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Investigation on hydraulic-mechanical properties in bentonite-sand mixture with consideration of salinity water

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Abstract. Bentonite with fine components much such as extremely expansive soil has been commonly required as buffer/backfill materials in order to prevent seepage for construction of further deep geological repository for disposal of high-level radioactive waste (i.e. HLW). The buffer received significant hydro-mechanical efforts from host rock at underground environment. While the construction/maintenance with long-time operation of a repository, it was predicted that high compacted bentonite will be progressively hydration due to pore water flow or infiltrated from surrounding host rock. The purpose of this study is to establish the connection among the basic mechanical properties, soil retention characters and chemical couple properties under unsaturated condition and saturated conditions for a bentonite-sand mixture. This conducted out some testing programs, which are soil-water characteristic curve test, unconfined compression test, creep test and triaxial compression test for unsaturated sodium bentonite sand mixture and saturated bentonite sand mixture. In addition, the influence of salinity water on mechanical properties is considered with comparison to saturated bentonite sand mixture subjected to swelled due to distilled water.

1 Introduction

Bentonite with fine components much such as extremely expansive soil has been commonly required as buffer/backfill materials in order to prevent seepage for construction of further deep geological repository for disposal of high-level radioactive waste (i.e. HLW) [1]. The buffer received significant hydro-mechanical efforts from host rock at underground environment. While the construction/maintenance with long-time operation of a repository, it was predicted that high compacted bentonite will be progressively hydration due to pore water flow or infiltrated from surrounding host rock. The purpose of this study is to establish the connection among the basic mechanical properties, soil retention characters and chemical couple properties under unsaturated condition and saturated conditions for a bentonite-sand mixture.

In this study, some results applied reliable stress-strain properties and determined the changing of strength parameters. A detailed investigation presents accuracy soil-water characteristic curves. Soil-water characteristic curves are measured that addressed the key feature in unsaturated soil mechanics, are useful to interpret the hydraulic-mechanical properties of unsaturated soils. Drying process and wetting process are applied to the specimens, and considering the changing of water content and dry density. Unconfined compression test and triaxial compression test for unsaturated-saturated bentonite-sand mixture. When unsaturated bentonite-sand mixture reached to saturation, two difference seepage water were used, and one was distilled water and other one was salinity water . The concentrations of components for salinity variety from 0.8 % in volume. Unconfined compression test conducted out under standard specification (JIS A 1216: Method for unconfined compression test of soils), and selected compression speed was 1.0 % per min for unsaturated and saturated specimens. The undrained triaxial compression tests were performed under several lateral confining pressures according wide ranges in order to definition and evaluation to strength parameters based on critical state in terms of stress variations. In addition, resulted apparent cohesion and angle of internal friction as mechanical factors obtained each critical state line with a range from 200 kPa to 2.0 MPa in lateral confining pressure. To apply saturation with and without salinity water produced the changing of couple phenomena as hydration-mechanical properties.

Also, this study conducted out the creep test without lateral confining pressure using sodium bentonite sand mixture and calcium bentonite sand mixture. All of specimens have a suction of 9.8 MPa, and it correspond to relative humidity of 93.1 %. Developed triaxial compression apparatus is used that installed air circulation system, and is possible to control the required relative humidity.

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2 Test procedure

2.1 Soil material and specimen

This study used two different bentonite and two different sand. A bentonite is Sodium bentonite that other one is calcium bentonite, other one is sodium bentonite. It is high content of montmorillonite, and a bentonite had fines content larger than 95 %. Measured density of soil particles was approximately 2.733 g/cm3. Also, SiO2 occupied more than 62 % as chemical components. This study prepared three different sands subjected of mixture into each bentonite, three sands are classified as silica sand, and name as Misawa sand, Silica No. 3 and Silica No. 5. All sands had highly unique grain size distribution obtained from grain seize analysis test. While test for bentonite-sand mixture, this testing program determined two ratios was 7 to 3, and ratio was 5 to 5 in limited. Air-dried bentonites and sands were humidified by spraying deionized water to reach confirmed water contents, which were 20.0 % and 18.0 % in this testing

2.2 Soil specimen

This study conducted out a series of testing programs, and use statically compacted specimen to unsaturated - saturated conditions for sodium bentonite sand mixture and calcium bentonite sand mixture. All of specimens have common size that a diameter of 38.0 mm and a height of 76.0 mm that are compressed using a hydraulic pump. The specimen had a further compression stress under uniaxial condition. It is remained ratio of height to diameter is 2.0. Sodium bentonite sand mixture has physical properties that the water content is 18.0 % and a dry density of 1.600 Mg/m3. Other hands, calcium bentonite sand mixture has physical properties that the water content is 20.0 % and a dry density of 1.600 Mg/m3.

