Journal of Rock Mechanics and Geotechnical Engineering. 2010, 2 (1): 79–85

CSRME

Journal of Rock Mechanics and Geotechnical Engineering

Journal online: www.rockgeotech.org

Hydro-mechanical behaviours of highly compacted sand-bentonite mixture

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Received 11 May 2009; received in revised form 10 October 2009; accepted 5 November 2009

Abstract: This paper presents the results of laboratory testing on a heavily compacted sand-bentonite mixture. To measure the soil-water retention curve (SWRC) of the mixture over a large range of suction, a pressure plate apparatus and filter papers were used. The obtained SWRC shows that the measurements via the two methods consistently agree with each other. By using a suction-controlled oedometer for unsaturated soils, a series of one-dimensional compression tests were performed on the unsaturated compacted sand-bentonite mixture at different constant suctions. The testing results indicate that the yield stress increases and compression index decreases with the increase of imposed suction. The results also demonstrate that the mixture wetted to saturation and subsequently dried to a certain suction level has a lower yield stress than that wetted directly to the same suction.

Key words: sand-bentonite mixture; buffer/backfill material; soil-water retention curve; compression curves

1 Introduction

To dispose of high-level radioactive wastes (HLRWs) from nuclear power stations, many countries have adopted the deep disposal system based on the multi-barrier concept. Figure 1 shows a cross section of the proposed disposal concept [1]. The disposal facility is currently planned to be constructed at a depth of several hundred meters.

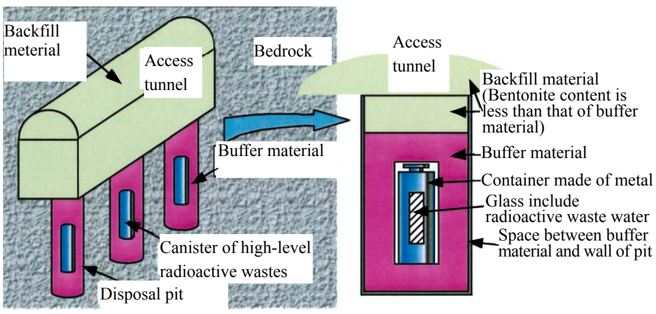

Fig.1 An example of disposal facility and pit for HLRW in Japan [1].

The heavily compacted unsaturated sand-bentonite mixture is generally used as buffer and backfill materials which are the important artificial barrier for HLRW disposal. Based on a number of tests in Japan, the mixing ratios for buffer material are preliminarily adopted as 7:3 between the dry mass of bentonite and sand, and 3:7 for backfill material between the dry mass of bentonite and other aggregates [2]. The physico-mechanical parameters of the buffer and backfill materials, including the degree of saturation (S_r), void ratio, suction and stress, change with groundwater level and surrounding stress field after construction of the disposal repository. Proper determination of these properties is crucial in developing an effective elastoplastic constitutive model for unsaturated sand-bentonite mixtures, and it also provides experimental results necessary for design, construction and future operation of the deep disposal project of HLRW.

The water-retention behaviour of unsaturated soils is described by the soil-water retention curve (SWRC). There has been increasing interest in the hydraulic behaviour of the heavily compacted bentonite recently. The experimental studies on the SWRC of the heavily compacted bentonite using different techniques have been conducted by many researchers. Chen et al. [3] measured the SWRC of compacted GMZ bentonite using the osmotic technique and the vapour equilibrium technique, and compared the measured data with the SWRC of GMZ bentonite calculated from the MIP test results under constant volume conditions [3]. Shen et al. [4] adopted the saturated salt

Doi: 10.3724/SP.J.1235.2010.00079
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Supported by the Innovative Foundation for Graduate Students at Shanghai University of China(SHUCX080168) and the National Science Foundation of China (10972130)

solution method to determine the SWRC of unsaturated bentonite. The above studies mainly involve the soil-water retention curve of bentonite [4]. Sun et al. [5] have studied the swelling characteristics of unsaturated bentonite under the K_0- compression stress condition. Their studies mainly involve the SWRC and the swelling characteristics of sand-bentonite mixtures. While the hydro-mechanical behaviours of heavily compacted sand-bentonite mixtures have significant influences on the safety evaluation for high-level radioactive waste disposal, a simultaneous study on SWRC and compression characteristics of sand-bentonite mixture using suction-controlled technique has not been found in literatures.

