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On the thermal hydro mechanical chemical behavior of bentonite sand mixture

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Abstract. The concept to high-level radioactive waste (HLW) repository generally involves an engineering-artificial barrier system, in which hardly compacted bentonite sand mixture blocks are placed carefully around the waste canister, and the canister is of stiffness in the design. Placed the bentonite sand mixture blocks, gradually receive hydration due to groundwater. Thermal-hydraulic-mechanical-chemical phenomena of compacted bentonite sand mixture after wetting, suction change and thermal effort are a critical parameter for buffered system This study proposes the influence of suction, relative humidity and thermal effort in thermal-hydraulic on deformation properties and mechanical properties for bentonite-sand mixture. A series of testing programs are prepared such as calibration test for changing of relative humidity with temperatures, measurement of volume change involving heating and changing of suction, determination of unconfined compressive strength, for thermal performance triaxial compression tests for both unsaturated bentonite sand mixture and saturated bentonite sand mixture. The obtained results are further interesting, and summary provide as following. To suction increment incorporation with thermal heating produce induces obviously shrinkage of the bentonite sand mixture, and lead the decrement of strength. Elevated temperature confirm further reduction for maximum deviator stress using a developed triaxial compression apparatus that is regardless of unsaturated condition and saturated condition.

1 Introduction

Compacted bentonite with high swelling performance is included in buffer and backfill materials in high-level radioactive waste (HLW). Extremely low hydraulic conductivity, strong swelling pressure, complex macro-micro structure, high water retention activity related to barrier made of bentonite [1-3]. It is required to restrict disseminate of radionuclides from the waste metal package. Severe problems such these properties, however, were produced by thermally-induced effects (i.e. heating performance) that the decay heat from waste caused [4].

This study proposes the influence of suction, relative humidity and thermal effort including in thermal-hydraulic on deformation properties and mechanical properties for bentonite-sand mixture. Successful to the aims of this study produced on triaxial compression test, unconfined confined compression test using a newly developed thermal triaxial compression apparatus. Vapor pressure technique recognized in the unsaturated soils mechanics is useful to conduct thermal hydraulic couple test, and determine the deformations properties for bentonite-sand mixture. Kunigel V1 was used in this testing program which was sodium bentonite. For mixture, silica sand, named Iitoyo No.4 is used as composing of material. The mixture ratio of sand and bentonite was 7:3 in dry weight. A developed thermal triaxial apparatus is used for measurement of unconfined compressive strength and maximum deviator within various lateral confining pressures for unsaturated and saturated specimens. Then, a series of this testing program consists of five different testing programs as following. (1) Calibration test in order to decision the temperatures and relative humidity using sealed steel chamber and air circulation system. (2) Measurement of volume strain induced by elevated temperature and changing of suction. (3) Unconfined compression test for unsaturated specimens subjected to heating and changing of suctions. (4) Performance the triaxial compression test for unsaturated specimens and saturated specimens under tow different temperatures for dry density of 1.600 Mg/m^3, and verify the influence of salinity water on strengths. (5) Considering the influence of different dry densities on shear resistance for saturated specimens.

2 Test procedure

2.1 Soil material and specimen

Variation of expansive materials are used for investigate the thermal-hydraulic-mechanical-chemical properties for experimental and largescale tests in the world. Kunigel V1 is used in this testing program which is sodium bentonite that is made in Japan. Swelling pressures of Kunigel V1 are measured detail as

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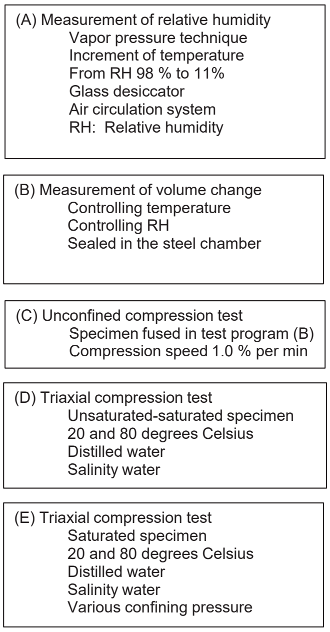

Fig. 1. Framework for this testing program.

hydration properties in previous many works. Having high content of montmorillonite on chemical properties, a bentonite has absolutely fined content larger than 95 %. measured density of soil particles is 2.733 Mg/m^3. Also, SiO_2 occupied 62 % as chemical component. For mixture, silica sand, named Iitoyo No.4, is used as composing of material, which has sufficiently unique grain size distribution obtained from grain size analysis test. Maximum size was evaluated as 2.0 mm. The mixture ratio of sand and bentonite was 7:3 in dry weight. This ratio often accepts on experimental tests.

