Journal of Environmental Science and Engineering B 7 (2018) 92-102
doi:10.17265/2162-5263/2018.03.002

# Changing of Properties of Unsaturated Compacted Bentonite due to Hydration Effort

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**Abstract:** Radioactive waste disposal is important facility for human and environment in the world. Compacted bentonite in radioactive disposal engineer barrier design really experience hydration effort as decreasing of suction during long-time. Hydration effort develop macro-micro void structure in bentonite under deeply geological environment. The bentonite occurred uncertainly problems or translation in various experimental interaction boundary conditions such as thermal-hydration-chemical condition. To detect accumulation of deformation or changing of bentonite behaviour due to these processes is important that the modified experimental methods are required. In addition, to interpret laboratory experimental results combine to establish mathematical modelling in possible. The overall investigation or performance of the bentonite have contributed to represent the intrinsic properties of engineer barrier systems. This study focused on changing of properties of unsaturated compacted bentonite related to hydration effort due to increasing of relative humidity. Changing of some properties revealed to become instability or uncertainly problems in practice. Soil-water characteristic curve was measured with considering of various temperatures using vapor pressure technique. Swelling pressure and creep behaviour such as mechanical components were described with hydration effort.

**Key words:** Bentonite, suction, soil-water characteristic curve, swelling pressure, creep deformation.

## 1. Introduction

Radioactive waste disposals have been produced from atomic plant, and decommissioning of the nuclear power plants have supplied severe problems to environment. Deep geological disposal of radioactive waste or some of decommissioning of the nuclear power plants are science, technically and societally challenging duty. Geotechnical or Geo-environmental engineers in the world have approached some kind of mandate with the necessary honour and usefulness for highly generational protection of human. Actually, mount of radioactive disposal waste with some levels arises according to the nuclear energy legislation or as result of powerful economic activity. Unsaturated soil mechanics is required to response within the accurate framework for planning, construction, operating and maintenances of the considerable deep geological repositories. The safety design analyses for a deep geological repository was modified based on a comprehensive methods or measurement program of expansive materials such as bentonite, expansive clay and host rock. The general procedure has been evaluated by many laboratory tests and *in-situ* investigation [1-8].

The bentonite is one of interesting materials which consist of engineered barrier for deep geological repository. There are so many experimental reports in area of physical, science or technical. Following preliminary laboratory test, the work on swelling pressure test updated the enormous database or interpretations on the experiments that a number of synthesis reports were presented [9-16].

Working developments must advise the establish safety program to barrier system for submission of license application: one low and intermediate level waste and one for spent fuel, high-level and long lived intermediate-level waste. It is necessary to evaluation

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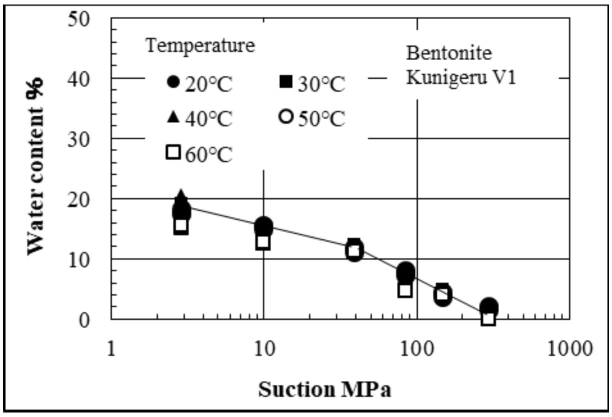


**Fig. 1 SWCC with various temperatures.**

of bentonite properties in unsaturated condition using suction control method or soil moisture retention concept [4, 17-27]. Many reports regard to soil-water characteristic curve or suction controlling procedure have been initiated to expand the mathematical simulation models [28-33]. Then, shear strength mechanics or experimental method with suction controlling supported the interpretation of unsaturated bentonite properties as scientific and technical background [34-46].

Recently, many data base obtained from geological field investigations in boreholes notice that there are uncertainly problems in the engineered barrier system such as hydration effort or thermal efforts. Hydration effort is one of factors associated to changing of relative humidity environment [47-53]. Thermal conductivity is one of parameters on Hydro-Thermal-Mechanical-Chemical simulations. Particularly, hydration effort induced the sever deformation to unsaturated bentonite. The deformation had closely creep behavior [54-61].

