The influence of the suction distribution on deformation property

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ABSTRACT

This study investigates the influence of suction distribution and soil moisture variation on the compression behavior of unsaturated soils. The research is motivated by the need to better understand soil deformation processes affecting monuments, buried structures, and archaeological remains under unsaturated conditions. To examine the effect of non-uniform suction conditions, a stainless-steel column mold apparatus was developed to apply different suction levels to the top and bottom surfaces of soil specimens. A modified oedometer apparatus was then used to evaluate compression behavior under controlled suction gradients. Several soil materials, including silty soil, kaolin, bentonite mixtures, and silica sand mixtures, were tested. The results show that suction gradients produce non-uniform water content distributions that significantly influence compression behavior and deformation stiffness. Specimens subjected to suction gradients exhibited different compression responses compared to specimens with uniform moisture conditions. In addition, the study investigates the influence of carbon dioxide gas on soil-water characteristic curves (SWCCs) under high suction conditions. The results indicate that carbon dioxide exposure modifies water retention behavior, particularly during the wetting process, and reduces hysteresis between drying and wetting paths.
Keywords: Suction, unsaturated soil, SWCC, deformation, carbon dioxide gas, relative humidity

INTRODUCTION

Ancient tombs constructed in layers of soils store buried treasures such as ruins and Haniwa, which should be carefully protected. Deformation of soil around buried treasures is an important concern. In addition, soils in unsaturated conditions have some suctions, and suction variations are closely related to deformations or looseness. This study focused on the influence of suction or soil moisture distribution on the compression deformation properties of some unsaturated soil materials. Also, considering that the effort of carbon dioxide gas led to develop water retention activity.

The relationship between the suction and water content was established to confirm the magnitude of the suction incline in the specimen. This study used two developed apparatuses: a developed stainless-steel column mold apparatus and an oedometer apparatus. The developed stainless-steel column mold apparatus makes it possible to apply different suctions to the top and bottom surfaces of the specimens. The water content distribution is measured, and the rate of suction incline is estimated axially. The developed oedometer apparatus was used to determine the compression properties beyond the suction distribution. A conventional oedometer test was performed, and the compression curve was evaluated. It was found that the magnitude of the suction incline induces different compression behaviours. Carbon dioxide gas changes the SWCCs on high suction ranges. Particularly, on the wetting portion, the results describe the chemical effort to soil physical phenomena that carbon dioxide gas increases absorption activity on the wetting portion.

LITERATURE

Effective stress for unsaturated soil

To identify relevant unsaturated soil properties and effective stress for unsaturated soils, it is important to define the variables that can be used to represent the stress state of the unsaturated soils. The stress state is the single element that establishes geotechnical engineering as a science. There now appears to be a fairly consensus that the stress state for an unsaturated soil should be described using two independent stress tensors with two independent normal stress variables. These two variables become a logical extension of the effective stress variable used for a saturated soil (Bishop & Blight, 1963, Fredlund & Morgenstern, 1977, Rahardjo & Fredlund, 1996).

Suction

Suction was measured using a combination of pore-air pressure, pore water pressure, vapor equilibrium, filter paper, and psychrometer. The observations concluded that variations in suction with soil moisture arise from changes in the total suction (rather than the osmotic component). Here, matric suction is generally defined as the difference between pore-air pressure and pore-water pressure using the pressure plate/membrane technique. The vacuum pressure technique has led to the definition of total suction using salt solutions as high suction ranges (Graham et al., 1995, Graham et al., 2001).

SWCC

Soil-water characteristic curves are defined as no single relationship between soil moisture, degree of saturation, and the amount of water in a soil. There are many possible scientific curves that are composed of bounding drying and wetting curves. The SWCC supports a wide suction range from 0 to 296 kPa. Geotechnical engineers have benefited immensely from the investigations undertaken in agronomy-related disciplines, such as soil physics (Klute, 1973, Fredlund, 2025).

Suction control

Unsaturated soil mechanical researches often involve suction control technique to conventional soil mechanical tests. Hilf, 1956 suggested that pore-air and pore-water pressures could both be raised to positive pressures to apply matric suction. The previous presentation of sand and silt behavior implied that capillary forces increase the contact forces between grains and therefore contribute to soil stiffness and strength. Alonso, 2003 considered the attraction force at soil particle together induced by a common meniscus and reported deformations in laboratory experimental tests using the vapor pressure technique. Required air flow could from bottom to top surface.