In this research, the SWRC of a heavily compacted sand-bentonite mixture is firstly obtained by using the pressure plate apparatus and the filter paper method. Secondly, a series of one-dimensional compression tests are performed on the unsaturated compacted sand-bentonite mixture at different constant suctions by using a suction-controlled oedometer to study its compressibility.

2 Testing program

2.1 Testing materials

Kunigel-V_1-Na^+-bentonite (produced in Yamakuchi Prefecture, Japan) and Toyoura sand were used in the tests. These materials were frequently used as the testing materials for engineered barriers for radioactive waste disposal in Japan [6]. The physico-chemical parameters of two materials are listed in Table 1 [5]. Komine and Ogata [7] analyzed the X-ray diffraction pattern, indicating that the Kunigel bentonite contains about 48% Na^+-montmorillonite and some quartz, feldspar, calcite, and pyrite, etc.. The deionized water was used during the tests to minimize the influence of ion exchange as the bentonite has a very high cation exchange capacity.

2.2 Testing apparatus

Figures 2 and 3 illustrate the setup of the suction-controlled oedometer used for testing. In compression with the pressure plate apparatus, this equipment can measure not only the soil-water retention but also the compressibility of unsaturated soils [8]. The water change in the specimen during testing can be measured through the volume tube which is connected to the bottom of the specimen (Fig.3). The pressure is applied by selecting either low or high pressure gauge with the low/high valve on the center of the pressure panel, depending on the targeted pressures (1–200 kPa at the low valve and 200–1 500 kPa at the high valve). The pressure in the pressure cell is applied according to the targeted value by turning the corresponding regulator knob on the pressure panel. The matric suction control is realized by adopting the axial-translation technique. That is, an air pressure equal to the imposed suction is applied with the pore water pressure remained at the atmospheric pressure. The oedometer for unsaturated soils can measure and control the pore air pressure and pore water pressure separately through the ceramic disk. The ceramic disk was fully saturated before testing so that water can freely flow through the disk during the tests.

2.3 Testing procedures

To determine the mechanical and hydraulic properties of sand-bentonite mixture, three different types of tests were conducted. The first one was the compression test under constant suction; the second was the determination of SWRC of the sand-bentonite

Table 1 Physio-chemical properties of bentonite and sand [5].

Bentonite					
Density of montmorillonite, ρ_m (Mg/m^3)	Density of minerals besides montmorillonite, ρ_{nm} (Mg/m^3)	Liquid limit (%)	Plastic limit (%)	Plastic index	Montmorillonite content, β (%)
2.79	2.79	473.9	26.6	447.3	48

Bentonite		Sand		
Cation exchange capacity of bentonite, *CEC* (meq/g)	Activity index, *A*	Density of sand, ρ_{sand} (Mg/m^3)	Average diameter, D_{50} (mm)	Uniformity coefficient, C_u
0.732	6.93	2.65	0.18	1.7

Fig.2 Oedometer-type pressure plate SWRC apparatus.