2.3 Test program

This study performed some tests which consist of soil-water characteristic curve test, unconfined compression test, creep test and triaxial compression test, and indicated the frameworks as shown in Fig. 1.

Testing program (A), the soil-water characteristic curves are measured using two sodium and calcium bentonite at suction range from 2.8 MPa to 296 MPa. The application for controlling suction require the vapor pressure technique [2][3]. Seven salt solutions establish variety of relative humidity in case of testing program (A), and drying path and wetting paths are produced to all specimens. Also, compacted specimens compare to no compacted specimens in changing of water content with suction increment/decrement. Volume change of calcium bentonite sand mixture are directly measured for compacted specimen with dry density 1.600 Mg/m3.

Unconfined compression test performed for sodium bentonite sand mixture with water content of 18.0 % and dry density of 1.600 Mg/m3, and its specimen received swelling performance due to distilled water and salinity

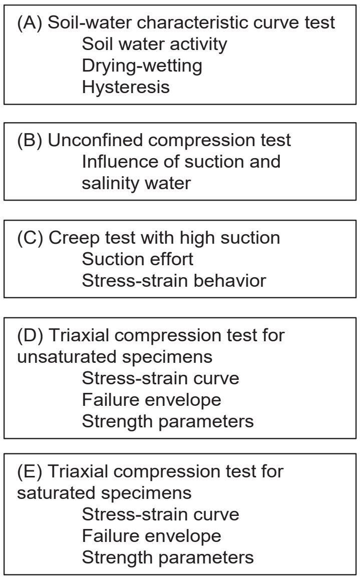

Fig. 1. Framework for this testing program.

water such as saturated specimen for Testing program (B). Two considering points are prepared that one is reduction of shear resistance allowing the delete of suction, and other one is refereeing for influence of chemical components.

In Testing program (C), sodium bentonite sand mixture and calcium bentonite sand mixture are used for attempting creep test under suction of 9.8 MPa, and the suction maintained in the relative humidity of 93.1 % due to Ammonium Dihydrogen phosphate. Unconfined compression derived, and correct the unconfined compressive strength for determined the maximum creep stress. Firstly, small creep stress was applied to the specimen without lateral confining pressure. Axial strain was measured continuously for each creep stress. Particularly, axial strain in expansion phenomena is observed when unloading is proceed.

Unsaturated soil triaxial compression test results are described in Testing program (D) that used specimens are sodium bentonite sand mixture, water content is 18.0 % and a dry density is 1.600 Mg/m3. Various lateral confining pressures are applied to the specimen in the triaxial chamber. The lateral confining pressures have a range from 50 kPa to 2.0 MPa, and all of specimen have allowed drain and exhaust at isotropic external loading. Subsequently, undrained conditions and unexhausted conditions is controlled during compression process. The measured stress-strain behaviour indicated maximum deviator stress for each confining pressure, and estimated stress paths for determination of shear strength parameters such as the angle of internal friction and apparent cohesion. The stress paths are defined using two times for lateral confining pressure and maximum principal stress, and calculate an average. The results indicated a relationship between mean principal stress and deviator stress for each confining pressure.

Saturated specimens are prepared due to swelling using a distilled water and salinity water for Testing program (E), which the specimens are sodium bentonite sand mixture with dry density of 1.600 Mg/m3, and compacted under water content of 18.0 %. The drained conditions are remained when the isotropic confining pressures are loaded for 200 kPa, 500 kPa and 2.0 MPa. It then is undrained conditions for compression process. Considering, the test results analysis the stress-strain curves and stress paths, and verify the failure envelop and shear strength parameters. As consequently, it is discussed salinity water with the concentration of 0.8 % induce the reduction of shear resistance regard less of confining pressures.

2.4 Apparatus used in this study

The experimental works are performed for a series of testing program, which prepared five difference tests. It then is divided to hydration test and mechanical test associated to considering the influence of salinity water as such chemical effort. The soil-water characteristic test used the vapor pressure technique, seven difference salt solutions are prepared, and the controlling suctions are from 2.8 MPa to 296 MPa in the glass desiccator.

