IS-PORTO 2023 PROCEEDINGS

Proceedings of the 8th International Symposium on
DEFORMATION CHARACTERISTICS OF GEOMATERIALS
Porto, 3rd - 6th September 2023

Deformations of bentonite-sand mixture without lateral confining pressure subject to high suctions changing

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ABSTRACT

Generation of electricity in nuclear power plants have supplied further energy to society in the world, and remain arising of radioactive waste as results of performance industry with activity. In fact, all of radioactive waste encourage some categories types as following; two most important points are high-level waste (HLW) and low- and intermediate-level waste (LLW). To end disposal completely, every country operated Nuclear Energy plant foresees further deep geological repository. This study conducted out measurement of deformations due to changing suction, which were volume change, axial strains and radial strains. Used triaxial compression apparatus was improved to be possible controlling suction for air flow circulation, and measured both axial and radial strains and variations of mass under drying-wetting cyclic in suction. Required suction rage is from 2.8 MPa to 296 MPa, and it corresponds to from 98.0 % to 11.0 % in relative humidity. Axial strains and radial strains for all of specimens have described obviously the shrinkage phenomena due to drying and wetting cyclic process regard to suction potential, and bentonite-sand mixture specimens are statically compacted. Axial strains compare that is larger than radial strains regard to all applied suctions. Subsequently, changing of void ratio was classified into two categories, which one was elastic components and other one was plastic component, and elastic component in void ratio was remaining larger than plastic component for high suction ranges.

Keywords: Suction controlling; Deformations; Vapor pressure technique; Elastic - plastic behaviour.

1. Introduction

1.1. Background

Generation of electricity in nuclear power plants have supplied further energy to society in the world, and remain arising of radioactive waste as results of performance industry with activity. In fact, all of radioactive waste encourage some categories types as following; two most important points are high-level waste (HLW) and low and intermediate-level waste (LLW). The third type is alpha-toxic waste (ATW) (Delage et al. 2010). Radioactive waste has to be isolated from the human habitat for absolutely so long time period until its radioactivity has decayed to an innocuous situation. To end disposal completely, all countries operate Nuclear Energy plant foresees further deep geological repository. All of the waste is enclosed in a tight and stable rock formation at a depth of several hundred meters more than 500 meters.

It is found out that bentonite and bentonite-sand mixture materials have interesting properties such as thermal, hydration, mechanical and chemical associated to couple phenomena (Cui and Tang 2013, Bernier et al. 2017, Chen et al. 2017, Chen et al. 2019). Interpretation of all of properties require to accumulate experimental results according to performance in many laboratory tests, and it should focus on individual component. Hydration effort occurred the deformation and swelling pressures due to changing of soil moisture either vapor movement and liquid movement in the structure (Blatz and Graham 2000, Nishimura and Fredlund 2001, Blatz et al. 2008). Almost of all swelling pressure testing used the distilled water or salinity water as liquid fluid, and determined the swelling deformation under lateral confirm using oedometer apparatus. It has been required to take the deformation properties of material used in the artificial barriers system, and particularly changing of relative humidity is majority factor, which is equilibrium to the change of suction in the materials. Vapour pressure technique is possible to realize the controlling relative humidity using some salt solutions, and at present the controlling technique has been widely accepted to measure strength factors as one of couple phenomena (CODE_BRIGHT, 2004. Gens 2010, Nishimura and Koseki 2021). The obtained results are further effectively to establish mathematical model in order to prediction at long time safety specification for waste disposal.

1.2. Purpose of study

This study conducted out measurement of deformations for bentonite-sand mixture due to changing suction, which were volume change, axial strain and radial strains. Used triaxial compression apparatus is improved to be possible controlling suction for air flow circulation, and measure deformation and changing of mass under drying-wetting cyclic performance in suction. Required suction range is from 2.8 MPa to 296 MPa, and it correspond to from 98.0 % to 11 % in relative humidity. Then seven difference salt solutions were used in order to create confirmed relative humidity. They are Potassium Sulfate, Potassium Nitrate, Ammonium

Dihydrogen phosphate, Sodium Chloride, Magnesium Nitrate, Magnesium Chloride and Lithium Chloride. Experimental room remained 20 degrees Celsius during experimental test at laboratory.