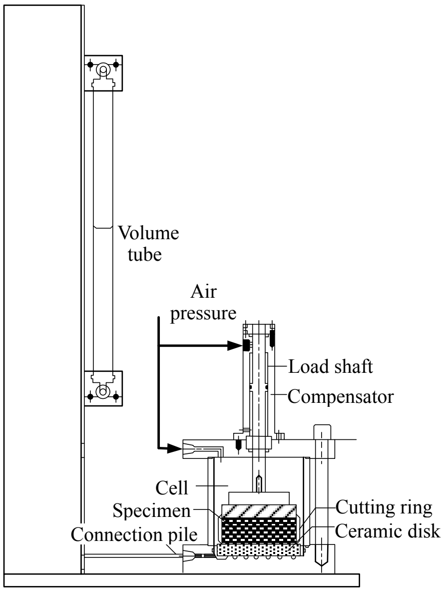

Fig.3 Sketch of oedometer-type pressure plate SWRC apparatus.

mixture using the pressure plate method; and the last was the measurement of the sand-bentonite mixture suction with the filter paper method. The mixing ratio of the sand-bentonite mixture was 3:7 between the dry masses of bentonite and sand particles. Table 2 shows the void ratio, water content and loading path for each test. All tests were performed under a constant temperature ((20 ± 1) °C).

2.3.1 *Constant-suction compression tests*

Tests No.1–6 (Table 2) are the compression tests on sand-bentonite mixture under different constant suctions. Sand and bentonite were firstly air-dried and then mixed with the required amount of de-ionized water to reach the specified water content (about 9%). The mixtures were sealed in polyethylene bags and stored in a constant-temperature, humidity-controlled room for several days to reach equilibrium. The specimen, 50 mm in diameter and 20 mm in height, was prepared by compaction in a mold at water content of about 9%. The specimen was compacted in three layers, each layer statically compacted several times according to the specified void ratio.

The compacted specimen was then placed on the ceramic disk while the valves connecting to water volume change tube were switched off. The vertical pressure was applied to the specimen through a vertical air cylinder at the top of the pressure cell [8].

2.3.2 *SWRC measurement using the pressure plate method*

Test No.7 is the SWRC measurement by using the pressure plate method. The method is based on the axial-translation technique, and can control and measure the pore water pressure and pore air pressure, separately, and thus can directly control and measure suction of the specimen. The pressure plate method is generally adopted for suction lower than 1 500 kPa. The specimen preparation and installation method are the same as above. The targeted pressure value is applied to the pressure cell by selecting either the low or high pressure gauge on the center of the pressure panel. The drain valve at the bottom of the specimen is opened after the adequate period of time. The pore water pressure equals the atmospheric pressure, i.e. u_w is 0. According to the axial-translation technique, the suction can be controlled by changing the applied pore air pressure u_a. It took about 7 to 10 days to reach a stable state for each suction stage. Before applying the next suction increment, the vertical displacement, water volume change and applied pore air pressure were recorded.

2.3.3 *Suction measurement using the filter paper method*

The filter paper method was used as an indirect means to measure soil suctions. The advantages of the method include its simplicity, cost-effectivity, and capability to measure suctions in a wide range [9]. The Whatman No.42 filter papers were used in this study. A high-accuracy electronic balance with the precision of 0.000 1 g was used to measure the weight of the filter paper. Tests No.8–11 are for the suction measurement of sand-bentonite mixture by the filter paper method. The specimen, 62 mm in diameter and 38 mm in height, was prepared in the same way as described in Section 2.3.1. The mixture specimen and filter papers were brought to equilibrium via both a contact (matric suction measurement) and a noncontact (total suction

Table 2 Water content, void ratio and loading paths in the tests.

No.	Initial water content (%)	Initial void ratio	Water content at equilibrium of suction (%)	Void ratio at equilibrium of suction	Loading path of suction s (kPa)	Remark
1	9.23	0.573	18.90	0.693	s_0→0→500	Compression at s =500 kPa
2	9.19	0.562	11.50	0.625	s_0→500	Compression at s =500 kPa
3	9.20	0.562	13.33	0.634	s_0→300	Compression at s =300 kPa
4	9.06	0.567	10.72	0.623	s_0→600	Compression at s =600 kPa
5	9.44	0.566	10.12	0.591	s_0→1 200	Compression at s =1 200 kPa
6	8.82	0.550	9.19	0.558	s_0→1 500	Compression at s =1 500 kPa
7	8.83	0.587	—	—	s_0→10→20→40→80→160→320→500→1 000	SWRC
8	10.52	0.606	8.80	0.599	s_0=2 839	Filter paper method
9	9.17	0.591	8.73	0.591	s_0=3 194	Filter paper method
10	9.36	0.632	8.48	0.618	s_0=4 018	Filter paper method
11	8.36	0.636	6.31	0.618	s_0=10 143	Filter paper method