2.2 Specimen used in this study

Subsequently the bentonite-sand required a water content of 17.0 %, regulation of water content conducted out by spraying the distilled water to the soil material. All of specimens was compacted statically in the stiffness steel mold using a hydraulic oil jack having a capacity of 70 MPa. Then, the size of specimens are a diameter of 3.8 cm and a height of 7.6 cm with remaining a ratio of 2.0 to the diameter against the height, and the ratio is certainly in common specimen used in soil mechanical laboratory shear test. To select the relatively small size specimen is effort to develop time consuming on the suction equilibrium time and swelling performance time. Initial specimens have a dry density of 1.600 Mg/m^3, void ratio of 0.710 and degree of saturation of 65.61 %, another one is dry density of 1.200 Mg/m^3, void ratio of 1.280 and degree of saturation of 36.4 % as physical variables. Also, while unsaturated specimen can permeate to saturation in swelling process, the stiffness mold is used that have high resistance to erosion due to salt compound.

2.3 A series of this testing program

This study focuses on thermal-hydraulic-machinal-chemical properties, which are obviously complex couple phenomena, and it requires the suggested testing programme. Also, the connection with together is necessary to be accurately. Figure 1 displays the framework and the flow through this testing programs which consist of (A), (B), (C), (D) and (E). Each testing procedure is mentioned in below sections.

2.4 Test program (A)

To measure temperature and relative humidity is necessary to develop the hydration-mechanical properties for bentonite sand mixture while artificial heating performance with various relative humidity. Interpretation for changing of relative humidity in the sealed space due to heating application is useful to application of the vapor pressure technique [5], and further suction component is osmotic suction that except the matric suction from total suction. Actually, many reports have solved some hydro-mechanical properties for expansive materials such as bentonite using osmotic suction controlling technique, and is accepted.
A miniature temperature & humidity logger (Product by KN-Labs Co. Ltd), in which had a diameter of 17.0 mm, thickness of 6.0 mm and a weight of 3.3 g. Instructions are exhibited as followings; temperature range is from minus twenty degrees Celsius to positive eighty degrees Celsius and relative humidity is permitted from zero % to 95 % depending on environmental temperature. Each physical quantity is enough accuracy that 0.1 degrees Celsius in temperature and 0.5 % in relative humidity. Various chemical substances (i.e. some salt compounds) are located with a small temperature & humidity logger into the steel chamber, which have a subject to create specialized relative humidity. The relative humidity against chemical substance is indicated into testing code: JGS 0151-2009 corresponding to vapor pressure technique for Test method for water retentivity of soils. The steel chamber put into the constant temperature chamber by Isuzu Manufacturing Co., Ltd. Temperatures in the internal chamber room is controlled from 20 degrees Celsius to 80 degrees Celsius. A miniature temperature & humidity logger measure the relative humidity and temperature step by step for directly in Testing program (A). Moreover, this study attempts changing of relative humidity with elevation temperature performance on another instruction, and air in the chamber possible to create flow circulation. The air circulation is induced by the air circulation system, that composed by a conventional pump with supply performance of 20 kPa, some valves and sufficiently long tube. The relative humidity and temperature are measured thought air circulation.

2.5 Test program (B)

Vapor pressure technique is useful to control the high suction, and heating performance is conducted to specimen placed in the steel mold as shown in Fig. 2 The steel mold has some specimens and salt solutions. Each salt solutions defines relative humidity values obtained from using Karlvin law under determined temperatures. Required salt solutions are Potassium sulfate,

Fig. 2. Specimens with a salt solution in the steel mold.

Ammonium Dihydrogen phosphate, Sodium chloride and Magnesium dichloride that correspond to 98.0 %, 93.1 %. 75.0 % and 33.0 % in relative humidity under 20 degrees Celsius, and estimate 2.8 MPa, 9.8 MPa, 39.0 MPa and 148 MPa using Karlvin law. In addition, all of specimen receive increment of temperature due to heating application that the temperature has a range from 20 degree Celsius to 80 degrees Celsius. All of the specimen is permitted free deformation in the steel chamber at a period of one month in Testing program (B). The free deformations that a diameter and an axial direction are able to permit the shrinkage or expansion due to changing of soil moisture caused by suction at equilibrium with each suction.