This study focused on hydration effort to properties of compacted bentonite, which was used as one component of radioactive disposal waste barrier system. Hydration induced volume deformation of compacted bentonite that changing of soil moisture cause, and vapour pressure technique was useful to control suction. Soil-water characteristic curve of compacted bentonite was indicated with both drying pass and wetting pass that increment of reduction in suction were applied to bentonite at term long-time. Also, swelling pressure was measured to compacted bentonite subjected to different suction. It was effort that suction decreased before swelling pressure test. All of these properties were measured using vapor pressure technique, which one of suction controlling methods. Also, the developed apparatus was used to appear creep behaviour of unsaturated compacted bentonite. After reduction of suction of bentonite, it was indicated that bentonite approached up to large deformation.

## 2. Soil-Water Characteristic Curve

### *2.1 Soil Material*

The water retention activity is important feature which described as the soil-water characteristic curve (i.e. SWCC). The SWCC was one of key parameters for establishing of mathematical models, and basic physical parameter. Mechanical and hydration properties were evaluated using the SWCCs in the general soil material. The soil-water characteristic curves for sodium type bentonite were measured, which was Kunigel V1. SWCC test was conducted out using vapor pressure technique. The soil-water characteristic curve of sodium bentonite was indicated in Fig. 1. The specimens had no compaction that was powder condition. The determined SWCCs had a wide range from 2.8 MPa to 296 MPa which was obtained using the various salt solutions. Using vapor pressure technique for high suction measurement is no longer special suction application in unsaturated soil mechanics. In this testing, SWCCs was controlled with various temperature, which had a range from 20 degrees to 60 degrees, and difference was ten degrees. Obtained water contents in SWCC decreased with suction in drying process, and influence of temperatures on water content was quite small. It was possible to define one curve having an inflection point. So, unique opinion associated with increasing of temperature was not confirmed from these data sets.

The compacted unsaturated bentonite was prepared that changing of both water content and degree of saturation were measured under RH of 98%. RH 98% equilibrium with suction of 2.8 MPa, which was less than initial suction of compacted bentonite. Hydro effort imposed to bentonite, and soil moisture increased according to time. Phenomena-induced hydration were shown in Figs. 2 and 3. Increment of water content was obtained to measure changing of weight of specimen with time, and degree of saturation was calculated using changing of weight and changing of both diameter and height at any time.

The compacted bentonite had a dry density of 1.600 g/cm$^3$ before applying of hydration. Increment of both water content and degree of saturation proved to induce the deformation of bentonite by increasing soil moisture due to hydration effort.

It is important to investigate the influence of salt solution on water retention activity of compacted bentonite. This study conducted out SWCC test for saturated bentonite in salt water. Saturated bentonites were prepared for measurement of SWCC that one was swelled in the distilled water, and another one was swelled in the salt water (i.e. NaCl water). Salt water had 3.5% in concentration, which was similar to nature sea water. Each bentonite was dry density of 1.600 g/cm$^3$ at initial condition and had no mixture sand. Compacted bentonite with water content of 8.0% was absorbed in each bentonite was dry density of 1.600 g/cm$^3$ at initial condition and had no mixture sand. Compacted bentonite with water content of 8.0% was absorbed in steel mould, and initial specimen size was a height of 2.0 cm and a diameter of 6.0 cm, respectively. Absorbing a bentonite specimen was conducted under constant initial volume during over one month. After swelling, it was confirmed that each specimen approached to saturation in the steel mould. Each saturated bentonite was placed into glass desiccator with salt solutions. Variety salt solutions produced specified relative humidity that was vapor pressure technique. This testing program used seven different salt solutions, and controlled relative humidity had a range from 98% to 11%. Using relative humidity ranges corresponded that suction had a rage from 2.8 MPa to 286 MPa.

