distribution curve of Dankyu-sand

(4) Check the water content of the mixture using the Method of Test for Moisture Content of Soils according to the Japanese Industry Standard, JIS A 1203-1979 (JSSMFE 1980).

Results of compaction tests, using freshwater, on bentonite Standard-sand mixture and bentonite Dankyu-sand mixture are given in diagrams in Fig. 6-2-3 a) and Fig. 6-2-3 b) respectively. Each of the mixtures exhibits a maximum dry density and an optimum water content, \( W_{opt} \). As shown in the diagrams, dry density of the bentonite Standard-sand mixture is 1.68 Mg/m\(^3\) and the corresponding optimum water content is 15%. Dry density of the Dankyu-sand mixture is 1.777 Mg/m\(^3\) and the corresponding optimum water content is 13.8%. As for determining the compaction water content of a soil-based barrier, it is worth noticing that many articles have reported that for a given compaction effort, the permeability is lower when the compacted clay is slightly wetter than its optimum value (e.g., Haug and Wong 1992). As a simple consequence of that, a mixture, for forming hydraulic barrier to retard water permeation, should be compacted with more water content in practice.

The purpose of this chapter is to verify that the low permeability of bentonite sand mixtures will not be degraded by shear deformation. Here, the water content for preparing the specimen to be used in the coupled shear and permeability test is determined to be the same as the optimum values for both kinds of bentonite sand mixture.

2. Specimen preparation

Testing materials are prepared with the same steps (1) and (2) described in the above procedure for the compaction test. The specimen is then prepared just before the coupled shear and permeability test with the same mould and rammer and the same procedures for preparing cylindrical specimens illustrated in section 5.4. The prepared specimens of the two kinds of mixture are shown in appendix A-4 and A-6 respectively.

6.2.3 Mechanical properties

To obtain the values of mechanical parameters which are necessary for calculating the shear strain distribution in the testing specimen, triaxial compression test (CU test) on the two kinds of
Fig 6-2-3 Compaction test results

(a) Bentonite standard sand mixture

(b) Bentonite Dankyu sand mixture
bentonite sand mixture, prepared with the same condition for preparation of the thick-walled hollow cylindrical specimen, are conducted according to the Japanese Industry Standard, JIS A 1216 (JSSMFE 1980). Results of the mechanical test are given in Fig. 6-2-4.

According to the above results, mechanical properties of the bentonite-sand mixtures can be summarized as in Table 6-2-3.

6.3 Testing System

The testing system developed for conducting the coupled shear and permeability test on bentonite-sand mixtures is similar to that described in Chapter 5, in which the constant-head permeability test apparatus is replaced by a constant flow pump and other apparatus, like carbon dioxide supplying apparatus, is added for dealing with testing of low permeability materials. The schematic drawing of the testing system is shown in Fig. 6-3-1 (see also appendix A-7) and its systematic components and functions can be described as follows:

1. Shear testing system
   This system is the same as that used for testing kaolin-sand mixture described in Chapter 5, where the specimen is replaced by that of bentonite-sand mixture. Specifically, the dimensions of the specimen are 4 cm and 10 cm in internal and external diameters respectively, by 4 cm in length.

2. Carbon dioxide supplying apparatus
   This apparatus is added for a rapid saturation of a low permeability bentonite-sand specimen by replacing the air in the specimen with carbon dioxide before saturating the specimen with freshwater prior to the coupled shear and permeability test. To insure a sufficient replacement of the air in the specimen, this process is continued for over 24 hours with a very low permeating pressure less than 0.005 Mpa. The apparatus mainly consists of a commercialized carbon dioxide cylinder, an electric heater and pressure regulating devices, as shown in Fig. 6-3-2.

3. Constant flow pump permeability test system
   The constant flow pump system developed in this study consists of the motor, worm gear,
Fig. 6-2-4 Mohr circles and envelops for bentonite-sand mixtures
<table>
<thead>
<tr>
<th>Mechanical parameter</th>
<th>Standard-sand mixture</th>
<th>Dankyu-sand mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion (kPa)</td>
<td>44</td>
<td>48</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Elastic modulus (MPa)</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>Poission's ratio</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Elastic limit stress (kPa)</td>
<td>161</td>
<td>176</td>
</tr>
<tr>
<td>Plastic modulus (MPa)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Plastic Poission's ratio</td>
<td>1.13</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Fig. 6-3-1 Testing system for coupled shear and permeability test on bentonite-sand mixture
Fig. 6-3-2 Carbon dioxide cylinder, electric heater and pressure regulating devices

Fig. 6-3-3 The flow pump equipment
speed-reduction gear box, actuator and regulating panel for adjusting the flow rates and changing the rotational direction of the motor. This kind of controlling system permits the measurement of the permeability of the specimen at various flow rates and for both infusion and withdraw condition of the flow pump. The photograph of the flow pump equipment developed in this study is illustrated in Fig. 6-3-3.

The head difference induced across the length of the specimen is monitored with a high-sensitivity pressure gauge at the infusion/withdraw port, which is connected to the lower end of the specimen, just ahead of the pressurized chamber. Another port connected to the upper end of the specimen is left free to the atmosphere. This kind of hydraulic head difference measuring method can help us to reduce the influence of pore pressure variation on the permeability test to its minimum, compared with the method of measuring the hydraulic head difference across the specimen by differential pressure transducer where the specimen is kept in a sealed state while fluid is infused into/or withdrawn from it.