Note: s_0 denotes specimen's initial suction.

measurement) methods in a constant temperature room. In the tests, two sheets of filter papers were put above the specimen with the noncontact method separated with the wire netting, three other sheets were put beneath the specimen, and the filter paper in the middle was used to measure matric suction (other two were used for protection). It took about 7–10 days to reach equilibrium between the filter papers and the specimen. After being removed from the containers, the water content of the filter papers was immediately measured. The corresponding suction value was then estimated by using the calibration curve presented by Rifat and Warren [10].

3 Testing results and analyses

3.1 SWRC of sand-bentonite mixture

Figure 4 shows the measured SWRC of sand-bentonite mixture and its fitting curve with the permeability function proposed by Fredlund and Xing [11]. The test results were obtained by using both the pressure plate method (for suctions up to 1 500 kPa) and the filter paper method (for suctions higher than 1 500 kPa), respectively. A part of the SWRCs of sand-bentonite mixture were measured by the pressure plate method in test No.7. The initial water content of the specimen No.7 was 8.83%, initial void ratio was 0.587 and the initial suction was 2 500 kPa measured by the filter paper method. The specimen No.7 firstly was wetted from initial suction to 10 kPa, and then was dried gradually until the suction reaches about 1 000 kPa. The slope of the saturation degree versus suction curve changes suddenly when the suction is increased to about 500 kPa. The inflexion of SWRC is defined as the air-entry value, which is about 500 kPa.

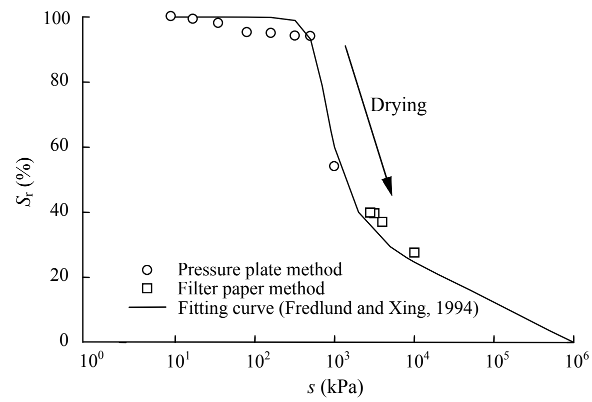

Fig.4 SWRC of the sand-bentonite mixture.

The specimen suction with low water content was measured by using the filter paper method. Table 2 shows the measured suction of four specimens (No.8–11) of compacted sand-bentonite mixture by the filter paper method. As shown in Fig.4, the obtained SWRC indicates that the results obtained both by the pressure plate method and the filter paper method are consistent.

The SWRC of sand-bentonite mixture shown in Fig.4 can be fitted by the general equation which can describe the SWRC over the entire suction range proposed by Fredlund and Xing [11]. The equation was expressed as follows:

$$S_r = \frac{C(s)}{\{\ln[e + (s/a)^n]\}^m} \tag{1}$$

where e is the natural constant, e = 2.718 28; a is approximately the air-entry value; n is a parameter which controls the slope at the inflection point of the SWRC; m is a parameter which is related to the residual water content; and $C(s)$ is a correcting function defined as

$$C(s) = 1 - \frac{\ln\left(1 + \dfrac{s}{C_r}\right)}{\ln\left(1 + \dfrac{1\ 000\ 000}{C_r}\right)} \tag{2}$$

where C_r is a constant related to the suction corresponding to the residual water content.