As first testing step, saturated bentonite was placed into RH 98% environment in glass desiccator, and this step maintained over one month. On evaluation of equilibrium with relative humidity to bentonite specimen, a period of one month was in generally accepted in SWCC test procedures, was recognized as one of practice methods in conventional. When specimen took an equilibrium, some parameters were measured which were weight, diameter and height for specimen, and determine water content and degree of saturation to controlled suction. Step by step, suction was decreased up to 286 MPa due to replace salt solutions in drying process. Relative humidity in glass desiccator according to be reduction that relative humidity was 11% at end of drying process. All of

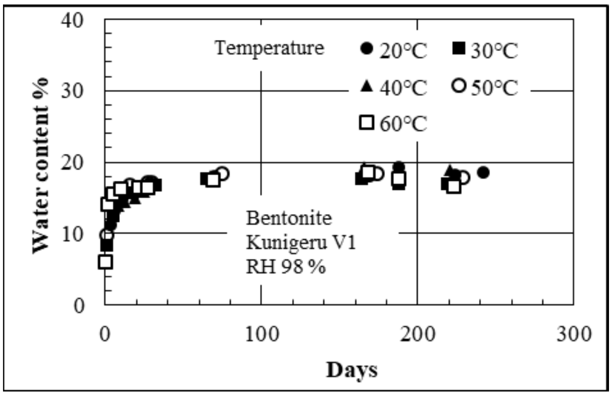


**Fig. 2 Increment of water content according to hydration.**

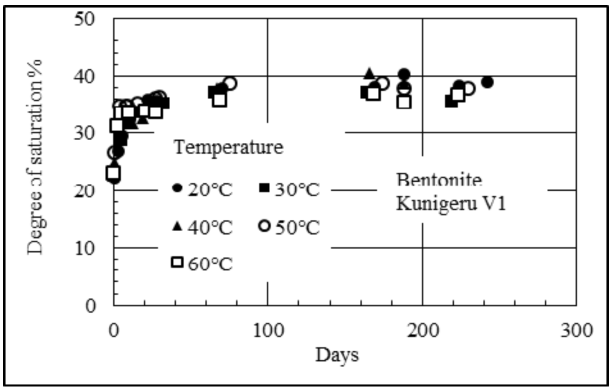


**Fig. 3 Increment of degree of saturation under according to hydration.**

suctions were seven different values in drying process.

Subsequently, wetting process-induced by reduction of suction was commencement to all bentonite specimens experienced drying process. Suctions on process in wetting procedure were quite same that it was easy to comparison to observing test results at drying process. Above mentioned, physical properties such as water content and degree of saturation were determined with same testing methods.

Both water content and degree of saturation such as parameters were used to describe each SWCC of bentonite (Fig .2 from 4 to 7). On drying process, soil moisture was obviously large for bentonite including salt component up to suction of 9.8 MPa. Beyond suction was 9.8 MPa, reduction of water content with increment of suction was indicated, and thus results were similar between bentonites with and without salt water at drying process. Also, water contents were