2.6 Test program (C)

The unconfined compression test is conducted out in Testing program (C), and all of specimens are used, which are subjected in heating efforts and variations of suctions in Testing program (B). So that, all of specimens are established changing of soil moisture, volume change and shrinkage cracks. While unconfined compression test, all of specimens are supplied the different temperatures in the developed triaxial compression apparatus mentioned as below. Controlled temperatures are 20, 40, 60 and 80 degrees Celsius, and are similar to the temperature range in Test program (B). While unconfined compression test, compression stage remains a compression speed of 1.0 % per min, and determining the peck compression stress such as unconfined compressive strength.

2.7 Test program (D) and (E)

To investigate the influence of confining pressures on the shear resistance is adequate importance matter for prediction of safety to barrier system. The triaxial compression test are performed using the developed triaxial compression apparatus, and unsaturated specimens and saturated specimens are prepared in Testing program (D). Other process is the subjection for establishing saturation. The specimens are placed in the steel mold during saturation process, which the steel mold has two cover plates installed porous stone in order to through a distilled water and a salinity water. The mold are put into either distilled water or salinity water

Fig. 3. Developed thermal triaxial compression apparatus.

with concentration of 3.5 %. The concentration of 3.5 % in salinity water is closely to nature see water. The specimens are confirmed isotopically in a range from 100 kPa to 1.0 MPa in confining stresses. The drained conditions that un-exhausted condition and undrained condition for unsaturated specimen, and undrained condition for saturated specimen. The axial deformations are applied to the specimens under 0.013 % per min. Twenty degrees Celsius and eighteen degrees Celsius are setting associated to thermal impacts. All of specimens are a dry density of 1.600 Mg/m^3 at compaction.

All of saturated specimen for Testing program (E), which are swelled using distilled water and salinity water with concentration of 3.5 %. The difference from Testing program (D) is a dry density, and is 1.200 Mg/m^3. Considering, the influence of dry density on thermal-hydraulic-mechanical-chemical properties difference between two dry densities.

2.8 Apparatus

A developed thermal triaxial apparatus is used for results associated to this study subjections. The apparatus is indicated as shown in Fig. 3 which could control temperature for isotropic thermal conductivity. The specimens are placed on the pedestal in the inner cell made of acrylic material. The inner cell is covered the heating water tube, which is made of stainless steel with a spiral in sharp. The outer chamber is made of stiffness steel material with high erosion resistance, and has high resistance to heating impact. The measurement of compression stresses is performed using a loading sensor installed in the chamber, which has a resistance to high temperature, and the capacity of maximum temperature is 120 degrees Celsius. Axial deformation was measured using the dial gauge ready installed outside of the outer cell. A membrane with a thickness of 0.5 mm covered the whole specimen on pedestal. The temperature probe surrounding specimen measured the temperature of heating water supplied in the cell. The water tube was connected to constant temperature control bath. Setting temperature that 20 and 80 degrees Celsius were controlled in the constant temperature controlling water bath.

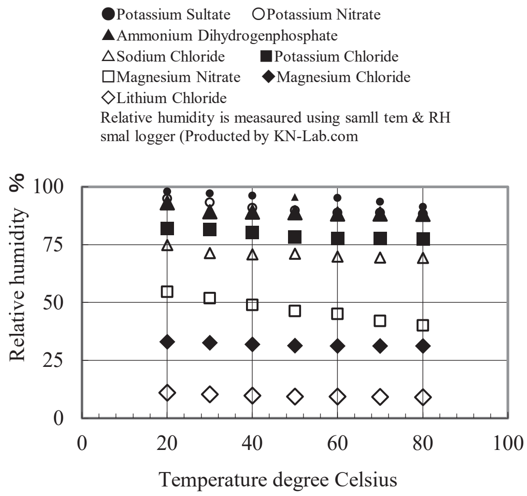

Fig. 4. Measured relative humidity in a sealed chamber.

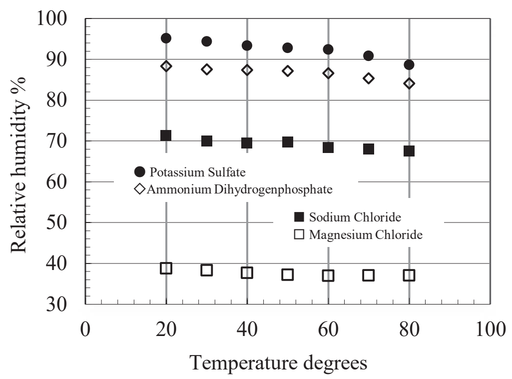

Fig. 5. Measured relative humidity in a circulation system.