The head difference monitoring system adopted in the present study can also be used to check the saturation degree of the specimen using a pore pressure reaction test when both the flow-in and flow-out ports are shut off.

However, special attention should be deserved to the design of the flow rate of the flow pump with consideration of the following factors:

1. Shear method has been determined to be the approach which tests the thick-walled hollow cylindrical specimen with different internal and external pressures, and the permeability test can be possibly conducted under the condition that permeating pressure is lower than the internal pressure which will be decreased as low as possible to perform a large shear deformation in the specimen.

2. High permeating pressure produces high pore pressure, and that will cause significant error for permeability measurement.

3. High permeating pressure also needs high confining pressure to the specimen. This not only causes an increase of equipment cost but also makes the testing condition quite different from that in situ.

4. It is very difficult to make a constant flow pump with an extremely small flow rate even by most recent skills in mechanics, and the relative error of measuring low pressure is greater than that of measuring high pressure for a pressure gauge with a given sensitivity and resolution. In other words, it is necessary to design a proper low flow rate of a flow
The design work on flow rate of a flow pump, to be used in a certain condition, can be executed based on the Darcy's law (see section 4.2) which is suitable for the steady flow state that will eventually reach during a constant flow pump permeability test. For the dimensions of the test specimen has been determined to be 4 cm and 10 cm in internal and external diameters respectively, by 4 cm in length, the cross-sectional area of the specimen can be easily calculated to be 65.9 cm². Then, a family of parallel lines which illustrate the relationship between the permeability and the maximum hydraulic pressure (head difference) at steady state induced across the specimen during a constant flow pump permeability test can be drawn as in Fig. 6-3-4 by substituting the specimen dimensions and the assumed flow rates into the Darcy's law.

Considering that the magnitude of permeability of bentonite-sand mixtures is less than 10⁻⁸ cm/sec (10⁻¹⁰ m/s), as reported in some literatures (e.g., Komine et al. 1991; Kenney et al. 1992), and possible maximum permeating pressure occurs during the permeability test will be kept lower than 0.01 MPa, it can be judged from Fig. 6-3-4 that the minimum flow rate required for making the flow pump should be about 10⁻⁶ ml/s. The capacity of the actually manufactured flow pump system is depicted in Fig. 6-3-5, in which dial number means the setting level of flow rates.

4. Data acquisition and monitoring system

The computer-based data acquisition and monitoring system permits automated record of all the physical parameters to be measured with a given interval. Run by a specialized program, the system can simultaneously display the plots and the current digital values of the measuring physical parameters, by which we can judge the experimental state and take any measurements immediately if necessary.

6.4 Testing Procedures and Conditions

Once the cylindrical specimen was prepared with the method described in section 6.2, it was tested with the procedures as summarized in Fig. 6-4-1 and as explained below:

1. Setting the specimen onto the testing apparatus
Flow rate  
- 0.01 (ml/s)  
- 0.001 (ml/s)  
- 0.0001 (ml/s)  
- 1E-05 (ml/s)  
- 1E-06 (ml/s)  

Permeability ($10^{-2}$ m/s)  

Fig. 6-3-4 The relationship between the permeability and the maximum differential head for given flow rates

Fig. 6-3-5 Capacity of the newly developed constant flow pump system
Applying confining pressure

Replacement of air in the specimen with carbon dioxide

Specimen saturation

Permeability test before shear

Permeability test during shear

Permeability test after shear

End

Fig. 6-4-1 The flowchart of coupled shear and permeability test for bentonite-sand mixture
Special care should be taken to prevent the cylindrical specimen from failure when setting it onto the testing apparatus. Any potential damage in this kind of weak and soft specimen caused by localized force or other reasons might result in the error of the test.

To diminish the loss of bentonite during the permeability test and to reduce the restraining effect occurs at the specimen ends, high molecular filter paper is placed between the specimen ends and porous metals on both of pedestal and cap. Furthermore, sealing faces and O-rings are spread with a thin layer of water-resistant silicone grease for ensuring the tightness of seal.

2. Applying confining pressure

Fill the cells and pipes with deaired water, then apply a lower confining pressure of 0.03 MPa (internal and external pressures) to the specimen. To minimize the error of volumetric measurement, air in the inner cell and pipes should be completely discharged or extruded. Again, the compressibility of the deaired water and the compliance of the volumetric measuring system should be calibrated before each of the tests by using a stiff metal specimen with same dimensions as those of the specimen consisting of bentonite-sand mixture.

3. Replacing air in the specimen with carbon dioxide

For a rapid saturation of the bentonite-sand specimen with extremely low permeability, air in the specimen is replaced with carbon dioxide prior to saturating the specimen with deaired fresh water. This process is performed at a pressure lower than 0.005 MPa for over 24 hours with the apparatus illustrated in the previous section.

4. Saturating the specimen

Saturating the specimen with deaired water is performed by means of a pressurized burette attached to the confining pressure supplying and regulating panel. The saturation condition could be checked with pore pressure reaction test method, but it takes a relative long time for the pore pressure to reach a steady state. Therefore, the saturation condition of the specimen in this study is simply judged by the outflow of the full saturating fluid, i.e., the deaired water, from the discharge pipe connected to the upper end of the specimen. This process generally required about one and a half month for waiting the outflow of full water, other than the water-gas blend, under a permeating pressure about 0.01 MPa.
5. Permeability test before shear

The permeability of the saturated specimen at various confining pressure states before shear test are conducted with the constant flow pump method for investigating the influence of confining pressure on the permeability of the specimen. This test is carried out by simultaneously increasing the internal and the external pressures step by step and measuring the permeability of the specimen at each of the confining pressure levels.