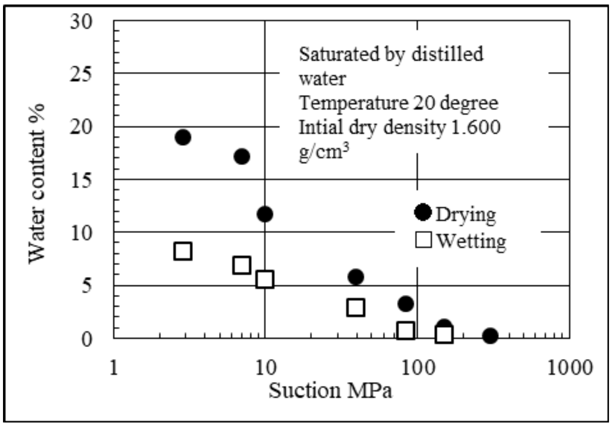


**Fig. 4 Changing of water content (distilled water).**

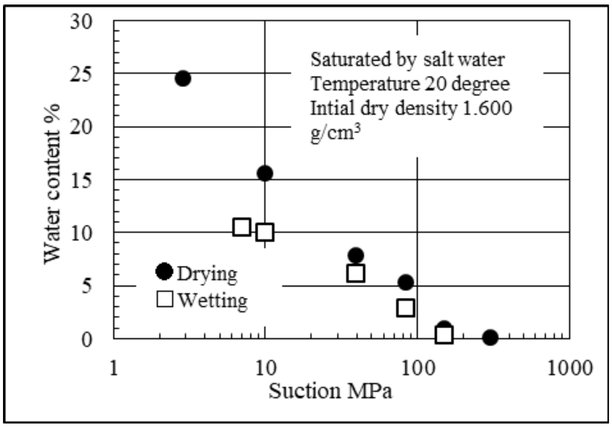


**Fig. 5 Changing of water content (salt water).**

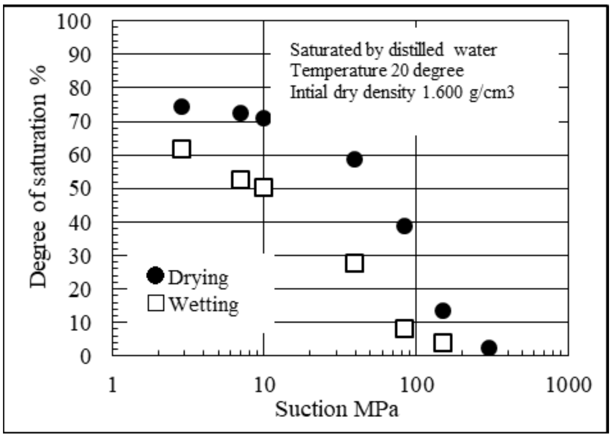


**Fig. 6 Changing of degree of saturation (distilled water).**

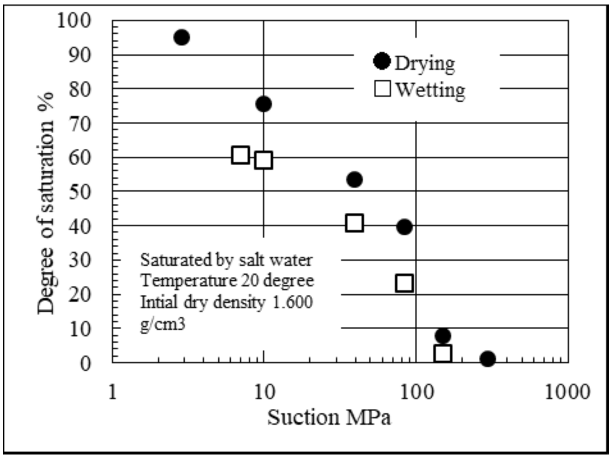


**Fig. 7 Changing of degree of saturation (salt water).**

measured near zero value regardless of imposing salt components at suction of 296 MPa.

On wetting process, all bentonite specimens described to increase soil moisture regardless of experience with and without salt water that it was widely accepted in water retention mechanics in unsaturated soils. Water content and degrees of saturation can seem to be not same with those data sets of bentonites in drying process that exist much hysteresis in hydro-processing. Particularly, the bentonite with salt component indicated large increment of soil moisture with reduction of suction comparison with observing results in de-stilled water. As results, few hysteresis was observed in the bentonite having salt components that strong efforts contributed to water retention activity associated with bentonite properties.

## 3. Swelling Pressure of Unsaturated Bentonite Subjected to RH

Swelling pressure is one of important key parameters for construction of radioactive waste disposal system which is supplied saturation process under deep ground during long term period. Many reports regard to swelling properties of variety bentonites had been established that almost of swelling tests were conducted to supply water absorbing to unsaturated bentonite directly. It is sure that barrier structure constructed using unsaturated bentonite was initially unsaturated condition, and considerable slow water flow is predicted as results of many mathematical simulation models. To reach to completely saturation situation spend extremely long times. While unsaturated bentonite become toward to saturation, hydration effort make slowly expansion in changing of suction of bentonite under deep tunnel. It was no consider that deformation of unsaturated bentonite occurs according to suction reduction (i.e. increment of relative humidity).