Takamatsuzuka Tumulus

Mimura & Ishizuka, 2006 referred that various fungi has recently appeared on the lime plaster wall on which the precious paintings are drawn together with intrusion of insects into the stone chamber, which seriously has damaged wall paintings. Mimura et al., 2009 conducted on undisaturbed samples of the compacted earth martials called “Hanchiku” from the mound of Takamatsuzuka Tumulus to evaluating the stability of the mound.

TEST PROCEDURE

Soil materials

This study prepared five different soil materials: silty soil, clay, Kunigel V1, GX, and silica sand. Each property is mentioned as follows: The described the maximum dry density and the optimum water content are 1.600 Mg/m^3 and 18.8 %, respectively. Other soil materials, bentonites, are prepared, namely, Kunigel V1 and GX.

Soil specimens

All soil specimens in the suction incline and oedometer tests were statically compacted in a stainless-steel mold, and the prepared sizes differed depending on each test. An oedometer test is prepared with a height of 15 mm and a diameter of 60 mm. The bentonite sand mixture specimens have mixture tow ratios of 3:7 and 1:9 against benitoite, and two dry densities are 1.600 Mg/m^3 and 1.200 Mg/m^3 with a constant water content (i.e., 17.0%). All the specimens remained without compaction for the soil-water characteristic curve test and contained both nitrogen gas and carbon dioxide gas under the pressure of 30 kPa.

Table 1. *Summary of each portion.*

Portion #	
①②	Chamber installed salt solution
③④	Conventional pump
⑤⑥	Developed steel mold with cap

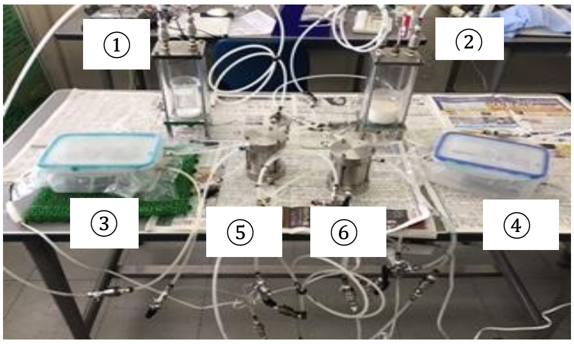

Photo 1. *System for air circulation*

Table 2. *Summary of each portion for developed steal mold*

Portion #	Processing
①②	Air space
③④	In flow from chamber installed salt solution
⑤⑥	Out flow / back to pump
⑦	Specimen
⑧⑨	Producing hydration directly

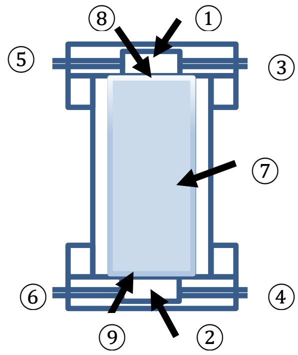

Figure 1. *Developed steal mold*

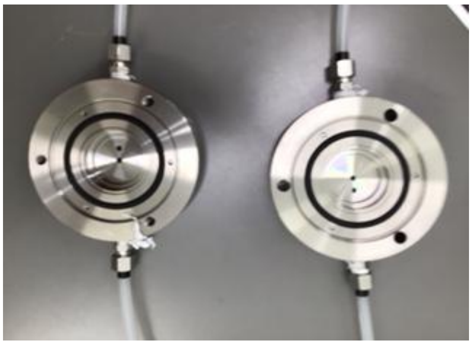

Photo 2. *Upper and bottom cover plate*

Apparatus for suction incline

This study has an innovation to suction control by making a suction incline in the specimen. A high suction value is selected so that the vapor pressure technique is satisfactory. The developed system has been proposed for controlling suction incline. The system, which is shown in Photo 1 and Table 1, and the specification are explained in various portions. The essential component of the system for controlling relative humidity is connected to the stainless mold, which comprises the stainless cylinder and two plates, and the illustration is shown in Fig. 1 and Table 2. Each potion is described with a table. Two stiffness plates are indicated in Photo 2. The air inflow and outflow are produced by an air pressure of 20 kPa in a conventional pump and a steady air flow is maintained in the tubes connected through some equipment. In addition, an oedometer apparatus is used to measure the deformations subjected to suction incline (i.e., nonuniformity water content distribution).