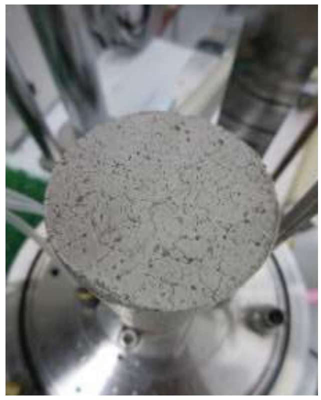

Fig. 6. Cracks under free deformations and heating.

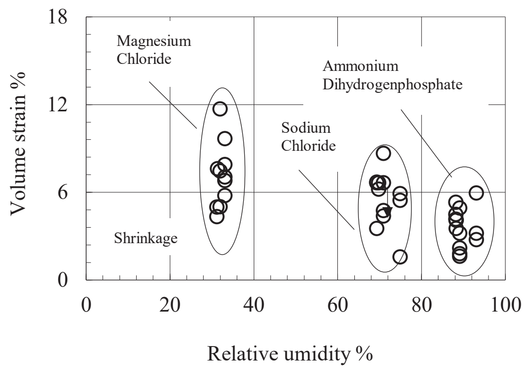

Fig. 7. Volume strain with different relative humidity.

3 Results

3.1 Calibration relationship between temperature and relative humidity

The steel mold is prepared that some salt solutions are installed in order to investigate relative humidity changing in Testing program (A). Whole the mold was placed in thermostat oven, in which controlled a range from twenty degrees Celsius to eighty degrees Celsius. Variations of salt solutions are used to confirm relative humidity ranges, and the results are described as shown in Fig.4. Determined relative humidity has a range from 95 % to 9.0 %. All of chemical substances have common tendency which are reduction with increment of temperature regardless of relative humidity at twenty degrees Celsius. Much reduction of relative humidity is indicated in such the tendency when Magnesium Nitrate is place in the mold, that it is from 54.7 % to 40.2 % in relative humidity.

In other words, attempting of measurement for relative humidity associate the equipped air circulation system, and it is obviously provided that measured relative humidity decrease with increment of temperature as shown in Fig. 5. All of salt solutions have similar with the results as shown Fig. 4. Relationship between temperatures and relative humidity as calibration specification is considerable useful to predict or evaluate applicable relative humidity on heating process.

3.2 Occurrence of shrinkage volume change

It is possible to predict that thermal heating performance often give some deformations such as cracks. Observing, cracks for unsaturated specimens subjected to increment of temperature as shown in Fig. 6. Further significant cracks are recognized in Testing program (B). So many small cracks are widely sprayed on the surface of specimen, and it is assumption to be either continuous distribution or discontinuous distribution. Probably, many cracks produce in side of the specimens, and are related to reduction of shear resistance and changing of void structure. Then, volume shrinkage strain is discussed like a thus cracks distribution. Volume of the specimens are directly measured from changing of diameter and height, and all of specimens subjected to heating and controlling suction verify the shrinkage properties. The obtained shrinkage strains in volume indicate few scatters at constant relative humidity, and Fig. 7 describes changing of shrinkage volume strain with increment relative humidity that has stability tendency. Many small cracks create the no continuous structures, and cause to establish scatter in data sets. Volume shrinkage strains corresponding to each strain in radius way are shown in Fig. 8. Strains in radius exhibit to be close to volume shrinkage strains, and the group for data sets distribute through a defined straight line with an approximately incline of 3.0. Positioning

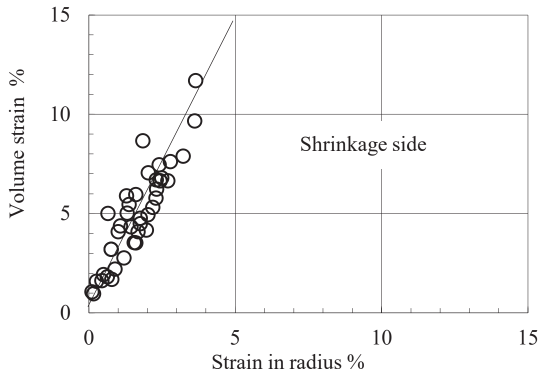

Fig. 8. Defined a straight line in deformations.