All deformations for specimen described obviously shrinkage phenomena due to drying and wetting cyclic process in suction, which was bentonite-sand mixture with statically compacted. Axial strain comparison with lateral strain that was larger than lateral strain regard to all suctions. Moreover, changing of void ratio was classified into two categories, which one was elastic components and other one was plastic component, and elastic component in void ratio was usually larger than plastic component for all of selected suction ranges. To dividing two components in void ratios is necessary properties associated to interpret yield surface, which is key future to simulate and predict the mechanical properties for unsaturated bentonite-sand mixture. This test results deformations due to suction changing for unsaturated bentonite-sand mixture without external loading such as oedometer compression test, separating elastic component and plastic component that decision the difference revise void ratio and residual void ratio.

2. Test procedure

2.1. Soil material

Various expansive soils with high montmorillonite fraction have been mined, encouraged and studied in the world on mechanical properties accomplishing of hydration, which are classified into Sodium type and Calcium type. As one of Sodium type bentonites, Kunigel V1was used in a series of two deformation measurement testing programs to confirm the hydro-mechanical properties of previous experimental studies that produced in Japan. Owing to its high montmorillonite content, the bentonite had a fines content greater than 95 %. In this study a silica sand required as mixture material into the bentonite, named Iitoyo No.4, which grain size distribution is rather uniformity and the maximum soil particle is less than 2.0 mm. Also, Kunigel V1 used in this study is common in the investigation on thermal-hydraulic-mechanical-chemical (THMC) phenomena at several times.

2.2. Soil specimen

The air-dried bentonite and silica sand were humidified by spraying deionized water to reach the desired water content, which was 17.0 % for all of specimens in two testing programs. To take care the prevent dumpling condition soil particles together is important to make uniformity for specimen when compaction performance to the specimens. All specimens had a diameter of 38 mm and a height of either 76 mm according to apply statically compaction. The prepared specimen size was relatively small scale that the proportional relations between height and diameter remained 2.0 for all specimens. Maximum compression forces using a hydraulic pump are over 1.0 MPa while compaction process at statically. The initial specimens had the following physical properties: a dry density of 1.600 Mg/m^3, void ratio of 0.710, and degree of saturation of 65.6 %.

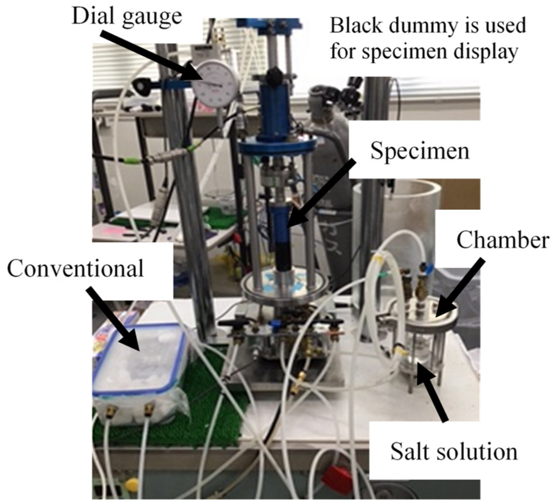

Figure 1. Developed triaxial compression apparatus

2.3. Developed apparatus in this study

The developed triaxial compression apparatus, which is shown in Fig. 1, performed the measurement of vertical displacement during controlling relative humidity through application of the vapor pressure technique. The developed triaxial compression apparatus composed the common triaxial compression apparatus, conventional pump and stiffness chamber, which is possible to produce controlling relative humidity and create fluid flow throughout. The salt solutions rest in the stiffness chamber installed the connect valve. The conventional pump maintained continuous air flow with the air pressure of 20 kPa. The air in triaxial cell smoothly circulated in steady, and hydration was formed at lateral surface for specimen.