6. Permeability test during shear

Decrease the internal pressure step by step to measure the permeability of the sheared specimen on each step with constant flow pump method for investigating the effect of shear strain on the permeability variation.

7. Permeability test after shear

Increase the internal pressure step by step to measure the influence of confining pressure on the permeability of the sheared specimen with constant flow pump method.

8. End the test

End the test and check the deformation status of the specimen.

Moreover, in the whole test process, ambient temperature as well as the in-cell temperature in both of the pressurized chamber and the permeating port are also monitored for modifying their influences on the permeability test, when it is necessary.

The setting values of the confining pressures to be used before, during and after the shear tests consistent with the above flow-chart for bentonite standard sand mixture are listed in Table 6-5-3 (see section 6.5). The setting values of the confining pressures to be used during the shear tests for bentonite Dankyu sand mixture are listed in Table 6-5-4 (see section 6.5).

6.5 Test Results and Analysis

6.5.1 Test results
The data obtained during the coupled shear and permeability test were those of the volumetric change of the specimen during shear, the time-dependent differential head across the specimen and the temperature variation during permeability test.

1. Volumetric changes

The volumetric changes measured inside and outside of the specimen, and the corresponding values of the calculated displacement of the inside and outside walls of the thick-walled hollow cylindrical specimen due to the change of the differential pressure conditions are tabulated in Table 6-5-1. It can be seen that the deformation of the specimen increased as the differential pressure between the internal and external pressures increased.

2. Differential head and temperature

Typical curves obtained during the permeability measurements with the constant flow pump method are plotted in Fig. 6-5-1 and Fig. 6-5-2 for bentonite standard sand mixture and bentonite Dankyu sand mixture, where tests were conducted out of and under temperature controlled conditions respectively. These figure show the time-dependent variation of the induced head difference across the specimen and the temperature of permeating water.

The upper curve in each figure indicates the head difference across the specimen when the flow pump was:

- a) infusing deaired water into the base of the specimen (upward flow);
- b) shut off without infusion into the specimen (zero flow); and
- c) withdrawing the deaired water from the base of the specimen (downward flow).

Moreover, the measured head difference includes a head difference presented during the zero flow condition and the response time (the time required to reach stable state after beginning or ending a period of flow through the specimen) were substantial, as reported by Olsen for clay specimens (1991).

The lower curve in each figure indicates the monitored temperature variation of the permeating water during permeability tests. From Fig. 6-5-1, it can be seen that temperature variation had a sensitive influence on the curve of head difference versus time. The possible reasons for the fluctuations of the head difference curve might be the thermal expansion or contraction of both water and testing system due to temperature variation (Stewart and Wong 1985). However, when
Table 6-5-1  The measured volume changes and displacements inside and outside of the hollow cylindrical specimen at each of shear steps

a) The mixture of bentonite and Toyoura standard sand

<table>
<thead>
<tr>
<th>External pressure (MPa)</th>
<th>Internal pressure (MPa)</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>Inside</td>
<td>Vi (ml)</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>Ui (mm)</td>
<td>0.36</td>
</tr>
<tr>
<td>Outside</td>
<td>Vo (ml)</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>Uo (mm)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

b) The mixture of bentonite and Dankyu sand

<table>
<thead>
<tr>
<th>External pressure (MPa)</th>
<th>Internal pressure (MPa)</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>Inside</td>
<td>Vi (ml)</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>Ui (mm)</td>
<td>0.42</td>
</tr>
<tr>
<td>Outside</td>
<td>Vo (ml)</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>Uo (mm)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Vo and Vi = The volume changes measured outside and inside of the hollow cylindrical specimen respectively

Uo and Ui = The calculated outside wall and inside wall displacements from the measured volume changes
Fig. 6-5-1 The time-dependent variation of the induced head-difference and temperature for bentonite standard sand mixture out of temperature controlled condition.
Fig. 6-5-2 The time-dependent variation of the induced head-difference and temperature for bentonite Dankyu sand mixture in temperature controlled condition.
the temperature variation was controlled within ±0.5 °C (see Fig. 6-5-2), no evident influence of the temperature on the curve of head difference across the specimen could be found. The head difference curve versus time is smooth when the permeability test is conducted under the temperature controlled condition.

6.5.2 Analytical results and discussions

1. Shear strain

Exact evaluation of shear strain distribution in the specimen subjected to the differential pressure between the inside and outside of the hollow cylindrical specimen can be done by means of the theoretical analysis developed in section 3.4. Substitute the mechanical properties of compacted bentonite sand mixtures in Table 6-2-3, the loading conditions for the coupled shear and permeability tests as well as the specimen dimensions into Eq. (3-4-13) and Eq. (3-4-17), the maximum shear strain distribution across the thickness of the hollow cylindrical specimen can be calculated (Fig. 6-5-3). Fig. 6-5-3 a) and Fig. 6-5-3 b) illustrate the calculated results for the mixture of bentonite and Toyoura standard sand and the mixture of bentonite and Dankyu sand respectively. These distributions of shear strain have the same characteristics as those obtained in section 5.5 for the compacted kaolin-sand mixtures.

For simplicity, shear strain in the specimen is also evaluated by its average value through the measured deformation of the specimen. By substituting the measured inside wall displacement \( u_1 \) and the outside wall displacement \( u_0 \) of the hollow cylindrical specimen in Table 6-5-1 into Eq. (5-5-3), the average shear strain in each of the specimen under different loading conditions can be computed in Table 6-5-2.