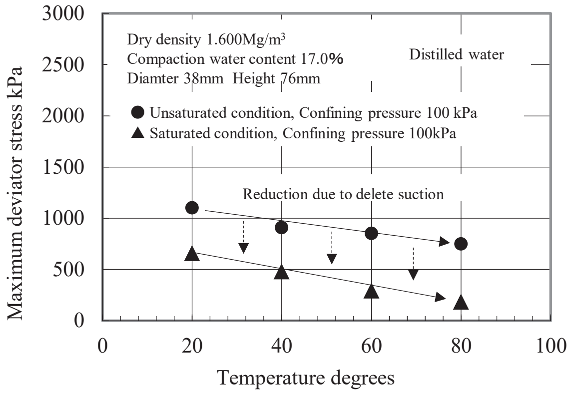

Fig. 10. Influence of heating on shear resistance.

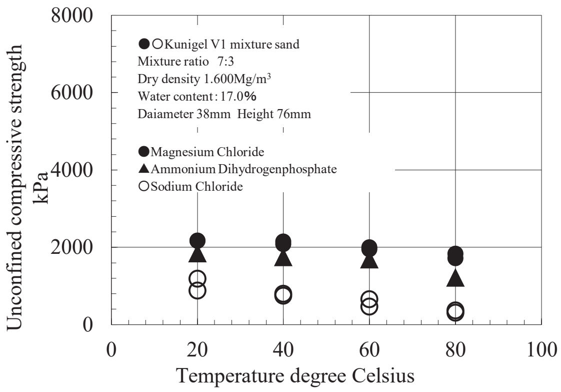

Fig. 9. Reduction of unconfined compressive strength.

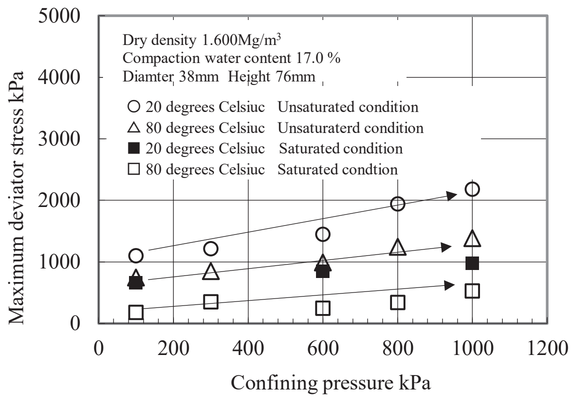

Fig. 11. Shear resistance unsaturated-saturated specimen.

3.3 Unconfined compressive strength

Unconfined compression tests are conducted out using the developed triaxial compression apparatus in Testing program (C), and remaining temperatures are 20, 40, 60, 80 degrees Celsius during compression process. As mechanical component, removing of unconfined compressive strength for unsaturated bentonite subjected to heating and developed relative humidity is one of significant factor. The specimens except of 20 and 40 degrees Celsius have some cracks, and variety of unconfined compressive strength are indicated as shown in Fig. 9. Reductions of unconfined compressive strength is clearly provided through four different temperatures. The assumption, as many cracks are distributing inside the specimens, large reduction is represented.

3.4 Triaxial compression test for unsaturated-saturated bentonite sand mixture

The shear resistances for both unsaturated bentonite sand mixture and saturated bentonite sand mixture are measured using the developed triaxial compression apparatus in Testing program (D), and involve two different temperatures as the factor (i.e. 20 degrees Celsius and 80 degrees Celsius). All of specimens used in Testing program (D) have a dry density of 1.600 Mg/m3. The pressures supplied into the triaxial cell are 100 kPa, 300 kPa, 600 kPa, 800 kPa and 1.0 MPa. The unsaturated specimen and saturated specimen are applied the changing of temperature, and it is 80 degrees Celsius from 20 degrees Celsius. All of the saturated specimens are swelled due to absorbed distilled water. To delete of suction of unsaturated bentonite sand mixture cause the decreasing of shear resistance under incorporation of confining pressure as shown in Fig. 10. Referred results indicate regardless of temperatures that is possible to define a straight line a range from 20 degrees Celsius to 80 degrees Celsius. Moreover, triaxial compression tests are performed to both unsaturated bentonite sand mixture and saturated bentonite sand mixture for two temperatures (i.e. 20 degrees Celsius and 80 degrees Celsius). Further wide range in confining pressure is supplied to the specimens, and the result verify that are the increment of maximum deviator stress with confining pressure and the decrement of shear resistance caused by delete of suctions as shown in Fig. 11. The obtained tendency is independent to elevated temperature actions.