The air flow from the stiffness chamber connected to triaxial basement, and the air drained from upper portion of the cell, went back to the pump. Previously, indicated relative humidity for air flow in the system using a miniature relative humidity and temperature sensor take coincident with referred relative humidity value in the Test code: JGS 0151-2009 in Japanese Geotechnical Society. The air go back to the pump, maintain the circulation in the system and offer the certain relative humidity caused by the salt solution. Also, the bellofram cylinder and displacement sensor (i.e., dial gauge) are connected to the triaxial cell, provided the application of vertical stress to the specimen and determine the changing of displacement in axial.

2.4. Series of testing program

A series of this testing program consist of measurement deformation due to suction changing (Test program A), which one is of measuring deformation for bentonite sand mixture subjected to suction increment-decrement cyclic process.

On the test program A, the specimen places into the triaxial cell without rubber membrane, and make a stability between a pedestal and cap. The system for controlling relative humidity connect to the triaxial cell which consist of the conventional pump, the stiffness chamber and salt solutions. Some salt solutions create the specified relative humidity in Kelvin law that the relative humidity in chamber measured using miniature relative humidity and temperature sensor in previous works. The collected relative humidity data sets provided that measured value were similar to referenced relative humidity mentioned in the Test method for water retentivity of soils (Test code: JGS 0151-2009 in Japanese Geotechnical Society). The used seven different salt solutions are Potassium Sultate (K_2SO_4), Potassium Nitrate (KNO_3), Ammonium Dihydrogenphosphate ($NH_4H_2PO_4$), Sodium Chloride (NaCl), Magnesium Nitrate ($Mg(NO_3)_2 \cdot 6H_2O$), Magnesium Chloride ($MgCl_2 \cdot 6H_2O$) and Lithium Chloride (LiCl). The created relative humidity had a range from 98 % 11 % at 20 degrees Celsius, and corresponding to 2.8 MPa to 296 MPa in suctions.

Firstly, the specimen was set up into the triaxial compression apparatus, and connecting relative humidity cyclic system for creating the defined relative humidity. The specimen has the load induced by cap and rod that lateral confining pressure not supply without rubber membrane. Ammonium Dihydrogenphosphate ($NH_4H_2PO_4$) was put into the chamber that required relative humidity was 93.1 % and suction was 2.8 MPa, and the air circulate into the triaxial cell through the system. The air in the triaxial cell remine the relative humidity of 93.1 %, and occurrence of hydration performance through the lateral surface of specimen.

Subsequently the period reached to near one month, the specimen was measured both height and diameter using a micro meter calliper, and evaluate strain in axial way and radius way. After that, relative humidity had increased or decreased according to replace to other salt solutions above mentioned. Measurement of specimen size was repeated through one month. Finally, relative humidity controlled to 11 % using Lithium Chloride (LiCl), and suction of 296 MPa was applied to the specimen, the shrinkage deformations were observed.

3. Experimental test results

3.1. Physical properties in soil-water characteristics curve with suction cyclic loading

The hydraulic behaviour of unsaturated bentonite-sand mixture is usually described using the suction insensitive stress variables, and suction controlling selected in this study is vapor pressure technique. As key parameters, water content, dry density and void ratio are described in the soil-water characteristic curve, and the indicated suction has a range from 2.8 MPa to 296 MPa as shown in Figs 2, 3 and 4. Firstly, the specimen had equivalate with suction of 9.8 MPa, which correspond to relative humidity of 93 % using a Ammonium Dihydrogenphosphate ($NH_4H_2PO_4$), and the obtained water content was 14.8 % that decreasing of water content proved to the initial water content of 17.0 %. Suction decrement and increment are produced repletely from 9.8 MPa and 2.8 MPa in suction, and water content described reduction due to cyclic performance in suction, when suction was 9.8 MPa. Next step, increasing suction, which was over 9.8 MPa. Water content obviously decreased, and the suction process defined to go back to suction of 9.8 MPa at once, subsequently increment suction passes were applicated. The end of pass is suction of 296 MPa. The water content subjected to increment-decrement cyclic performance in suction provided the decreasing at suction of 9.8 MPa. When end of the test, water content provided a 11.6 % at suction of 9.8 MPa.

