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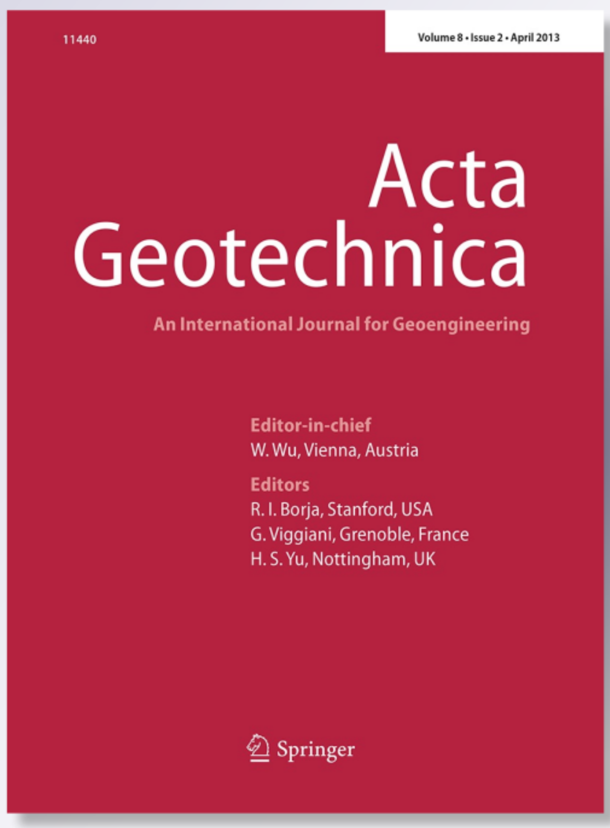

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RESEARCH PAPER

Swelling pressure–suction relationship of heavily compacted bentonite–sand mixtures

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Abstract This paper presents results of an experimental work to determine a relationship between swelling pressure and suction of heavily compacted bentonite–sand mixtures. For comparison, tests were also carried out on heavily compacted bentonite specimens. A series of swelling pressure tests were performed using multi-step constant-volume method where suction of the specimens tested was reduced in a stepwise manner toward a zero value. The suction reduction was induced using vapor equilibrium and axis-translation techniques. It is shown that compacted specimens did not exhibit any collapse upon suction decrease and exhibited maximum swelling pressures at zero-equilibrium suction. The development of swelling pressure with decreasing suction of the specimens showed threshold suctions below which a further reduction in suction yields an increase in the swelling pressure of the same magnitude. The magnitude of threshold suction was found to be a function of bentonite content in compacted specimens.

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Keywords Axis-translation technique · Bentonite–sand mixtures · Expansive soils · Suction · Swelling pressure · Vapor equilibrium technique

1 Introduction

Heavily compacted bentonite–sand mixtures have been proposed to be used as sealing and buffer materials for the underground nuclear and hazardous waste repositories in Germany. For example, a mock-up test was carried out in an abandoned salt mine in the city of Sondershausen where heavily compacted unsaturated 50/50 bentonite–sand mixture in the form of bricks was used as the sealing and buffer materials [30]. Wetting of compacted bentonite–sand bricks is expected to occur due to the ingress of water and saline solution from the host rock. The prevailing boundary conditions in the repositories dictate the development of swelling pressure under constant volume conditions. Therefore, studies concerning swelling pressure of sealing and buffer materials simulating the boundary conditions are extremely relevant in the assessment of long-term performance of the whole repository construction.

The rate of development of swelling pressure during the initial stage of wetting process is influenced by the magnitude of initial total suction and permeability of the barrier materials at macroscopic and microscopic levels. It is anticipated that the development of swelling pressure in heavily compacted bentonite–sand bricks would take place in a stepwise manner following suction reduction due to the ingress of liquid under constant volume conditions. The main focus of the paper is to examine experimental suction–swelling pressure relationships of heavily compacted bentonite–sand mixtures. For comparison, suction–

swelling pressure relationships of heavily compacted bentonite are also studied.

2 Background

Swelling pressure is defined as the pressure needed to maintain constant volume conditions when water is added to an expansive soil [23, 32]. There are a host factors known to affect the magnitude of swelling pressure exhibited by an expansive soil. The internal factors are the mineralogy, the specific surface area, the cation exchange capacity, and the characteristics of pore water (i.e., concentration and type of cations present in the pore water), whereas the external factors are the compaction conditions (i.e., dry density and water content), method of placement (i.e., compaction type and energy), and properties of the bulk fluid used for hydrating the soil. The dependency of swelling pressure on the dry density, when all other factors are held constant, has been reported in numerous publications (see [6]). The effect of aging on swelling pressure has been reported. For example, it was shown in [34] that an aged clay specimen exhibited a lower swelling pressure than an unaged specimen.

The development of swelling pressure is a physico-chemical process that occurs when water (or other fluids) is introduced to an expansive soil under certain boundary conditions. The measured swelling pressure is a macroscopic phenomenon which may, to a certain extent, be represented by the behavior of the soil at microscopic level. The expansion of clays at the microscopic level is well described in the past. For instance, according to the diffuse double-layer theory, the swelling of clay is attributed to the interaction of electrical double layers surrounding the clay platelet surfaces [24, 31].