Apparatus for gas

A conventional oedometer apparatus is developed that makes it possible to supply air to the top and bottom surfaces of the specimen. The air can control different relative humidity. The air maintains the flow in the relative humidity control circulation system, which consists of a conventional air pump, a chamber containing a setting solution, and a connecting tube. The compression stresses are loaded from 50 to 400 kPa. The top and bottom surfaces of the specimens are retained by the difference in relative humidity hydrations during the compression test.

A chamber is prepared that connects to a carbon dioxide gas cylinder and the pressure of the supply gas is regulated using a pressure regulating valve for 30 kPa. The pressure regulating valve is R-8 in the product model number, which is made in Sakaguchi Co., Ltd. The standard flow rate is 25 L/min. The capacity ranges from 0.1 to 0.3 MPa in pressure.

Chadwick at al. (1994) stated that carbon is sequestered in soils by recalcitrant organic matter accumulation and by bicarbonate weathering of silicate minerals. Carbon fixation by ecosystems helps drive weathering processes in soils and, in turn, diverts carbon from annual photosynthesis-soil respiration cycling into the long-term geological carbon cycle. Novak, 2007 presented the mathematical derivation and evaluation of a suite of inversion techniques that determine the instantaneous soil carbon dioxide source-density distribution from corresponding values of soil carbon dioxide concentration at depths of 0, 0.1, 0.2, 0.4, and 0.8 m and, for some methods, the surface carbon dioxide flux density.

The glass container has a height of 45 mm, a diameter of 21 mm, and a volume of 8 cc. The specimen in the glass remains under a constant carbon dioxide gas pressure. The pressure in the chamber was measured at periodic intervals using a standard pressure sensor that checked the constant pressure of 30 kPa.

Test program for suction incline

A series of this testing program is composed of the controlling suction for establishing suction incline in the specimen and oedometer compression test, which have common suction control based on the vapor pressure technique. In general, measurement and control of suction can be divided into two categories: pressure plate technique using a high air entry disc (i.e., ceramic plate in general) and vapor pressure technique on Kelvin law using a variety of salt solutions.

In particular, the vapor pressure technique is closely related to producing high suction ranges, such that the high suction is recognized as over 1.0 MPa. It is easy to compose a mechanical test process for high suction range. Some differences in relative humidity were referred to make suction inline distribution in the space, which were 98.0%, 75.0%, 33%, and 11.0%. Soil suction is quantified in terms of the relative humidity immediately adjacent to the water surface and is called “soil suction.” Soil suction is related to the adsorptive force associated with water and a solid surface. Each relative humidity corresponds to suction pressures of 2.8, 38, 148, and 296 MPa. Beyond the equilibrium of each suction, the water content distribution is measured, and the compression curves are verified.

SWCC test program for gas

Three different soil materials are used in SWCC test including both nitrogen gas and carbon dioxide gas that are Kunigel V1, bentonite GX and Kaolin. All soil materials are placed into the chamber. The two gas filling supply to the chamber for two weeks. The changes in the weight of the samples are measured at regular intervals during the application of gases. Beyond equilibrium with each gas filling, the SWCC test is conducted out that the suction range has from 2.8 to 296 MPa with increase/decrease. It corresponds from 98% to 11% relative humidity. As with other suction processes, suction values reduce after equilibrium on suction 296 MPa, which is a wetting process. The obtained SWCCs are useful for comparison and interpretation of the influence of carbon dioxide chemical activity.