2. Permeability

Evaluation of permeability at each of the sheared steps can be calculated from four conditions occurred in the permeability test. They are:

1) steady condition evaluation using Eq. (4-2-11) where the stabilized head differences in infusion and withdrawing conditions are defined as those illustrated in Fig. 6-5-1 and Fig. 6-5-2;

2) whole transient phase evaluation based on minimizing Eq. (4-4-3) using Eq. (4-3-9) and
Fig. 6-5-3 The shear strain distribution in the specimen corresponding to various loading conditions

a) Standard sand and bentonite mixture

b) Dankyu sand and bentonite mixture
Table 6-5-2 The average shear strain in the specimen at different loading conditions

<table>
<thead>
<tr>
<th></th>
<th>External pressure (MPa)</th>
<th>Internal pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>Bentonite standard sand mixture (%)</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>Bentonite Dankyu sand mixture (%)</td>
<td>0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The average shear strain in the specimen at different loading conditions.
the whole data measured in the entire transient phase;

3) early time transient phase evaluation based on minimizing Eq. (4-4-3) using Eq. (4-3-9) and half of the data measured in the early time; and

4) zero flow condition evaluation based on minimizing Eq. (4-4-3) using Eq. (4-3-10) and the data measured in the zero flow condition.

2), 3) and 4) can be accomplished by means of the parameter identification approach and the program developed in section 4.4.

For the coupled shear and permeability test on the mixture of Toyoura standard sand and bentonite was conducted without temperature control, the measured data of the head difference across the specimen involve relatively more noise. Here the permeability of the compact bentonite standard sand mixture at each of the sheared conditions are simply evaluated through the above condition 1) (Table 6-5-3).

The values of the permeability and the corresponding values of specific storage of the specimen, as well as the storage capacity of flow pump system obtained from the above analysis for bentonite Dankyu sand mixture (which was tested under temperature controlled condition) are tabulated in Table 6-5-4. Simulated curves for whole infusion process and zero flow process are then produced by means of the equations and the parameters corresponding to the individual process, and an example is drawn in Fig. 6-5-4 in solid lines for comparison with the measured data. It is obvious that the simulated curves fit quite well with the measured data.

From the above analysis for the permeability measurement on bentonite Dankyu sand mixture, we can obtain the following important findings or observations:

1) The permeability evaluated for all conditions with the proposed method in this study (see Chapter 4) are lower than that obtained from steady condition evaluation using Eq. (4-2-11). This can be explained that the steady flow in the specimen was still not completely established at the end of the infusion process, thus the actual head difference across the specimen at the steady state should be larger than that illustrated in the Fig. 6-5-2. The time required for establishing the steady flow state is longer when testing the materials with lower permeability and higher specific storage. However, the judgement of the steady state during permeability test is sometimes difficult without waiting for a sufficient long time. Therefore, to evaluate the permeability using the method proposed in this study is suggestible.

2) The permeability and specific storage of the specimen kept almost unchanged or showed
Table 6-5-3  Results of permeability of bentonite standard sand mixture at constant flow rate of \(6.636 \times 10^{-6}\) ml/s

<table>
<thead>
<tr>
<th>External pressure (MPa)</th>
<th>Internal pressure (MPa)</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>(6.1 \times 10^{-11}) Infusion: 6.7 \times 10^{-11}</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>(4.3 \times 10^{-11}) Infusion: 4.8 \times 10^{-11}</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>(4.3 \times 10^{-11}) Infusion: 5.3 \times 10^{-11}</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>(5.2 \times 10^{-11}) Infusion: 4.1 \times 10^{-11}</td>
</tr>
<tr>
<td>0.5</td>
<td>0.05</td>
<td>(4.4 \times 10^{-11}) Infusion: 4.1 \times 10^{-11}</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1</td>
<td>(3.9 \times 10^{-11}) Infusion: 4.2 \times 10^{-11}</td>
</tr>
<tr>
<td>0.5</td>
<td>0.2</td>
<td>(5.3 \times 10^{-11}) Infusion: 3.6 \times 10^{-11}</td>
</tr>
</tbody>
</table>
Table 6-5-4  Parameters evaluated from permeability test of bentonite Dankyu sand mixture at different shear steps

<table>
<thead>
<tr>
<th>Pressure (KPa)</th>
<th>Parameters</th>
<th>Upward flow</th>
<th>Zero flow</th>
<th>Average</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Early time</td>
<td>Whole time</td>
<td>Upward</td>
<td>Downward</td>
</tr>
<tr>
<td>External</td>
<td>Internal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>K (m/s) x10^{-11}</td>
<td>5.38</td>
<td>5.99</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ss (1/m) x10^{-3}</td>
<td>2.78</td>
<td>2.39</td>
<td>2.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ce (m^3/KPa) x10^{-9}</td>
<td>1.37</td>
<td>1.48</td>
<td>1.12</td>
</tr>
<tr>
<td>500</td>
<td>100</td>
<td>K (m/s) x10^{-11}</td>
<td>6.57</td>
<td>6.60</td>
<td>5.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ss (1/m) x10^{-3}</td>
<td>3.29</td>
<td>3.29</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ce (m^3/KPa) x10^{-9}</td>
<td>2.89</td>
<td>2.75</td>
<td>3.06</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>K (m/s) x10^{-11}</td>
<td>4.39</td>
<td>4.32</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ss (1/m) x10^{-3}</td>
<td>2.97</td>
<td>3.09</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ce (m^3/KPa) x10^{-9}</td>
<td>4.65</td>
<td>4.22</td>
<td>4.74</td>
</tr>
<tr>
<td>500</td>
<td>30</td>
<td>K (m/s) x10^{-11}</td>
<td>3.54</td>
<td>3.82</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ss (1/m) x10^{-3}</td>
<td>1.03</td>
<td>1.03</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ce (m^3/KPa) x10^{-8}</td>
<td>1.99</td>
<td>1.86</td>
<td>1.98</td>
</tr>
</tbody>
</table>
Fig. 6-5-4 Comparison between the measured and simulated hydraulic head curves versus time for flow pump permeability test.
only little increase at first shear step, i.e., when the internal pressure was decreased from 0.05 MPa, the initial value of which and equivalent to that of external pressure, to 0.1 MPa. In the next two shear steps, both the permeability and specific storage of the specimen decreased owing to the time and confining pressure related swelling effect of bentonite in the mixture.