As mechanical test, unconfined compression test for unsaturated specimens and triaxial compression test for unsaturated specimens and saturated specimens used the developed triaxial compression apparatus. The apparatus developed to conventional and standard triaxial cell to measure maximum deviator stress such as shear resistance. The apparatus consists of inner cell, out cell, piston, stainless steel basemen, variety pressure controlling path compartment, controlling along axial displacement equipment, load transfer, dial gauge and stiffness steel frame structure. The soil specimens were place between pedestal and cap, and they had coarse porous stone. A soil specimen in inner cell was subjected to an isotropic confining pressure. A constant air pressure was applied to the specimen which controlled regulator valve with high sensitivity.

The developed triaxial compression apparatus used for creep test [4][5] in Testing program (C). Performing 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, a 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 axial deformations

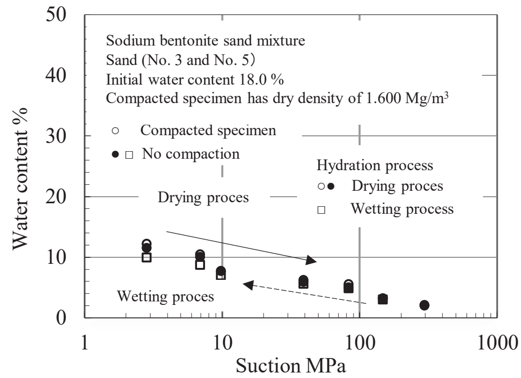

Fig. 2. Soil-water characteristic curve for sodium bentonite sand mixture.

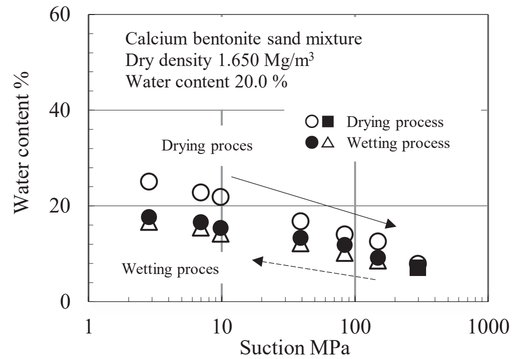

Fig. 3. Soil-water characteristic curve for calcium bentonite sand mixture regard to water content.

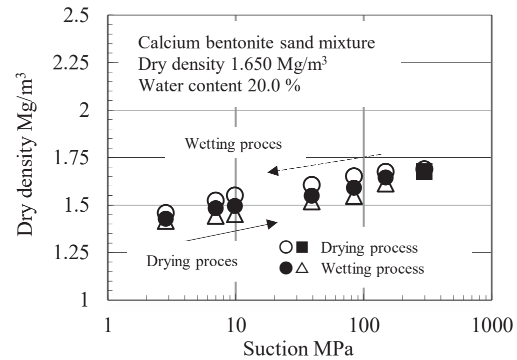

Fig. 4. Soil-water characteristic curve for calcium bentonite sand mixture regard to dry density.

3 Test results

3.1 Soil water characteristic curve

Regard to hydration properties, soil-water characteristic curves are measured for tow kind bentonites, and are describe high suction ranges (i.e., from 2.8 MPa to 296 MPa) that is shown in Figs. 2 to 4. Sodium bentonite sand mixture having water content of 18.0 % with/without compaction indicate the changing of water

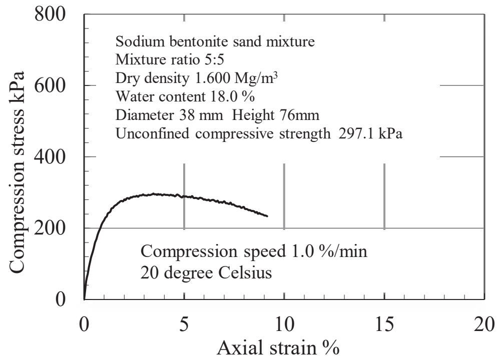

Fig. 5. Stress strain curve obtained from unconfined compression test for unsaturated sodium bentonite sand mixture.