TEST RESULTS

Water content distribution for silt

Silty soil directly supplies two different RH sets: one is the top surface with a RH of 11% and the bottom surface with a RH of 75%. The other one is the top surface with a relative humidity of 98% and the bottom surface with a relative humidity of 75%. The water content distributions for all the silty soil specimens were determined (Fig. 2). Water contents were plotted to the distance from the top surface of each specimen, and the water content at nearly each boundary surface corresponds closely to that correspond to suction verified in soil-water characteristic curve measured in previous works. The incline

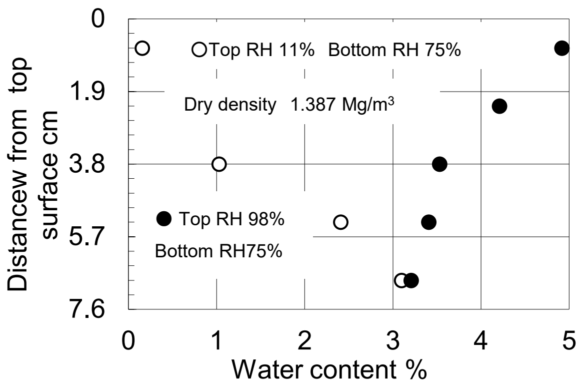

Figure 2. *Distribution for silt*

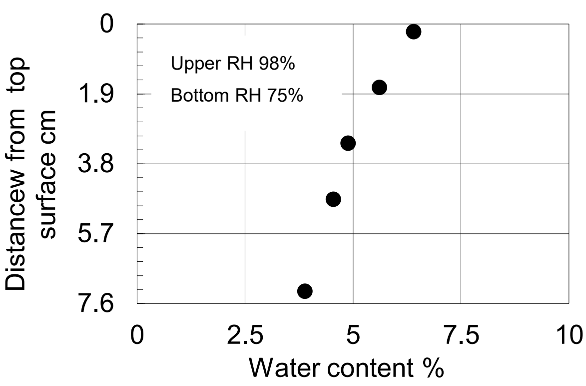

Figure 3. *Distribution for Kaolin*

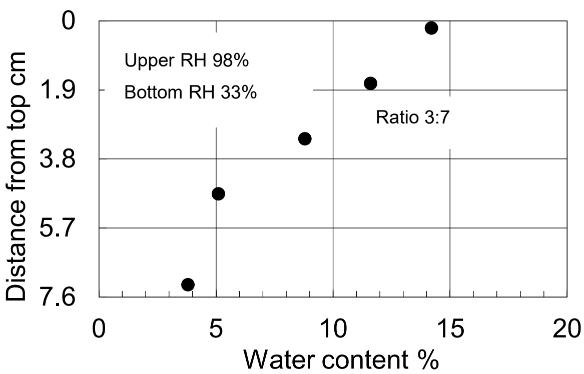

Figure 4. *Bentonite:sand (3:7)*

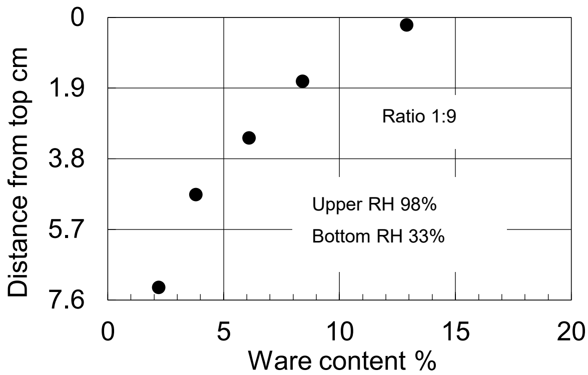

Figure 5. *Bentonite:sand (1:9)*

of the water content distribution is larger than that of the inverse difference variation in suction. It is possible to predict the non-uniformity in aggregation or no continued structure of soil.

Water content distribution for Kaolin

Water content distributions for all clay specimens were determined to five layers, as shown in Fig. 3. The relative humidity condition is that the top surface has a relative humidity of 98% and the bottom surface has a relative humidity of 75%. Water contents were plotted to distance from the top surface, and the measured water content at nearly each boundary surface is close to that corresponding to suction verified in soil-water characteristic curve. The obtained distribution appears to be a straight line.

Water content distribution for 3:7 and 1:9

The water content distribution for bentonite sand mixture specimens with different mixture ratios is described in Figs. 4 and 5. The relative humidity condition is that the top surface has a relative humidity of 98% and the bottom surface has a relative humidity of 33%. Bentonite has a high water retention activity with a water content of more than 2% and a relative humidity of 33% near the bottom. Similar the abovementioned two materials, such as silty soil and clay, the water content distribution verifies the interesting lines.