3) The permeability back calculated from the early time measurements (using half of the data measured in the infusion condition), whole time measurements (using all of the data measured in the infusion condition) and zero flow measurements are almost same. Sufficiently using all information obtained from the measurement could increase the reliability of the analytical results. Also, we can judge from the results that it is possible to shorten the permeability test time because the early time evaluation provided almost the same values of the parameters as those obtained from whole time evaluation. However, the relative error of measurements is larger when monitoring the small values of the physical parameters using a sensor with a given sensitivity and resolution. The subject of determining a proper short time to end a permeability test with an expected precision remains to be further studied, for example by means of an approach of on-line analysis which permits obtaining the values of the measuring parameters during permeability test. Then the permeability test could be ended when the on-line analyzed values of the parameters become constants or vary around the constants within a certain extent.

4) The storage capacity $C_e$ of flow pump system increased step by step during the series of shear and permeability tests. This may due to the increase of the ratio of air-rich water in the flow pump system which was withdrawn from the specimen during the downward flow process, and some other reasons like the changing of water quality during the long term series test. The important phenomenon has not been recognized in flow pump permeability test and the similar transient pulse permeability test by now. Therefore, if we use other kinds of method, e.g., the graphic method, to evaluate the parameters, it is necessary to calibrate the storage capacity of the testing system just before the permeability test and using the same permeating fluid.

3. Impact of shear strain on the permeability

The relationship between the average maximum shear strain and the permeability of the specimen is drawn in Fig. 6-5-5 a) and Fig. 6-5-5 b) for the mixture of bentonite Toyoura
Fig. 6-5-5 The relationship between the average shear strain and the permeability
standard sand and the mixture of bentonite Dankyu sand respectively. The relationships between the maximum shear strain occurred at the inner surface of the hollow cylindrical specimen and the permeability for both of the mixtures are then plotted in Fig. 6-5-6. From Fig. 6-5-5 and Fig. 6-5-6, it can be found that the permeability of both specimens were not significantly influenced by the maximum shear strain of up to about 10% or the average shear strain of about 3%. Therefore, the compacted bentonite sand mixture can be effectively used as an engineered barrier material where shear strain might occur in it and keep its low permeability initially constructed.

6.6 Conclusions

The impact of shear strain on the permeability of the compacted bentonite-sand mixtures, one of which composed of Dankyu sand will be used in the low level radioactive nuclear waste disposal facilities in Japan, was examined by means of the recently developed coupled shear and permeability test method. In this study, the constant flow pump method was used for testing the extremely-low permeability specimens. The permeability of the specimen was calculated from the measurements by means of the new method established in Chapter 4 for interpreting the flow pump permeability test. Conclusions drawn from this chapter are as follows:

1. The fact that the shear and volume change measuring system consisted in the coupled shear and permeability test apparatus can be effectively used to conduct the shear test and to simultaneously measure the small volume change for calculating or checking the deformation status of the specimen during the test is further confirmed.

2. The permeability of the bentonite sand mixtures with 15% of bentonite was not significantly influenced by the shear deformation with its maximum shear strain of up to about 10% or the average shear strain of about 3%, the tested range in this study. The permeability of the mixtures remained almost unchanged owing to the swelling and the so called self-healing properties of the bentonite. The results can also be extended to conclude that the permeability of bentonite sand mixtures with sufficient content of bentonite will not change so much due to some external factors which may cause a little change in volume of the mixture.

3. The constant flow pump permeability test method can be effectively used to measure the permeability on (or less than) the order of $10^{-11}$ m/s of impermeable materials with relatively low hydraulic gradients and with acceptable short test duration. In this study, the hydraulic gradients are less than 20 which can be computed by dividing the stabilized differential head across the
Fig. 6-5-6 The relationship between the permeability and the maximum shear strain (External pressure fixed at 0.5MPa)
specimen (see Fig. 6-5-1 and Fig. 6-5-2) by the specimen length (4 cm), and the permeability test duration for each of the permeability test under different conditions lasts only about tens of hours.

4. Swelling of bentonite at low confining pressures is notable. It not only decrease the permeability of the bentonite-sand mixture, but also reduce the specific storage of the mixture. Therefore, bentonite is a very efficient component in the mixture for water retarding barriers.

5. Temperature variations have a sensitive influence on the permeability measurement. Temperature controlled laboratory can provide a favorable condition for permeability test and the series tests which totally take relatively long time. The influence of temperature on permeability test using flow pump method can be eliminated or reduced to its minimum limit when the temperature variation is controlled within $\pm 0.5^\circ$ of a setting temperature (see Fig. 6-5-2).