A nonlinear curve-fitting algorithm using the least-squares method has been used to determine the parameters n, m and a in Eq.(1), that is, n= 4.85, m= 0.51 and a = 500. The curve in Fig.4 is a fitting one by Eq.(1).

3.2 Compressive behaviour of sand-bentonite mixture under various suctions

Figure 5 shows the change in the water contents of specimens No.3–6 due to the suctions reduction from the initial value s_0 to the corresponding targeted values. The initial water contents of 4 specimens were rather close. During the change in suction, water uptake happened in the 4 specimens, which meant that the initial suction was larger than all the targeted suctions. Moreover, the water content increased with a decrease in the targeted suction, e.g. specimen No.3 had the highest water content with the targeted suction of 300 kPa, while the specimen No.6 had the lowest one with the targeted suction of 1 500 kPa.

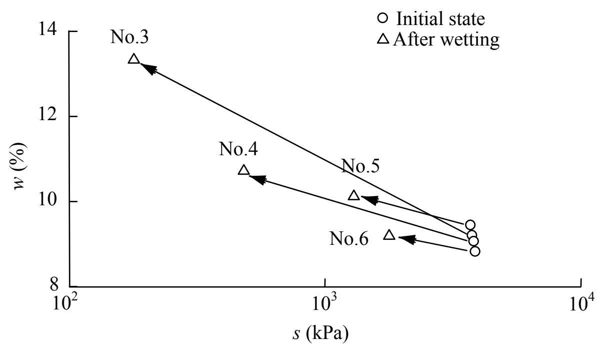

Fig.5 Change in water content during equilibrium.

Figure 6 shows the change in void ratios as the suctions reduced from the initial value s_0 to the respective targeted suctions. The initial void ratios of the specimens No.3–5 were rather close, while that of the specimen No.6 was smaller. During wetting, all these specimens swelled to various extents due to the water uptake. The void ratios increased with a decrease in the targeted suction, e.g. the specimen No.3 experienced the largest expansion with the targeted suction of 300 kPa, while the specimen No.6 experienced the smallest expansion with the targeted suction of 1 500 kPa.

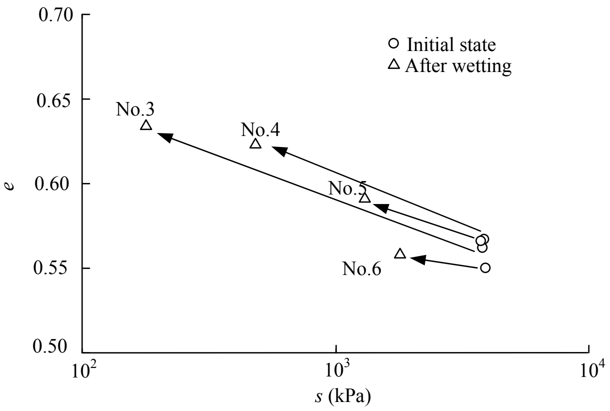

Fig.6 Change in void ratio during equilibrium.

Figure 7 shows the compression curves of the sand-bentonite mixture under different constant suctions. The water contents and void ratios under initial states and subsequent targeted suction states are shown in Table 2. Although the initial void ratios are close, the void ratios of the four specimens just before compression are different because of different swelling deformations induced by different targeted suctions. From Fig.7, it can be seen that all the compression curves have obvious yield points. The yield stresses can be estimated using Casagrande's method. The compression index $\lambda(s)$ can be determined by the slope of the compression curve after yielding.