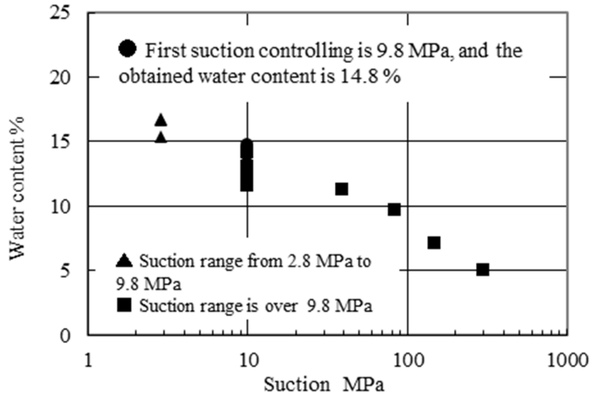

Figure 2. Soil-water characteristic curve

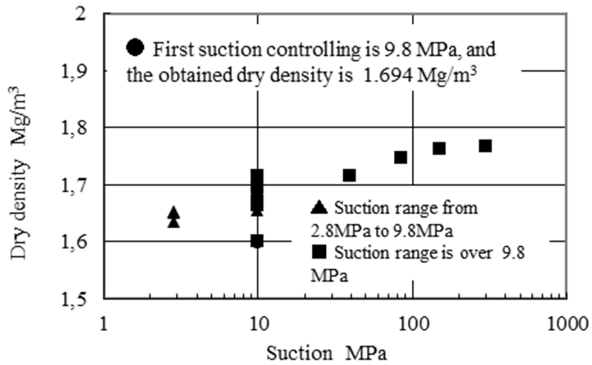

Figure 3. Increasing dry density with suction

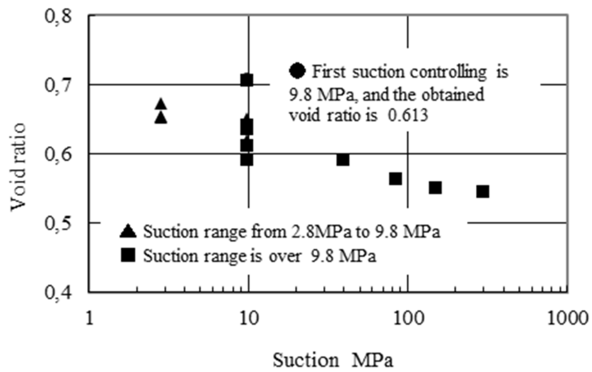

Figure 4. Decreasing of void ratio with suction

The deformation of volume can be determined by the dry density and void ratio on the Test program A as shown in Figs. 3 and 4. Cyclic suction loading induced the changing of dry density that the dry density gradually increased with suction increment. When suction was 296 MPa, dry density indicated 1.767 Mg/m^3. It is found the dry density smoothly increased by suction increment-decrement cyclic loading. Void ratio was quotative expressed from changing of dry density, similar to changing of dry density, suction increment-decrement repeating applied further influence on void ration, and when suction range had from 2.8 MPa to 9.8 MPa, reduction of suction verified the volume expansion. Associated to suction increment, void ratio obviously decreases that void ratio reached to 0.546 at suction of 296 MPa. It is however that two void ratios between suction of 148 MPa and 296 MPa compared, and it was significant small. It can be predicted that void structure translated to be dense. When suction changed from 296 MPa to 9.8 MPa, void ratio indicated from 0.546 to 0.592 that it proved to maintain swelling phenomena on further dense condition and rather few soil moisture retentions.