6. The general model and the back analysis method proposed in Chapter 4 for flow pump permeability test can be practically used to obtain not only the permeability and the specific storage of the specimen but also the storage capacity of flow pump system itself from the early time measurements of the transient phase of the time-dependent head difference across the specimen. Therefore, the process in systematical studies on permeability and its variations of extremely low permeable materials like bentonite-sand mixture due to varying environmental factors could be accelerated if we would adopt the constant flow pump method for permeability test which requires relatively short test duration. The studies could be performed in the similar way adopted in the present study only by changing the testing conditions into other influence factors to be examined.

6.7 Permeability Test on The Specimen With a Pre-formed Shear Plane

6.7.1 Objective

The coupled shear and permeability test on the thick-walled hollow cylindrical specimen showed that the permeability of compacted bentonite-sand mixtures was not significantly influenced by the shear deformation with its maximum shear strain of up to about 10% or the average shear strain of about 3%. Although it is possible to produce even greater shear strain in the hollow cylindrical specimen by increasing the differential pressure between the pressures applied on the outside and inside walls of the specimen, it might be impossible to produce an extremely great shear strain so that a visible shear plane or planes (sliding plane or planes) can be formed in the specimen. Moreover, if the initially applied confining pressure to the hollow
cylindrical specimen is much higher than the ground pressure acting on the soil mass in situ, the specimen may be heavily over-consolidated and the measured permeability of the specimen may be quite different from that in situ. In order to see the effect of a large shear deformation on the permeability of a specimen, comparative permeability tests on a complete specimen and the specimen with a pre-formed shear plane produced by means of a direct shear apparatus are conducted.

6.7.2 Test details

1. Specimen

The mixture of bentonite and Dankyu sand are used to prepare the specimens for the comparative permeability test. Testing materials were prepared with the same conditions and procedures described in section 6.2 for preparing the thick-walled hollow cylindrical specimen. The method for preparing complete specimen is as follows:

(1) Compact the mixture by means of the rammer and the mould (100 mm in diameter) for Standard Proctor compaction test. The mixture was compacted in the mould with the compactive effort equivalent to that for the Standard Proctor compaction.

(2) Set the mould onto a hydraulic jack extruder, and remove the compacted sample from the mould slowly with a proper distance.

(3) Cut off the extruded portion with a knife, and trim the end of the remaining sample flush with a wire saw.

(4) Set the mould onto the extruder in the opposite direction, and remove the sample from the mould in the reversed direction slowly with a proper distance to make the length of the specimen be 40 mm.

(5) Cut off the extruded portion with a knife, and trim the end of the remaining sample flush with a wire saw.

(6) Remove the specimen from the mould, and measure its actual dimensions.

With this method, the complete specimen is taken from the middle part of the sample compacted in the mould.

The procedures for preparing the specimen with a pre-formed shear plane are as follows:

(1) Compact the mixture into the specially designed split mould (six segments) as shown in Fig. 6-7-1. The inner diameter of the mould is 100 mm, the same as that for the Standard
Fig. 6-7-1 The specially designed split mould
Proctor compaction. The length of the mould is 120 mm, a little longer than that of the mould used for the Standard Proctor compaction so that a large distance of shear deformation can be performed (see testing equipment). The compactive effort applied to the unit volume of the mixture, however, is equivalent to that for the Standard Proctor compaction by adjusting the blow of rammer to an appropriate times.

(2) Set the mould onto the hand-operated direct shear equipment, and restrain the mould in the vertical direction so that the volume change of specimen during the shear is controlled to be zero (Fig. 6-7-2 a)).

(3) Dismantle the appropriate bolts, and apply a shear force to the side end of the upper box causing the specimen to shear along the plane defined by the split between the upper box and lower box. The shear displacement is designed to be 2.5 cm so that a visible shear plane can be formed in the specimen (Fig. 6-7-2 b)).

(4) Fasten the upper box and lower box tightly together by means of the appropriate bolts, and take the mould away from the shear equipment.

(5) Dismantle the end plates and the appropriate screw bolts.

(6) Take off the four segments carefully at both ends of the sample, and cut off the portions out of the shortened mould by means of a knife.

(7) Finally trim the ends flush by means of a wire saw.

(8) Slightly loosen the fasten bolts, and remove the specimen with the pre-formed shear plane from the shortened mould.

(9) Check the density and the dimensions of the specimen.

2. Testing equipment

The permeability tests for the complete specimen and the specimen with the pre-formed shear plane were conducted in the pressurized cells for triaxial test. The pedestals and caps were improved to fit the dimensions of the specimens. Other necessary improvements, such as on coupling spacer and pipe lines, were also done to make the permeability tests possible. The constant flow pump was used to measure the permeability of the specimens. The head difference induced across the specimen was monitored by means of the high-sensitivity pressure gauge at the port connecting to the base end of the specimen. Another port connecting to the top of the specimen was left free to the atmosphere.

The tests were conducted in a temperature controlled laboratory. The temperature and the head
Fig. 6-7-2 The hand-operated direct shear equipment

Front-view of simple shear apparatus

Side-view of simple shear apparatus

a) Before shear
Fig. 6-7-2  The hand-operated direct shear equipment
difference were recorded by means of TDS-601, a sophisticated data acquisition device for recording the electrical outputs from various kinds of electrical transducers. The testing apparatus for the complete specimen and the specimen with the pre-formed shear plane are shown in Fig. 6-7-3.