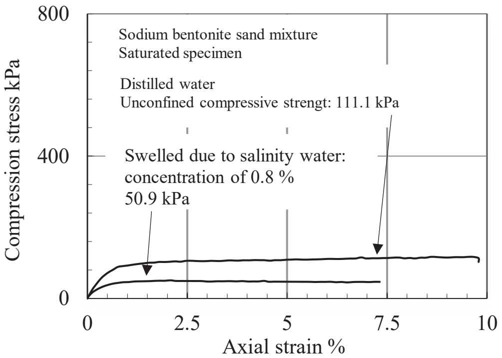

Fig. 6. Stress strain curve obtained from unconfined compression test for saturated sodium bentonite sand mixture.

content through drying path and wetting path. The specimen had a compaction, a dry density is 1.600 Mg/m^3. Reduction of water content indicated smooth according to suction increment regardless of the compaction producing that it is possible to define a certainly straight line on logarithmic scale. The water content is 2.1 % for suction of 296 MPa at end of drying paths.

The decreasing of suction commence as next suction step, namely is wetting process. Volume of soil moisture increase smoothly, and the variation is similar to the incline under drying process. It is not so much difference between drying path and wetting path through suction ranges required by testing condition. The hysteresis is confirmed to the obtained soil-water characteristic curve. The compacted calcium bentonite sand mixture specimens described the soil-water characteristic curves such as water content and dry density as shown in Figs 3 and 4. Soil moisture volume decrease due to drying and wetting cyclic performances, and plotted water contents remove to down portion for suction ranges. Other hands, the changing of dry densities verify the increment due to shrinkage, and it is probably that increment and decrement in suction like a drying and wetting ensure to grow the plastic volume deformation.

3.2 Unconfined compressive strength

It is knowledge that suction contribute to remine of shear resistance for unsaturated soils, and is one of stress variables composed by matric suction and osmotic suction. This study focuses on the suction effort through unconfined compression test. Stress strain curve for unsaturated sodium bentonite sand mixture is indicated in Fig. 5 which dry density is 1.600 Mg/m^3 and water content is 18.0 %. Increment of compression stress is further at begging of compression, and estimated unconfined compressive strength is 297.1 kPa. Same specimens subjected the swelling using distilled water and salinity water in order to delete suction due to saturation. The volume is maintained in the steel mold during swelling process, and the concentration of salinity water is 0.8 %.

Two saturated specimens indicate the stress-strain curves that maximum deviator stresses approach at small axial strain compare with unsaturated specimen as shown in Fig. 6, and it is clear to be reduction due to saturation performance. Approaching to unconfined compressive strength, maintaining the constant compression stress according to process of compression axial deformations. Owing saturation, the saturation specimen due to salinity water indicate most small unconfining compressive strength, and it present that the influence of salinity water is significant to shear resistance for sodium bentonite sand mixture specimen.

3.3 Creep behaviour

The creep deformations for sodium bentonite sand mixture and calcium bentonite sand mixture in unsaturated condition are investigated using a developed triaxial compression apparatus. All of specimens have constant suction of 9.8 MPa corresponding to relative humidity of 93.1 % at 20 degrees Celsius. The suction controlling is applied in the triaxial chamber due to air circulation performance, and the detail explanation is mentioned in Section 2.4. Also, specimens have no lateral confining pressure in the triaxial chamber, vertical stresses only apply during the test. Conventional unconfined compression test conducted out on compression speed of 1.0 % per min for determined the unconfined compressive strength subjected to suction of 9.8 MPa, and the obtained unconfined compressive strength reference as maximum creep stress. Figure 7 is stress-strain curve for sodium bentonite sand mixture with suction of 9.8 MPa, and 834.5 kPa is determined as unconfined compressive strength.

A vertical stress of 258 kPa has been loaded to the specimen for a period of creep test as shown in Fig. 8. Due to loading of 258 kPa, axial strain has 0.38 % at once, and the axial deformations increase with elapsed time. Finally, produced axial strain verify 0.43 %. Subsequently, unloading is applied, and observing the axial strain with time. Axial strain changes from 0.43 % to 0.23 %, and the axial strain decease with time that expanded specimen describe 0.15 % at end of unloading performance.

This creep test investigates to calcium bentonite sand mixture, too that previously, standard unconfined

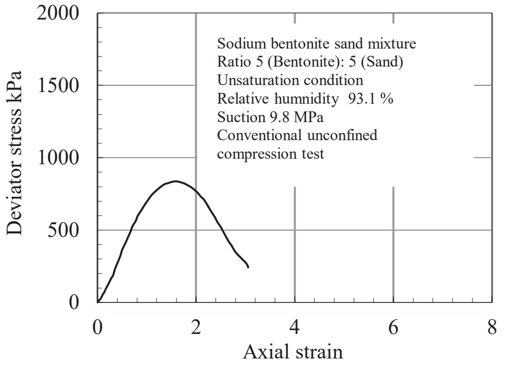

Fig. 7. Stress strain curve for unsaturated sodium bentonite sand mixture with suction of 9.8 MPa.