A swelling pressure testing apparatus was developed to determine swelling pressure in a constant relative humidity environment. The apparatus consists of a triaxial chamber and relative humidity control circulation system. The modified swelling pressure testing apparatus was shown in Fig. 8 that consisted mainly of a triaxial chamber, a pedestal, a steel mold, a double glass burette, a differential pressure transducer, a difference displacement sensor, load cell sensor and relative humidity control circulation system. The relative humidity control circulation system was established using a conventional pump, along with a small chamber with salt solution. The air flow maintained a constant relative humidity surrounding the compacted bentonite. All compacted bentonite specimens were placed into steel mould. Moving water in the double glass burette due to absorption in bentonite was permitted at the low portion of specimen. Absorption water volume change in the double burette was measured using the differential pressure transducer. Initial total volume was maintained constant for all compacted bentonite specimens.

Sodium bentonite was used for measurement of swelling pressure. Silica sand had uniformity grain size distribution which was mixed with bentonite at a ratio of 30% by dry weight. The specimen was statically compacted in stiffness steel mold at an initial water content of 5.9%. The compacted bentonite

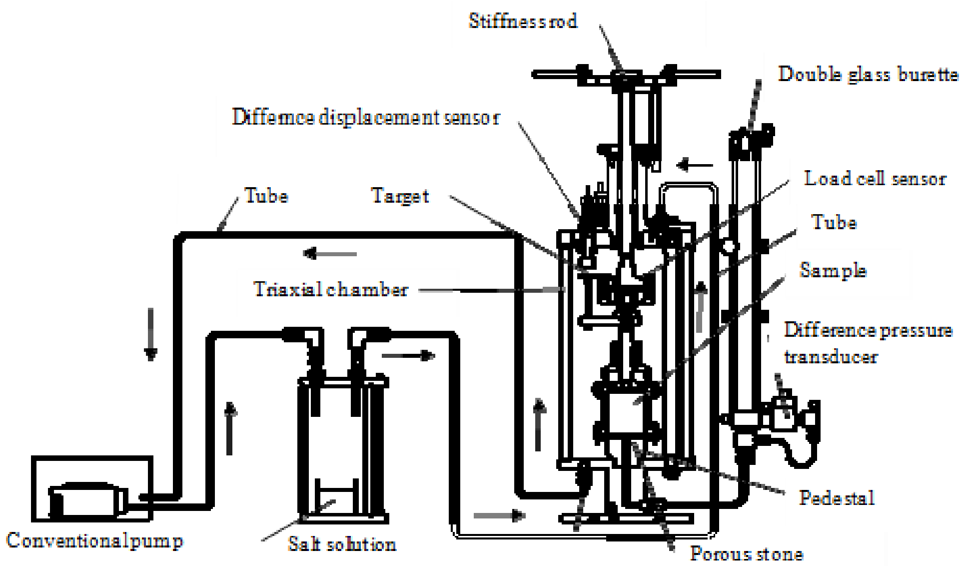


**Fig. 8 Modified swelling pressure test apparatus.**

specimen had a dry density of 1.600 g/cm$^3$ as target value. The height of specimen was 25.5 mm. Compacted bentonite specimens with two different soil suctions were prepared for swelling pressure tests.

Initial compacted bentonite had a soil suction of 105 MPa. Soil suction of 2.8 MPa was imposed using vapor pressure technique and used salt solution was Potassium Sulfate.

Soil suction of 2.8 MPa corresponds to relative humidity of 98%. The gravimetric water content increased that vapour moisture in RH 98 was absorbed into void structure of bentonite having suction of 105 MPa. As result, the gravimetric water content of the compacted bentonite sample subjected to relative humidity of 98% increased to 9.7% from 5.9%. Also, deformation in expansion occurred, grew with time. Finally, deformation of bentonite specimen took large expansion in vertical direction, and was 9.5% in swelling. During hydration process, void structure constructed macro-micro structure produce complexly expansion in clay structures together. Changing of total volume was useful to determine dry density. The dry density of the sample after equilibrium soil suction of 2.8 MPa decreased to 1.427 g/cm$^3$ from 1.600 g/cm$^3$.