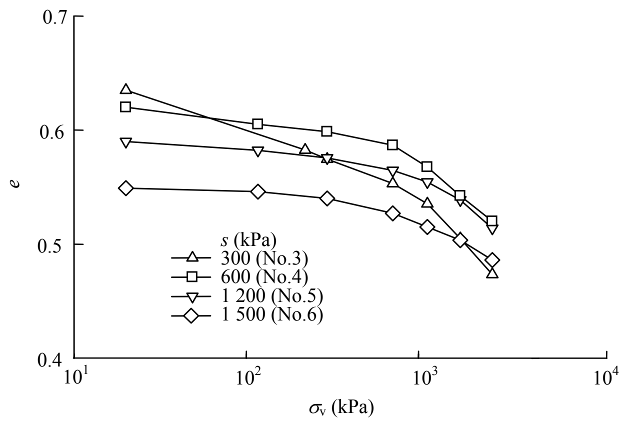

Fig.7 Compression curves at different constant suctions.

Figure 8 shows the relation between the compression index and suction. It can be seen that the compression index decreases with increasing suctions.

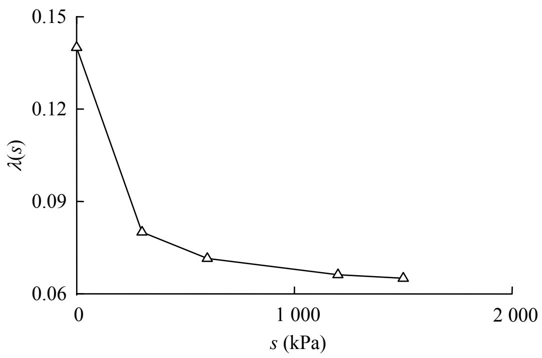

Fig.8 Change in compression index with suction.

The compression index of the specimen No.3 is the largest with a suction of 300 kPa, and that of the specimen No.6 is the smallest with a suction of 1 500 kPa.

Figure 9 shows the relation between the yield stress and suction resulted from the compression tests under different constant suctions. It can be seen that the yield stress increases with increasing imposed suction. The yield stress of the specimen No.3 is the lowest with a suction of 300 kPa, and that of the specimen No.6 is the highest with a suction of 1 500 kPa. The curve is defined as the initial yield curve (IYC), which is similar to the loading-collapse (LC) yield curve proposed by Alonso et al. [12]. When the stresses lie inside the initial yield curve, the elastic deformation occurs, but when the stresses lie on or outside the initial yield curve, the specimens yield, and the elastoplastic deformation occurs.

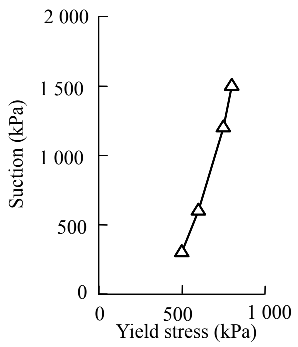

Fig.9 Change in yield stress with suction.

Figure 10 shows the changes in the degree of saturation of specimens No.3–6 during compression under different constant suctions. From Fig.10, it can be seen that the degree of saturation increases with the vertical stress under constant suction. Moreover, the increases in the degree of saturation of the specimens No.3 and No.4 are more evident than that of the specimens No.5 and No.6. This is because the stiffness increases with the imposed suction, and thus the specimen is difficult to be compressed under high constant suction. Meanwhile, there are little water content changes during compression. Therefore, the changes in the degree of saturation of the specimens No.5 and No.6 with higher suctions are smaller than those of No.3 and No.4 with lower suctions. In Fig.10, all the four curves have the evident inflexions as well as the yield points in Fig.8. It can also be found that the stresses corresponding to the inflexion in Fig.10 are equal to the yield stresses in Fig.8. The changes in the degree of saturation are not significant when the stresses are less than the yield stresses. Once the vertical stresses reach or exceed the yield stresses, the slopes of the curves in Fig.10 increase drastically. That is, the increasing tendency of the degree of saturation is more evident than that before the yield point. Moreover, the degree of saturation with a lower suction is higher than that with a higher suction, e.g. the degree of saturation of the specimen No.3 is the highest with a suction of 300 kPa, and that of No.6 is the lowest with a suction of 1 500 kPa.