Finally, degree of saturations was calculated using above mentioned data sets as shown in Fig. 5. Focusing, which are swelling phenomena during suction increment-decrement cyclic. Expansion behaviour and absorbed soil moisture induced by suction reduction are sure accurate regardless of magnitude of suction.

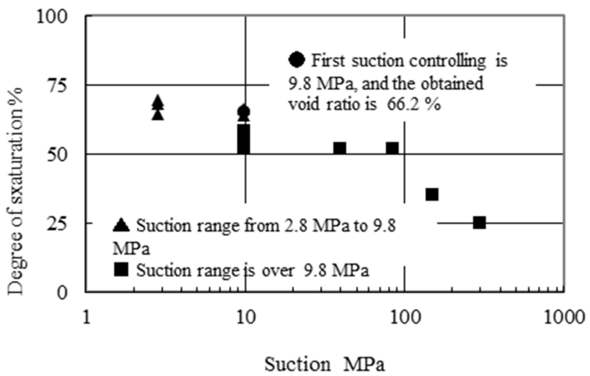

Figure 5. Decreasing of degree of saturation with suction

3.2. Deformations under suction cyclic loading

The deformations in both diameter and height for bentonite-sand mixture had been measured under a variety of suction using a micro calliper at each suction equivalent condition. It is generally common to measure only vertical swelling deformation using oedometer mould type during hydration process on water injection. To measure directly specimen deformations is actually advantages application on many experimental reports.

At first step, suction of 9.8 MPa applied to the specimen, and strain in radius way was 0.2 % as shown in Fig. 6. The shrinkage deformations were accumulated due to increase suction and it was clear to influence of suction. It is then considered through suction increment-decrement cyclic process that reduction occurred the expansion deformation for all of suction controlling in this testing program. The specimen had a strain of 1.5 % in the suction of 296 MPa, and when suction was 9.8 MPa at suction reduction process, the strain verified 0.47 %. Observing is confirmed that swelling deformation occurrence for the specimen subjected to suction increment-decrement cyclic paths. The tendency obtained from measurement to radial strains compared to axial strain phenomena as shown in Fig. 7, and the calculated strain values are different with radial strains values, but the tendency associated to relationship between suction and deformations are further coincident.