3. Testing procedures and conditions

Testing procedures and conditions for the comparative permeability test are as follows:

(1) Set the specimen onto the testing apparatus.
(2) Fill the cell and pipe with deaired water, then apply a lower confining pressure of 0.03 MPa to the specimen.
(3) Replace the air in the specimen with carbon dioxide for a rapid saturation of the specimen.
(4) Saturate the specimen with deaired water by means of pressurized burette and check the saturation condition with pore pressure reaction test.
(5) Increase the confining pressure step by step, and conduct permeability measurement on the specimen after consolidation at each of the loading steps. The confining pressure steps for both specimens are 0.3 MPa and 0.5 MPa.

During the whole procedures, measures and care similar to testing the thick-walled hollow cylindrical bentonite-sand specimen should be taken.

6.7.3 Test results and conclusions

The data obtained from the comparative permeability test are those of time-dependent differential head across the specimen for each specimen under different confining pressure conditions. The curve of differential head across the specimen versus time is similar to that obtained from the coupled shear and permeability test on thick-walled hollow cylindrical specimen. For the objective of the comparative permeability test is to see the relative values of permeability of the complete specimen and the specimen with pre-formed shear plane, here the permeability is calculated from the stabilized differential head by means of the Darcy's Law. The permeability of the specimens measured at various confining pressure conditions are tabulated in Table 6-7-1.

The permeability of the complete specimen is larger than that of the specimen with the pre-
a) The testing apparatus for the complete specimen

b) The testing apparatus for the specimen with pre-formed shear plane

Fig. 6-7-3 The testing apparatus for comparative permeability tests
Table 6-7-1 The results of comparative permeability test

<table>
<thead>
<tr>
<th>Confining pressure (MPa)</th>
<th>Condition</th>
<th>Complete specimen ($10^{-11}$ m/s)</th>
<th>Specimen with a pre-formed shear plane ($10^{-11}$ m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upward flow</td>
<td>2.27</td>
<td>2.15</td>
</tr>
<tr>
<td>0.05</td>
<td>Downward flow</td>
<td>2.04</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>2.16</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Upward flow</td>
<td>1.75</td>
<td>2.40</td>
</tr>
<tr>
<td>0.5</td>
<td>Downward flow</td>
<td>1.05</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>1.40</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Fig. 6-7-4 Two possible arrangements (fabrics) of identical sets of particles at same void ratio relative density (After G. A. Leonards)
formed shear plane at each of the confining pressure conditions. It can be concluded that the impact of the method for preparing specimen on the permeability is relatively greater than that of the shear deformation. The specimen with the pre-formed shear plane was taken out from the split mould with less disturbance to the sample. The sample for preparing the complete specimen was moved in the compaction mould two times in the reversed directions by means of the hydraulic jack extruder for trimming the ends of the specimen. Also the specimen was removed from the mould by extrusion with relatively strong force. By these procedures, the complete specimen was taken from the compaction mould with relatively more disturbance to the sample. The magnitude of the permeability of both specimens, however, are on the same order of $10^{-11}$ m/s. Therefore, the mixture of bentonite and sand can provide low permeability for creating hydraulic barriers retarding the water flow.

To further give a convincing interpretation to the phenomena (the permeability of the specimen with pre-formed shear plane is lower than that of the complete specimen) seems to be difficult. A possible interpretation may be that the structures of the specimens are different due to the different procedures to prepare them. Although the densities of the specimens are obtained almost the same from the different procedures (the density of the complete specimen is 1.97 Mg/m$^3$; and the density of the specimen with pre-formed shear plane is 1.78 Mg/m$^3$), the structures of the specimens may be different and lead to the different permeability results. A simple example is shown in Fig. 6-7-4, in which the two "samples" have identical particle sizes and distributions, void ratios, and relative densities. Yet they have very likely to have markedly different engineering properties, such as permeability, compressibility, and static strength (Juang and Holtz 1986). Therefore, the permeability is dependent on the density of a sample but not controlled by the density. A strict construction control in situ should also be done on the management of permeability of a barrier itself, rather than its density.

REFERENCES


Chapuis, R. P., 1990, Sand-bentonite liners: Field control methods, Canadian Geotechnical

Department of Science and Technology (DST), Disposal of Low-Level Radioactive Nuclear Waste (Document).


Chapter 7 SUMMARY AND CONCLUSIONS

With the growing importance of environmental issues in our society towards the twenty first century, extremely low-permeability geotechnical materials are being studied increasingly for their long term physical and chemical stability and effectiveness in retarding the transport of hazardous wastes, including radioactive wastes. They are being used as liners or barriers in the waste disposal facilities to retard the underground migration of contaminants accompanying water movement to the surrounding environment. The waste disposal facilities are generally expected to perform effectively for long times or long long times, from several hundred years for low-level radioactive waste disposal to several ten thousand years or even longer for high-level radioactive waste disposal during which the permeability of the barrier materials might be deteriorated and increased due to the varying performance conditions. The present study examines the impact of shear strain, which may occur in the barriers due to geologic events and processes such as earthquake and gradual tectonic deformations, on the permeability of bentonite-sand mixtures based on the development of the coupled shear and permeability test method for soil-based hydraulic barriers. One of the tested mixtures, the mixture of Dankyu sand and bentonite, will be used in low-level nuclear waste disposal facilities in Japan. The contents, results and conclusions of each chapter are as follows:

Chapter 1 described the background and the purposes of the present study.