Swelling pressure of bentonite with two different suctions were measured under constant volume, which changing of a height of specimen was not permitted through swelling test.

Fig. 9 shows observing the swelling pressures with water absorb for compacted bentonite at initial water content of 5.9%, and specimen had an initial soil suction of 105 MPa at beginning test. The measured swelling pressure described rapidly growing during almost 50 hours periods. Strong increment of swelling pressure seems to be one of characters on swelling properties for compacted bentonite with high suction. Determined swelling pressure at 50 hours was 220 kPa. Behind 220 kPa in swelling pressure, bentonite described traditionally small reduction with time. Reduction continued smoothly till elapsed time was 350 h, and measured swelling pressures had date sets with both increment and decrement such as a frequency cyclic motion. Once again, the bentonite showed small increment, which appeared increment and decrement in swelling pressure. Its smoothly increasing was maintained till swelled bentonite took equilibrium, and elapsed time was nearly 1,000 hours. Confirmed maximum swelling pressure corrected as 267 kPa.

The compacted bentonite with soil suction of 2.8 MPa shows smoothly increasing of swelling pressure at beginning of test as shown in Fig. 10. There was quite difference comparison to swelling behaviour of initial suction of 105 MPa. It was obviously that

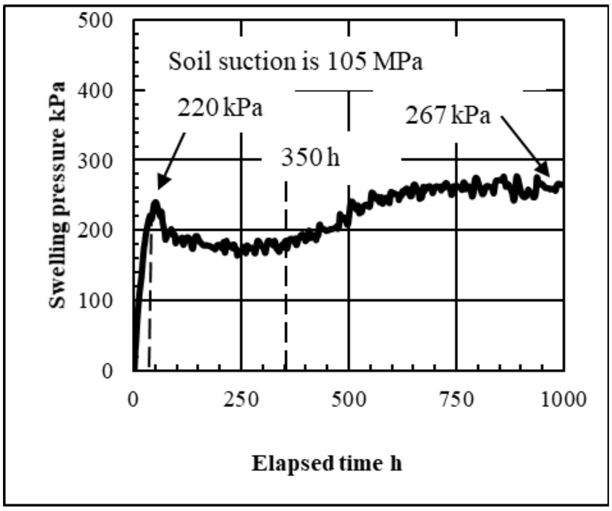


**Fig. 9 Processing of swelling pressure (no hydration).**

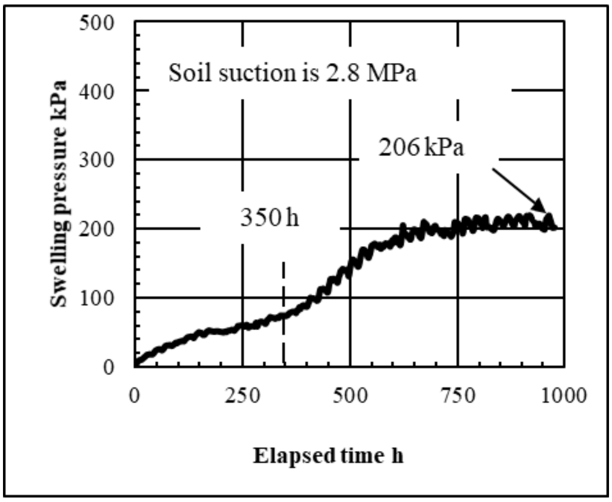


**Fig. 10 Processing of swelling pressure (hydration).**

performed swelling pressure was smaller than that of suction 105 MPa at beginning that was revealed as the influence of suction of bentonite before absorbing. Growing of swelling pressure was extremely slow till elapsed time was 350 h that was entirely difference against to swelling pressure increment mentioned in Fig. 9.

After the elapsed time of 350 hours, accumulation of swelling performance became to be developed, and it reached to 200 kPa at 650 hours. Beyond 750 hours, bentonite seemed to be equilibrium that 206 kPa was measured as maximum swelling pressure. Bentonite showed that hydration effort caused reduction of swelling pressure, and at same time growing processes of swelling pressure was quite difference between with and without hydration effort before swelling process. Consequently, degree of saturation obtained from water content at end of test reached to saturation regardless of magnitude of suction value before swelling.