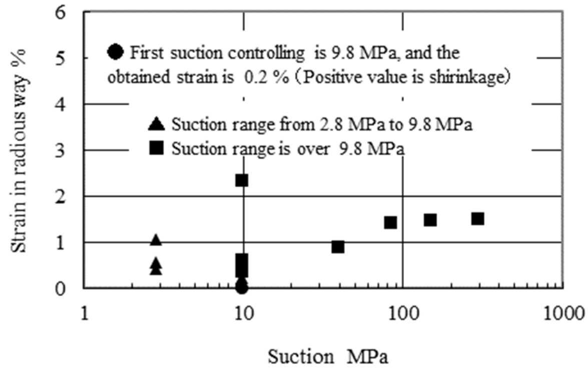

Figure 6. Changing of strain in radius way with suction

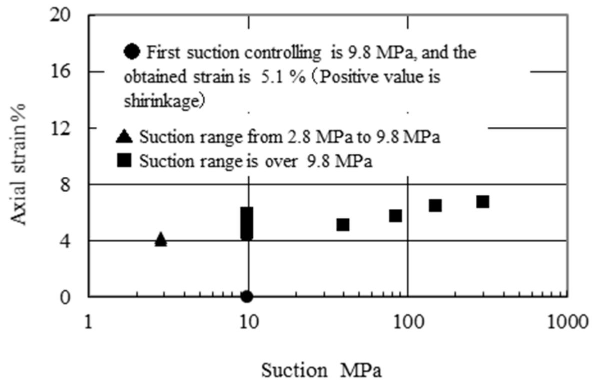

Figure 7. Changing of axial strain with suction

It is provided that processing of shrinkage deformation is stability with increasing of suction. the axial strain was up to 6.7 %, when suction was 296 MPa that was namely four times comparison to the radial strains at the suction of 296 MPa. It is sure to observe the different deformation phenomena between radial strains and axial way on hydration effort due to suction changing. The results on deformations for bentonite sand mixture are summarized as volume strain, which is relationship between suction and volume strain as shown in Fig. 8. The shrinkage deformations are processing with suction increment-decrement cyclic paths, and it was obviously that shrinkage strains became large with suction increment. Large strain was indicated as 9.5 % when suction was 296 MPa. When suction was 9.8 MPa at the end of test, volume strain occurred the expansion behaviour according to reduction of suction, and the measured volume strain described 3.9 % in shrinkage. Consequently, the bentonite-sand mixture has created shrinkage deformation and expansion deformation in hydration properties during suction increment-decrement cyclic paths that shrinkage deformation clearly accumulated with step by step in suction increment.

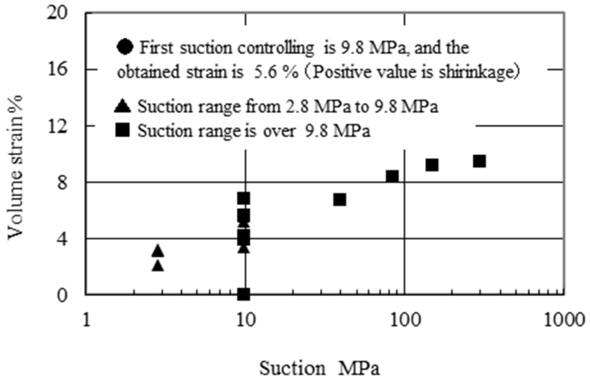

Figure 8. Volume strain with suction

3.3. Elastic-plastic variations void ratio under suction cyclic loading

The changes of void ration during suction cyclic loading paths was corrected in above mentioned, and the influence of suction is significant important matter on void ratio for the multi-stage. It proved that void ratio described the changing due to hydration performance such as suction variations the around contact point clay fraction structure (i.e., macro-micro structure or aggregation). The expansion deformations were provided through swelling performance by suction decrement, which were composed elastic phenomena as one of elastic-plastic behaviour in deformations. To evaluate each component magnitude value according to dividing the measured the changing of void ratio is useful to consider the hydration phenomena for the bentonite-sand mixture deformation characteristic.