Deformations for bentonite sand mixture 3:7

Silica sand mixture to bentonite Kunigel V1 with ratio 3:7. The compaction water content is 17%. Relative humidity control: top surface is 98% and bottom surface is 33%. The developed oedometer apparatus is used mentioned above. The specimen without relative humidity control is prepared to the deformations as other condition which is remine water content uniformity. Beyond reaching equilibrium with each relative humidity. An oedometer test was conducted to determine the change in void ratio for the interpretation of compression curves. Figure 6 shows two different compression curves, with the common maximum compression stress of 400 kPa and the unloading process of 100 kPa. The term in NO RH is water content uniformity without relative humidity control. The occurrence of suction inline

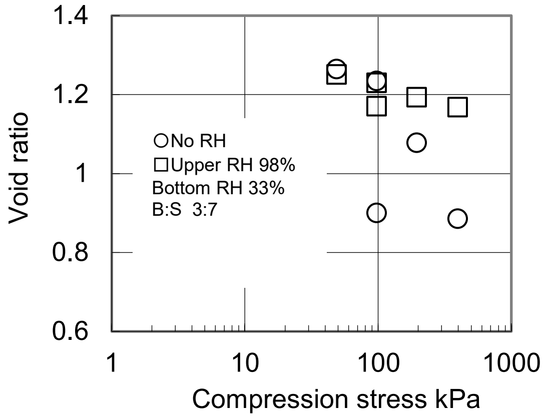

Figure 6. Bentonite sand mixture (3:7)

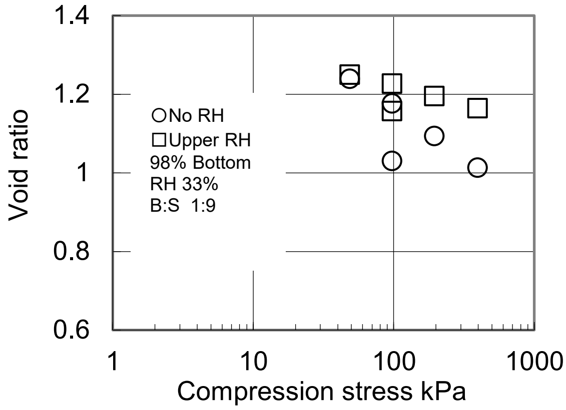

Figure 7. *Bentonite sand mixture (1:9)*

causes an increment in compression stiffness and a small reduction in void ratio compared with the uniformity of water content in the specimen.

Deformations for bentonite sand mixture 1:9

Another mixture ratio of 1:9 is prepared for the investigation of deformations under compression process that is 1:9 in bentonite sand mixture. The comparison in Fig. 6 shows that the occupation is so much that the dry density and compaction water content are remaining. The specimen having water content uniformity indicated the reduction of deformation compared to the results shown in Figs. 6 and 7. The void ratio at a compression stress of 400 kPa is 1.013, and the bentonite sand mixture ratio is 1:9. On the other hand, the void ratio is 0.886 for a bentonite sand mixture ratio of 3:7. The fraction of the sand mixture is proportional to increment, and the deformations are small. The resistance of deformation due to vertical loading increases considering the suction incline effort. It has a similar tendency in two different bentonite sand mixture ratios.