## 4. Creep Test

This study mad above mention that hydration effort such as reduction of suction improved both water retention capacity and swelling performance in compacted bentonite. Revised basic properties to compacted bentonite was induced at macro-micro structure as extremely fine structures. This testing conducted out creep test and finding relationship between main chief factor in hydration effort and strength resistance in mechanical properties. It is defined in generally for the soil mechanics that creep test is conducted under constant effective stress to saturated soils. The changing of macro-micro void structure due to hydration effort had closely the deformation on creep behavior. The modified creep test apparatus was shown in Fig. 11. The apparatus employed a conventional cyclic relative humidity control system, which was possible to apply a required RH using vapor pressure technique. This apparatus consists of triaxial chamber, air cyclic flow pump. A dynamic activity of the conventional pump had at least 10 kPa pressure, which maintained steady air flow through the system.

Creep stresses were determined using unconfined compressive strength in experimental data sets what was deviator stress without confining pressure. Controlled relative humidity was either 98%. In case of RH 98%, suction of 2.8 MPa corresponding to RH 98% was considerable lows level suction comparison with suction of bentonite in initial condition. Used specimen had both a height of 100 mm and a diameter of 50 mm, respectively. Also, dry density was 1.600 g/cm$^3$ as target value.

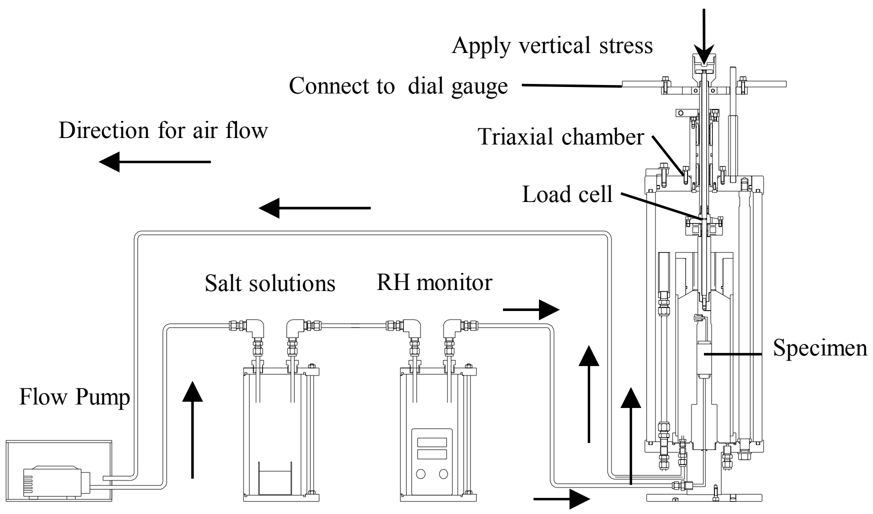


**Fig. 11 Modified creep test apparatus.**

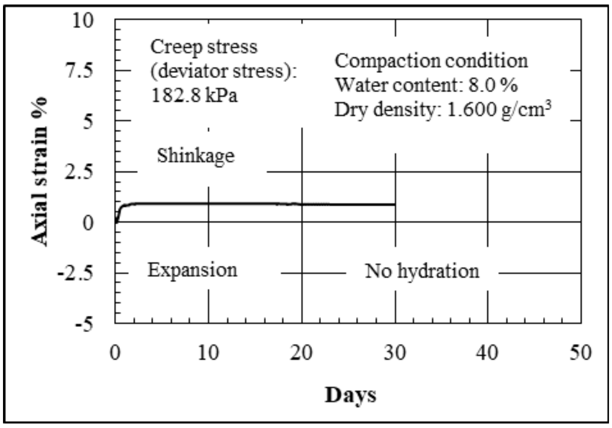


**Fig. 12 Case of no hydration for creep test.**

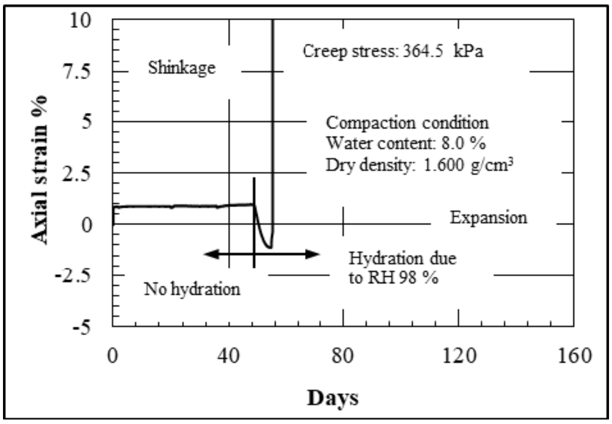


**Fig. 13 Case of application of hydration for creep test.**

Observing axial strain under subjection of external vertical loading was shown in Fig. 12. Prepared creep stress was 182.8 kPa and was maintained till end of test. Then, positive value in axial strain expressed that specimen occurred compression deformation. The axial strain in shrinkage was approximately 1.0% at beginning of external loading, which was produced by deviator stress as mechanical action. The axial strain was remained a period of 30 days (i.e. up to end of test). It was able to predicate that the specimen described growing shrinkage deformation under no hydration environment.

As other case, axial strains with elapsed time was indicated as shown in Fig. 13, and applied creep stress was 364.5 kPa more than that mentioned in Fig. 12. Though bentonite had creep stress of 364.5 kPa under no hydration till fifty days, compression deformations were measured at commencement of supplying vertical load. While fifty days, axial strain described a stable, and the strains were similar with measured strain on beginning of loading of stress. There were not observing increment of shrinkage strain such as creep deformation.