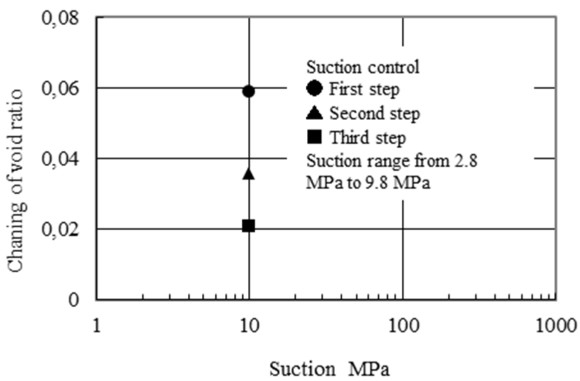

Figure 9. Changing in void ratio in elastic phenomena

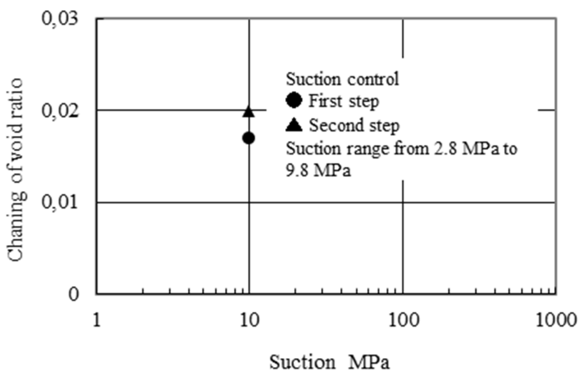

Figure 10. Changing of void ratio in plastic phenomena

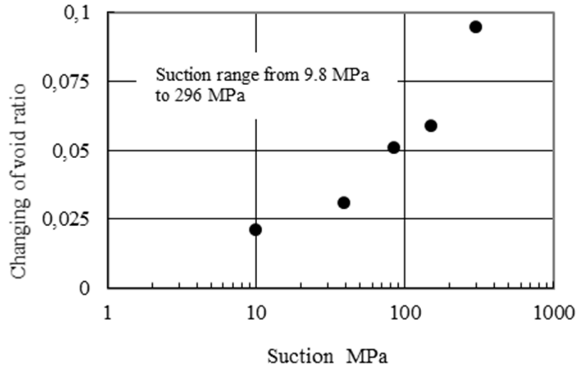

Figure 11. Changing of void ratio in elastic phenomena

Each variation in void ratio dividing into two components (i.e., elastic and plastic) are plotted against applied suctions are described as shown in Figs from 9 to 11, and the verified results have considered a suction range. Fig. 9 and 10 at suction range from 2.8 MPa and 9.8 MPa indicated that number of repetitions in suction increment-decrement gradually occurrence the reduction variation of void ratio in both elastic and plastic phenomena. It is then seemed that elastic phenomena are larger than that of plastic phenomena in variation magnitude.

Moreover, dissolving the comparison two components in variation for void ratio when suction is overt 9.8 MPa as shown in Figs. 10 and 11. Evaluated variations in elastic phenomena is larger than that of plastic phenomena through suction ranges for used in this testing program A. According to increase suction, the observed variations for both elastic and plastic components detected the increasing, and when suction is over 39.0 MPa the variation of elastic components extremely increased with suctions. Then, it expressed that the elastic components are reproduced high values with all of suctions.

4. Conclusions

This study conducted out measurement of deformations for bentonite-sand mixture associated to suction increment-decrement cyclic paths, which were volume change, axial strain and radius way strains. The developed triaxial compression apparatus are useful to investigate the deformation properties with a variety of suction changing (i.e. relative humidity changing). The apparatus composed with conventional triaxial compression apparatus, air circulation flow system and stiffness chamber with resting salt solutions. High suction range is required for this testing program with seven difference salt solutions. The obtained results are summarised as following;

1) It is found out obviously that the influence of suction increment and suction decrement cyclic paths on hydration behaviour as water content, dry density, void ratio and degree of saturation in interpretation of the soil-water characteristic curves.

2) Observing, which suction increment produced shrinkage, and suction reduction gradually induced volume expansion and increment of soil moisture. After suction increment and suction decrement are prepared at several times, the shrinkage deformations have

progressed further comparison to initial volume for bentonite sand mixture. Also, the axial strains are then larger than that of radius way strains to required suction values.

3) Variations of void ratio were classified into two categories, which one is elastic components and other one is plastic component. Two components described that the increment represent with increasing of suction, and the variation of elastic components in void ratio maintain to be larger than that of plastic component to all of suctions used in this test program.

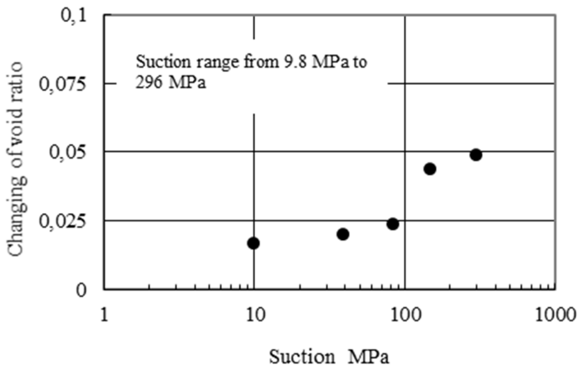

Figure 12. Changing of void ratio in plastic phenomena

Acknowledgements

This study was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (C) JP 21K04259.

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