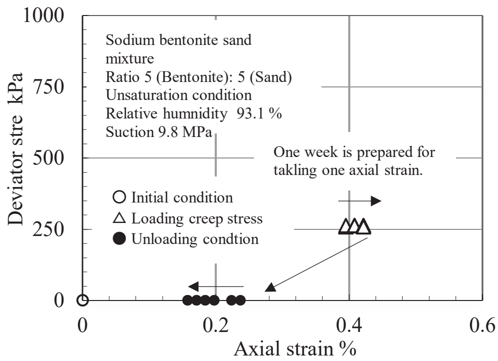

Fig. 8. Changing of axial strain due to loading and unloading process for sodium bentonite sand mixture in creep test.

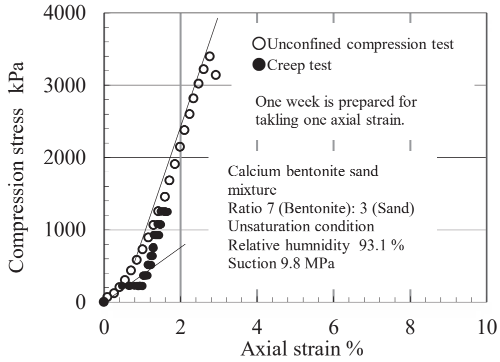

Fig. 9. Changing of axial strain due to creep stress increment for calcium bentonite sand mixture in creep test.

compression test conducts out, and take stress-strain cure as shown in Fig. 9. The compression increases smoothly at beginning compression, and the tendency remain till axial strain is over 1.0 %. After axial strain is 1.0 %, large increment of compression stress is obviously, unconfined compressive strength of 3397 kPa is provided at axial strain of 2.76 %.

Eight creep stresses (black circle symbol) are prepared in the creep test which are a range from 221 kPa to 1245 kPa, and maximum creep stress is less than 50 percentage of unconfined compressive strength. The deformation is same with stress-strain curve above mentioned, when creep stress of 221 kPa is applied. The deformations grow according to elapsed time on constant creep stress of 221 kPa that is till 1.03 %. The specimen describes the contact with stress-strain curve due to creep stress of 923 kPa. Moreover, produced axial strains are same with stress-strain curve at creep stress of both 1069 kPa and 1245 kPa. The axial strain increases with the time under maintaining of creep stress. Beyond the creep stress of 1245 kPa, the specimen suddenly takes a completely failure.

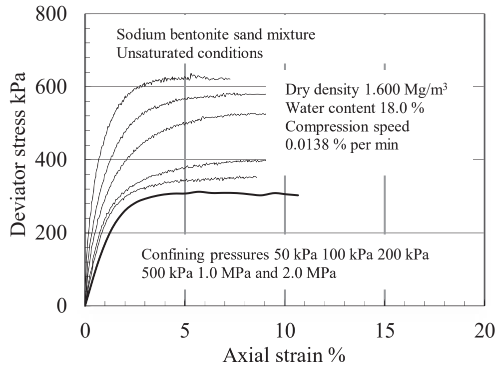

Fig. 10. Stress strain curves for unsaturated sodium bentonite sand mixture.

3.4 Triaxial compression test for unsaturated bentonite sand mixture

Various confining pressures are supplied to the unsaturated sodium bentonite sand mixture, which have a range from 50 kPa to 2.0 MPa. Compression speed is required as 0.013 % per min under undrained condition and unexhausted that the obtained results are indicated as stress strain curves as shown in Fig. 10. Increment of deviator stress are seem to be straight line at beginning compression application, and each incline depend on confining pressure that the incline of straight line is large when confining pressure is 2.0 MPa. Relationship between axial strain and deviator is like a curvature according to process the axial deformation, and approaches to maximum deviator stress.

All of cases of confining pressures verified maximum deviator stress, when axial strain is till approximately 8.0 %. Beyond, stress-strain curves display horizontal line with compression deformation. It is clear that shear resistance increases with confining pressure. Then, mean principal is calculated, and plotted with maximum deviator stress as shown in Fig. 11 (Black circles symbol) that the failure envelope is defined in order to estimate strength parameters such as the angle of internal friction (i.e. shear resistance angle) and apparent cohesion. The failure envelops compare to the difference specimen (White circles symbol), which are compacted with water content of 17.0 % and a dry density of 1.600 Mg/m3. The specimen consists of sodium bentonite and Iitoyo sand, and the ratio of sodium bentonite to Iitoyo sand is 7:3. Even if a dry density is same, the specimen indicated low strength parameters, when the percentage of sodium bentonite is low.