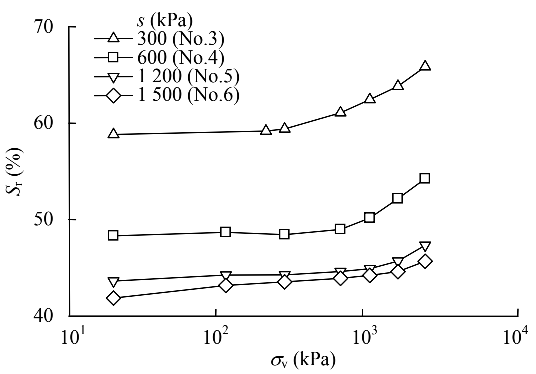

Fig.10 Change in degree of saturation during compression.

Figure 11 shows the compression curves of the sand-bentonite mixture experiencing different suction paths. The specimen No.1 was wetted to 0 kPa from the the initial suction (about 2 531 kPa) by decreasing the suction step by step, and then the imposed suction was increased to 500 kPa. The specimen No.2 was wetted directly to 500 kPa from the initial suction step by step. After the imposed suction of 500 kPa reached equilibrium, the compression tests were conducted on the specimens No.1 and No.2. The compression curve of the specimen No.1 just has six measured points due to the limitation of test conditions, however, the inflexion of the curve is quite evident and the slope of the curve after inflexion becomes larger. As shown in Fig.11, the yield stress of the specimen No.1 is lower than that of the specimen No.2, and the slope of the specimen No.1 is bigger than that of the specimen No.2 after yielding along the compression curve, that is, the compression index of the specimen No.1 is bigger than that of the specimen No.2. This is because the specimen wetted to saturation before compression test swells due to water uptake, and it has a larger void ratio than the other specimen wetted directly to the targeted suction. Therefore, the specimen No.1 has a lower stiffness and is easier to be compressed than the specimen No.2.

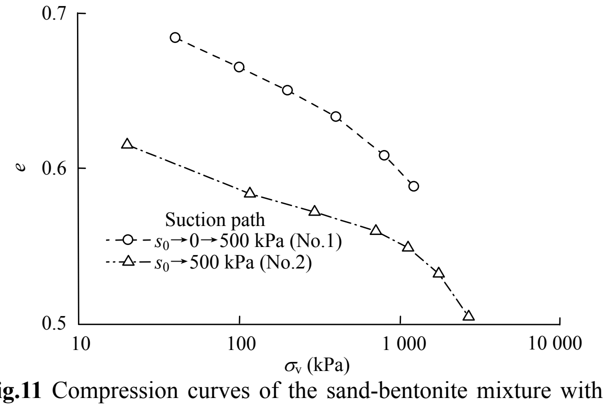

Fig.11 Compression curves of the sand-bentonite mixture with different suction paths.

4 Conclusions

The measurement of the soil-water retention curve and a series of one-dimensional compression tests under different constant suctions were conducted on compacted sand-bentonite mixtures to study the hydro-mechanical behaviours of the unsaturated sand-bentonite mixture. Based on the test results, the following conclusions can be drawn:

(1) The soil-water retention curve of the sand-bentonite mixture was measured with the pressure plate method and the filter paper method. The obtained soil-water retention curve shows that the results from the two methods are consistent.

(2) The compression tests on the sand-bentonite mixture under different constant suctions show that the yield stress of sand-bentonite mixture increases with the imposed suction, and the compression index decreases with the imposed suction. Moreover, the degree of saturation increases with the compression stress in compression test under constant suction.

(3) The compression curves under the same suction are obtained from the specimens experiencing different suction paths. The test results indicate that the change in suction paths significantly influences the mechanical behaviours of specimens, e.g. the yield stress of the specimen firstly wetted and then dried to a targeted suction, is smaller than that of specimen wetted directly to the target suction.

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