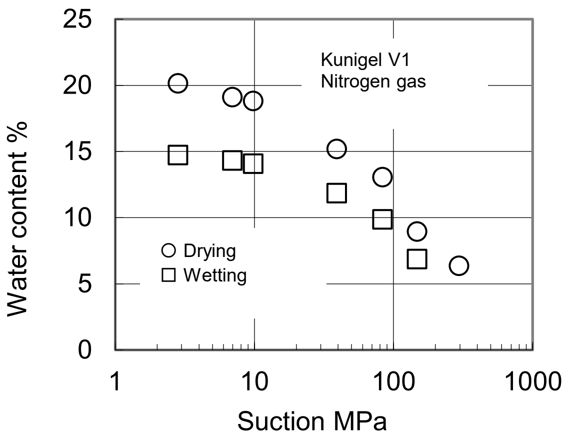

Figure 8. *SWCC for Kunigel V1 (Nitrogen)*

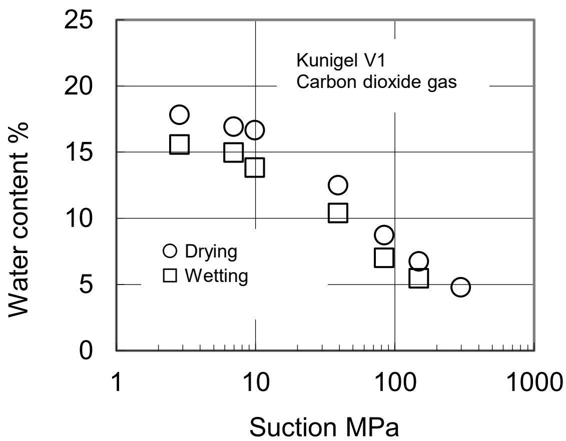

Figure 9. *SWCC for Kunigel V1 (Carbon)*

SWCC for Kunigel V1

Variation of soil moisture due to suction changes is able to develop as soil-water characteristic curve and plays an important role in the determination of unsaturated soil properties. The soil-water characteristic curve for a Kunigel V1 demonstrates that the water content changes with suction, as shown in Figs. 8 and 9. Figure 8 shows the result for a Kunigel V1 imposed nitrogen gas pressure. Soil moisture recorded to be generally curve and obviously reduction in water content according to suction increment. It is possible to draw a straight line in the relationship between suction and water content beyond a suction of 83.4 MPa. At the end of the drying portion, the water content increases with decreasing suction in the wetting portion. Furthermore, the hysteresis reactions are maintained through SWCC tests. Measured soil water retention activity for Kunigel V1 was attempted, which was imposed carbon dioxide gas under a pressure of 30 kPa and a supplication period of 2 weeks. The controlled