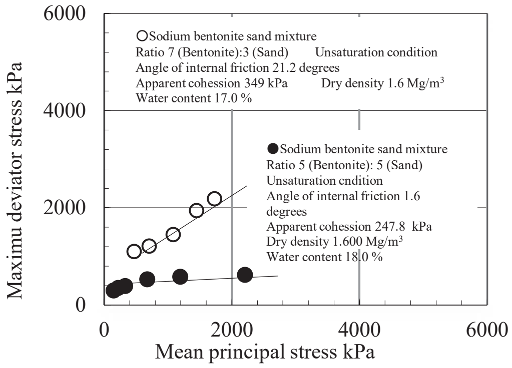

Fig. 11. Comparison failure envelope with two unsaturated sodium bentonite sand mixtures.

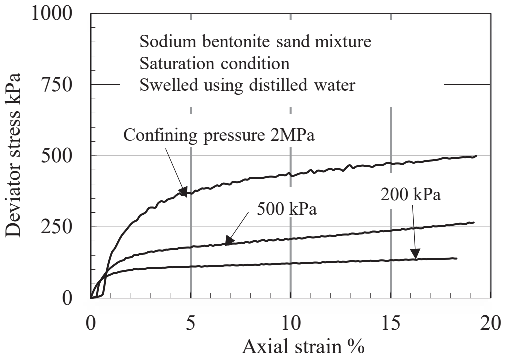

Fig. 12. Stress strain curves for saturated sodium bentonite sand mixture (Distilled water).

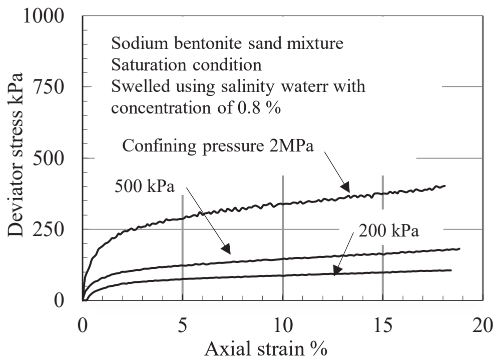

Fig. 13. Stress strain curves for saturated sodium bentonite sand mixture (Salinity water, concentration of 0.8 %).

3.5 Triaxial compression test for saturated bentonite sand mixture

Two difference saturated specimens are prepared that one saturated specimen is swelled by distilled water, and other one is saturated using a salinity water with concentration of 0.8 %. All of saturated specimens have three difference confining pressures for triaxial compression test that are 200 kPa, 500 kPa and 2.0 MPa. The obtained results verified the stress strain curves as shown in Figs. 12 and 13. The stress strain curve indicate smooth increment without confining pressure of 2.0 MPa till axial strain is 1.0 % that further small increment is observed regardless of involving salinity. Similar with unsaturated bentonite sand mixture specimens above mentioned in Fig. 11, relationship between mean principal and maximum deviator stress is estimated, and defined the strength parameters. Two angles of internal frictions are close that are approximately 5.2 degrees. It is however evidences that apparent cohesion is influenced of salinity water, decreases from 71.0 kPa to 51.2 kPa.

4 Conclusions

This study represented hydraulic-mechanical-chemical properties for both sodium bentonite sand mixture and calcium bentonite sand mixture on five difference tests that are soil-water characteristic curve test, unconfined compression test, creep test and unsaturated-saturated triaxial compression test. The obtained results are summarized as followings: (1) The hysteresis is induced due to drying process and wetting process, soil moisture decreased, and dry density increased by shrinkage. (2) Saturation is of reduction associated to delete suction, and salinity water established further decrement for unconfined compressive strength. (3) The growing of axial strain is recognized for tow difference bentonite sand mixture with suction of 9.8 MPa. (4) Unsaturated-saturated sodium bentonite sand mixture is estimated strength parameters such as the angle of internal friction and apparent cohesion, and saturation performance cause the reduction of strength parameters. Moreover, salinity water with concentration of 0.8 % induced the decreasing of apparent cohesion.

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