3.5 Saturated bentonite sand mixture in different dry density

The specimens with a dry density of 1.200 Mg/m^3 are used in Testing program (E), and all of specimens are saturated due to either a distilled water or a salinity water with concentration of 3.5 %. Testing program (E) suggest the considering the influence of salinity water to thermal-hydraulic-mechanical properties. Maximum deviator stress decrease associated to involving salt

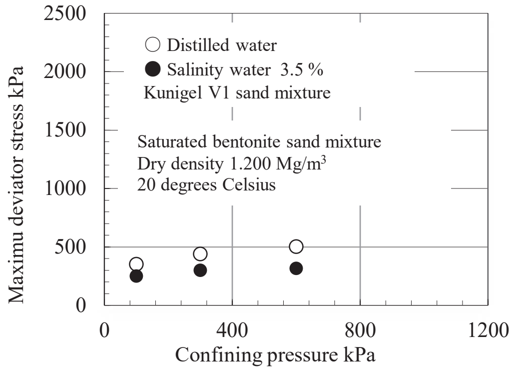

Fig. 12. Shear resistance for dry density of 1.200 Mg/m3

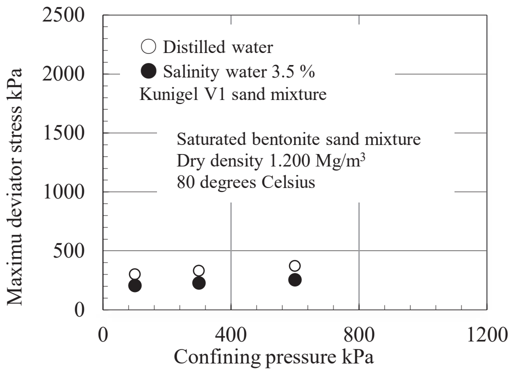

Fig. 13. Shear resistance for 80 degrees Celsius.

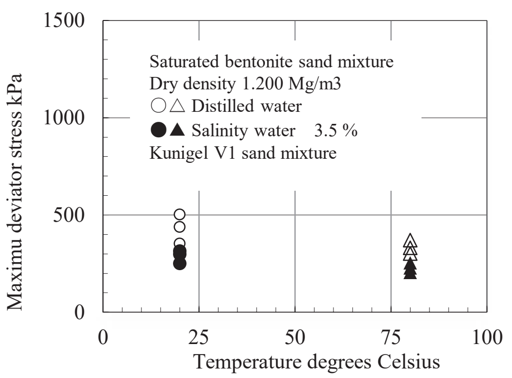

Fig. 14. Reduction due to heating performance.

component as shown in Fig. 12 through some confining pressures at 20 degrees Celsius. Reduction of shear resistance caused by salinity water with concentration of 3.5 % obviously recognize for 80 degrees Celsius as shown in Fig. 13. Finally, the results are summarized as shown in Fig. 14 that shear resistance decrease for saturated bentonite sand mixture according to temperature induced by thermal heating producing, and its tendency is similar with a case of saturated specimen due to a salinity water.

4 Conclusions

This study proposes the influence of suction, relative humidity and thermal effort in thermal-hydraulic on deformation properties and mechanical properties for bentonite-sand mixture. A series of testing program is prepared such as calibration test for changing of relative humidity with elevated temperature, measurement of volume change involving heating and changing of suction, determination of unconfined compressive strength, for thermal performance triaxial compression tests for both unsaturated bentonite sand mixture and saturated bentonite sand mixture. The obtained results are effectively to interpretation, and summary is provide as following. (1) Relative humidity in the sealed steel chamber using a miniature relative humidity and temperature sensor obviously decrease according to increment of temperature and creating relative humidity is based on vapor pressure technique. (2) To suction increment incorporation with thermal heating produce induces obviously shrinkage of the bentonite sand mixture, and lead the decrement of unconfined compressive strength. (3) To increase the temperature, confirm further reduction for maximum deviator stress using a developed triaxial compression apparatus that is regardless of unsaturated condition and saturated condition. It is common that delete of suction is significant related to reduction of shear resistance. (4) The decreasing of the maximum deviator stress under confining pressures due to thermal heating that provide for both distilled water and salinity water.

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