Chapter 2 briefly introduced the mechanism of fluid flow through porous media and the factors influencing the permeability of soils. Then the state of the researches on liner or barrier materials, composed of bentonite or other kinds of clay and sand, was briefly reviewed. The importance of studying permeability variation of bentonite-sand mixtures due to shear strain was further stressed from the viewpoints of long-term safety evaluation of the radioactive nuclear waste disposal facilities and taking the environmental control as a design tool before construction, rather than a treatment of accidents. In addition, the importance of developing a method for earning more reliable permeability of impermeable materials with relatively low hydraulic gradients on the orders of those in situ was indicated. Simultaneously, the necessity for developing a method to instantaneously monitor small volume changes of a specimen during triaxial test was also emphasized.

Chapter 3 proposed the general requirements for the coupled shear and permeability test on geotechnical materials. The appropriateness of investigating permeability variation of soils along
the shear plane or planes was pointed out. Then, the perspective method which shears a thick-walled hollow cylindrical specimen by means of the differential pressure between the pressures applied on the outside and inside walls of the specimen was proposed based on the review and discussions of the shear testing methods commonly used in geotechnical laboratories. Theoretical analysis of the shear testing method considering the material's non-linear stress-strain relationship and the dilatancy character obtained from the improved triaxial tests was then derived.

Chapter 4 analyzed the appropriateness of each of the prevailing laboratory permeability test methods and clarified the remaining problems in each of the methods for testing geotechnical materials with extremely-low permeability. For the sake of its capacity of testing impermeable materials with relatively low hydraulic gradients (close to those existing in situ) and short test durations, the constant flow pump permeability method has been improved in order to eliminate the influence of equipment compliance on the measurements of small permeabilities and to further shorten the testing time. The more general theoretical solution based on the new mathematical model of the flow pump permeability test was then developed and described in detail. Application of the newly developed solution to the 'theoretical permeability test' illustrated how the new method can obtain, precisely and rapidly, not only the permeability and specific storage of the specimen but also the storage capacity of permeability testing system itself. Meanwhile, the technique for minimizing the highly non-linear error function to identify parameters with vast 'searching regions' from permeability measurements was also demonstrated.

Chapter 5 developed the systems for coupled shear and permeability test on general soil materials and conducted the coupled shear and permeability tests on kaolin-sand mixtures in which the constant-head permeability test method was adopted. The test and analytical results revealed that the new coupled shear and permeability test apparatus can be effectively used to, qualitatively and quantitatively, investigate the influence of shear strain on the permeability of soils, provided that the values of the mechanical parameters of the testing specimen involved in the analysis of the shear test method established in Chapter 3 are properly determined. The permeability of a nonexpansive soil is generally increased almost linearly with the increase of shear strain produced in the specimen. In the cases of the compacted mixtures of the Standard sand and kaolin, their permeabilities, in the range of $10^{-8} \sim 10^{-7}$ m/s, were increased to about two fold when they were sheared with the maximum shear strain of about 10% which locates in the post-failure region of the stress-strain path of the materials.
Chapter 6 conducted the coupled shear and permeability tests on bentonite sand mixtures in which the constant flow pump method, capable of testing materials with permeability lower than $10^{-9}$ m/s with acceptable test time, was used for permeability measurements. Test results showed that the permeabilities on the order of $10^{-11}$ m/s ($10^{-9}$ cm/s) of bentonite sand mixtures were not significantly influenced by the shear strain of up to about 10%, the tested range in the study and locates in the post-failure region, owing to the swelling and the self-healing properties of the bentonite. The effectiveness of the new method established in Chapter 4 for interpreting flow pump permeability measurements was demonstrated from the practical applications. In addition, the results demonstrated that how the new method can further shorten the permeability test duration, and why the method can be used to accelerate systematic permeability and specific storage studies of barrier materials. The comparative permeability test on the complete specimen and the specimen with a pre-formed shear plane showed that the influence of the way of preparing specimen on the permeability is relatively more sensitive than that of shear strain. Thus, it is very important to strengthen the control or management during construction of the engineered barriers in situ.

Chapter 7, i.e., this chapter, summarizes the results and conclusions obtained from the present study.

This study has clearly revealed that the newly developed method for coupled shear and permeability test on extremely-low permeability barrier materials can be effectively used to evaluate, qualitatively and quantitatively, the influence of shear strain until post-failure region on the permeability of the materials. Applications of the method can be also extended to investigating the coupled hydro-mechanical behaviors of similar general geotechnical materials encountered in many engineering practices. The new theoretical solution and the parameter identification approach of flow pump permeability test method can be used to obtain both the extremely-low permeability and specific storage of materials rapidly and precisely with relatively low hydraulic gradients and elimination measurement errors caused by equipment compliance. The method can be promisingly used to accelerate systematic permeability and specific storage studies of barrier materials considering various kinds of influence factors before construction, and thus can improve the reliability of design for barriers which will leap over long-term performing times.
APPENDIX

A-1. Kettle, Toyoara standard mold and their missions

A-1 Kaolin, Toyoura standard sand and their mixture

A-2 Thick-walled hollow cylindrical specimen of compacted mixture of kaolin and Toyoura standard sand
A-3 Bentonite, Toyoura standard sand and their mixture

A-4 Thick-walled hollow cylindrical specimen of compacted mixture of bentonite and Toyoura standard sand mixture
A-5 Bentonite, Dankyu-sand and their mixture

A-6 Thick-walled hollow cylindrical specimen of compacted mixture of bentonite and Dankyu-sand mixture
A-7 The coupled shear and permeability test system using flow pump method for permeability test on extremely-low permeability materials
Kodak Color Control Patches

Kodak Gray Scale