Subsequently, the hydration was applied to bentonite due to air flow having RH 98%, and suction surrounding of specimen approached rapidly 2.8 MPa in suction. As point of view regard to presence or absence in hydration effort, beyond fifty days the bentonite occurred the expansion distinctly with days. It was sure that the effort of hydration was revealed with measured changing of vertical strain. The processing of hydration effort developed macro-micro structures in bentonite, and large increment of expansion was described from forty days to fifty days. At fifty days, specimen had large expansion comparison with initial height that measured expansion strain was approximately 1.0%. Subsequently, the bentonite evidenced the shrinkage deformation such as up to destruction. Thus, axial strain data sets indicated straight line in vertical direction. Crushed specimen was clearly observed in chamber. Then, the hydration effort can be defined as decrement of suction in stress variables that induced the destruction combined large deformations for unsaturated bentonite.

## 5. Conclusions

This study represented properties of bentonite such as extremely expansive soils on experimental resulting. The hydration effort to compacted bentonite was referred as one of significant impact factors, which induced uncertainly conditions on engineered properties to unsaturated bentonite. On supporting unsaturated soil mechanics, some experimental laboratory tests were conducted used modified apparatus that were SWCC test, swelling pressure test and creep test for unsaturated compacted bentonite. These tests had enough advantage to investigation above mentioned physical and mechanical properties of compacted bentonite. Particularly, interpretation incorporated suction controlling methods were useful to understand the influence of hydration effort such as reduction suction on bentonite properties:

(1) The bentonite had high water retention activity at high suction ranges such as larger than 2.8 MPa in suction. The hydration effort induced expansion of the volume under reduction of suction, and, increment of soil moisture occurred at same time. Also, reduction of suction was controlled using vapor pressure technique that relative humidity was directly controlled in mythology.

(2) The obtained soil-water characteristic curves of bentonite can affirm that the influence of temperature on water retention activity was negligible. Other hands, the salt water produced to be high soil retention activity that bentonite absorbed, swelled in the salt water.

(3) Due to suction reduction, the swelling pressure with time indicated smoothly growing comparison to initial condition (i.e. before applying of hydration). As results, peak swelling pressure decreased that the transmutation of macro-micro void structure in bentonite immediately related to performance of swelling behavior.

(4) Through creep test, when hydration effort such as suction reduction was applied to compacted bentonite, it was obviously that axial strain in expansion direction was observed, and unsaturated compacted bentonite reached up to failure as result of maintain of both hydration effort and creep stress loading.

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