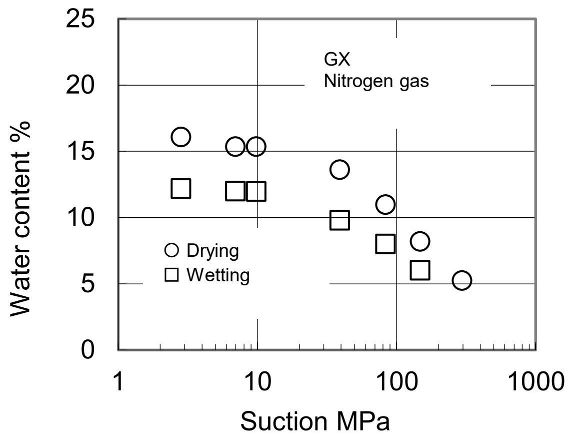

Figure 10. *SWCC for GX (Nitrogen)*

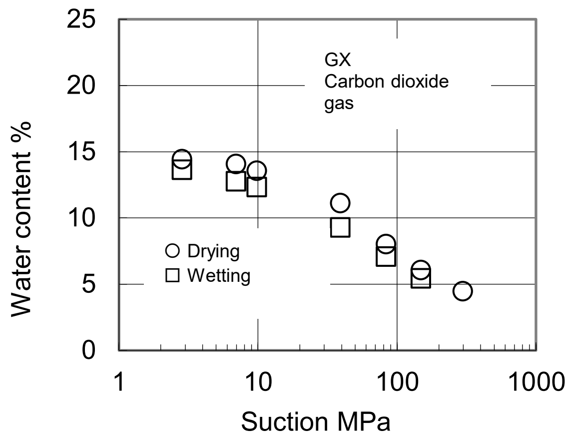

Figure 11. *SWCC for GX (Carbon)*

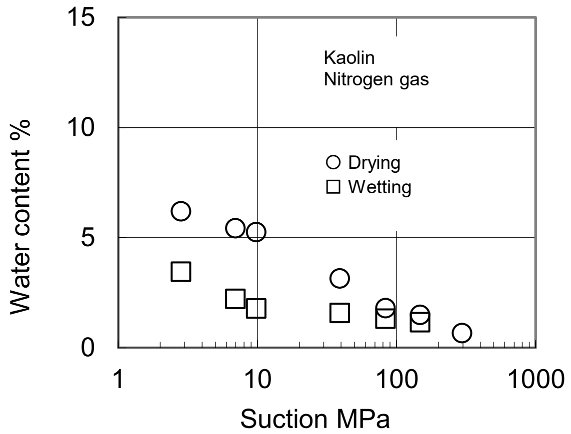

Figure 12. *SWCC for Kaolin (Nitrogen)*

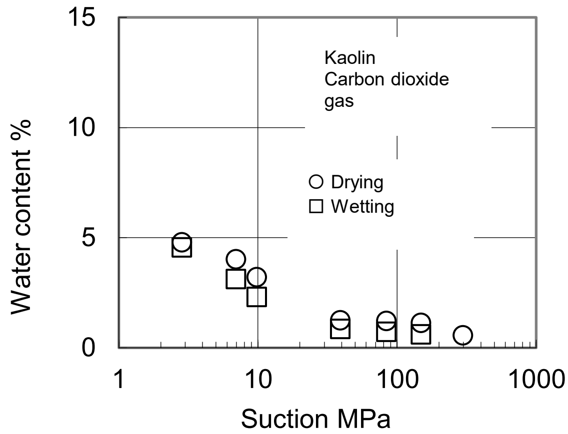

Figure 13. *SWCC for Kaolin (Carbon)*

suction under the drying and wetting portions are the same as the case of nitrogen gas pressure, as shown in Fig. 8. The key future is small in the difference between the drying and wetting portions, that is, the degree of hysteresis procedure through all suctions, as shown in Fig. 9. The difference in water contents at a suction of 2.8 MPa is less than 2.0 %. The estimated gap in water content is 6.0 % in the case of nitrogen gas, as shown in Fig. 8. The results verified that the effort of carbon dioxide gas reduced the reduction of hysteresis in water retention activity.

SWCC for GX

The water retention curves for bentonite GX with the application of nitrogen gas and carbon dioxide gas show that the water content changed according to suction (i.e., more than 2.8 MPa), as shown in Figs. 10 and 11 for suctions. Soil moisture was recorded to be around 5.0 % according to the dry process at a suction pressure of 296 MPa. The incline of the straight line at a suction of 39.0 MPa seems to be a large thought reduction phenomenon. Comparison that GX subjected carbon dioxide gas produces small soil moisture during both drying and wetting processes, indicating that there is little hysteresis activity with regard to water retention. To delete the hysteresis performance due to supply carbon dioxide gas is similar to the SWCC result obtained from Kunigel V1.

SWCC for Kaolin

The soil-water characteristic curves for kaolin are shown in Figs. 12 and 13. The water retention activity is small compared with other materials, such as Kunigel V1 and bentonite GX. The measured water content ranges from 6.2 % to 0.66 % through all suction values. The hysteresis for SWCC curves is associated with nitrogen gas application. However, the difference between the drying and wetting portions is few due to the supply of carbon dioxide gas.

CONCLUSIONS

Understanding soil conditions around monuments, ancient tombs, and archaeological remains is important for their preservation and long-term stability. This study contributes to the development of methods for evaluating deformation and stiffness behavior in unsaturated soils, which may help support the protection of archaeological heritage sites. The obtained results are contribute to remain archaeological site preservation. This study focuses on the water content distribution as a result of the suction incline using the difference suction controlling technique. Measurement of deformation was conducted using an oedometer test for specimens having suction incline. In addition, the influence of nitrogen gas pressure and carbon dioxide gas pressure on soil-water characteristic curves in high suction ranges was determined. The summary obtained from this testing program is as follows:

(1) The soil-water characteristic curve measured used in vapor pressure technique effectively predicts the effect of suction distribution on water content distribution. Two different RH values were applied to the top and bottom of the specimen, and the obtained water content distribution indicated no uniformity distribution.

(2) The deformations obtained from the oedometer test using the developed apparatus indicate the influence of suction incline. The decrement of the void ratio according to the compression stress loading change associated with the production of a suction incline for the bentonite sand mixture.

(3) This study investigates the influence of both nitrogen and carbon dioxide gas pressures on soil water retention activity. Soil materials, such as Kunigel V1, GX, and Kaolin, were prepared for the hydraulic tests. The difference between the drying and wetting portions is that the application of carbon dioxide gas pressure is improve soil-water moisture activity. Hysteresis, such as the difference between the drying and wetting portions, improves the small.

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