The total suction of a soil consists of matric and osmotic suctions. The osmotic suction is solely attributed to the dissolved salt (or ion) concentration in the soil. The capillary and the sorptive forces could then be regarded as the matric suction [37]. The contribution from the sorptive forces is considered relevant, particularly for unsaturated clays with very high surface charge. The sum of osmotic and sorptive forces is equal to the total water potential since the magnitude of capillary force in expansive soils is negligible [3, 4]. The total water potential of an unsaturated soil is negative when the potential of distilled water is assumed to be zero [16].

Bentonites possess inherent osmotic suction due to the presence of ions in pore water. Hydration of surfaces of clay platelets and exchangeable cations when a dry bentonite is in contact with water increases the interlayer separation distance to about three monomolecular layers of water or about 19 Å (1.9 nm) [14]. The swelling induced by the hydration of cations and surfaces of the clay platelets is called crystalline swelling [36]. Only after completion of the crystalline swelling, the subsequent swelling is attributed to the osmotic process and is called the osmotic swelling [36].

Compacted bentonites usually possess pores of different sizes, such as the interlayer pores between the unit layers, the interparticle pores between the clay particles inside the aggregates, and the interaggregate pores between aggregates made up of clay particles (Delage et al. [10]). Addition of sand to bentonite may significantly influence the swelling properties of the mixture. The influence of sand on the mechanical behavior of a bentonite–sand mixture is dominant at low bentonite content primarily due to the presence of intergranular contact between sand grains. In this case, the properties of the mixture (e.g., shear strength, coefficient of permeability, and swelling potential) at different compaction dry densities are influenced by load-deformation characteristics of the sand Stewart et al. [33]. Graham et al. [13] and Blatz et al. [7] studied the influence of suction on the shear strength and stiffness of an unsaturated compacted bentonite–sand mixture. Sun et al. [35] studied the volume change characteristic of several sand–bentonite mixtures. Compacted sand–bentonite mixtures may produce metastable structure, which in turn may exhibit collapse upon inundation at high applied stresses under K_0 condition [35]. The collapse behavior was observed for compacted mixtures with low sand content and for mixture dry density of less than about 1.25 Mg/m^3. For compacted bentonite–sand mixtures with very high bentonite content, the sand grains are expected to be entirely covered by bentonite particles. In this case, there is no sand–grain contact and the macroscopic behavior is primarily governed by the swelling properties of the bentonite used.

For saturated expansive clays, osmotic suction and swelling pressure can be considered equivalent since the contribution from sorptive forces to the swelling pressure is null. In this case, swelling pressure balances the forces induced by the osmotic pressure and therefore has a value which is similar to the initial total suction (i.e., osmotic suction) of the clay. However, for unsaturated expansive clays, the combined influence of sorptive forces and osmotic suction gets manifested on the total suction. Studies concerning the relationship between initial total suction and swelling pressure for initially unsaturated compacted clays are very limited.

Kahr et al. [17] noted that the measured swelling pressures of very dense bentonites were in good agreements with the corresponding total suctions deduced from the sorption isotherm curve of the materials. Lloret et al. [22] noted three distinct zones during suction-controlled swelling pressure tests on heavily compacted bentonite samples.

In zone I, a large suction reduction caused a relatively small swelling pressure development. In zone II, a decrease in suction caused collapse of the macrostructure of the clay samples that was manifested on a reduction in the swelling pressure. In zone III, which occurred at low applied suctions, a decrease in suction produced a further increase in the swelling pressure. The latter swelling pressure development was attributed to have microstructural origin. Macroscopically, this condition is only possible when the clay is essentially saturated.

Several laboratory techniques have been used in the past for applying or controlling suction of unsaturated soils. The vapor equilibrium technique (VET) is used to apply total suction to a soil specimen, whereas the osmotic technique and the axis-translation technique (ATT) are used to control matric suction of soils. Kassiff and Ben Shalom [18] used osmotic technique for gradually reducing suction of compacted expansive soil specimens, whereas [22] used the VET for carrying out multi-step swelling pressure tests on heavily compacted bentonite specimens. Romero et al. [27] used the ATT to study the influence of suction decrease on the swelling pressure of compacted Boom clay specimens.

Limitations of the VET have been discussed in detail (see [25, 26]). These researchers noted that although equalization time was reduced due to forcing humid air to flow through a soil sample, the equilibrium suction in the sample was different from that of the applied suction. Similarly, circulation of humid air at the top and bottom of samples with an increased flow rate via porous disks may as well affect the applied suctions at the boundaries.

3 Material properties and specimen preparation

The materials used in the investigation were mixtures of a calcium-type bentonite, Calcigel [28], and quartz sand. The liquid limit (LL) and plasticity index (PI) of the bentonite were found to be 130 and 97 %, respectively. The specific gravity (G_s) of the bentonite and the sand used was found to be 2.65. The bentonite consisted of about 40 % clay-sized particles, with 100 % of the particles being smaller than 75 μm.

From the results of a mineralogical study using the X-ray diffraction technique, the bentonite was found to contain about 50–60 % montmorillonite, 5–10 % quartz, and other minerals, such as feldspar, dolomite, and calcite. The external specific surface area of the bentonite and sand was measured using the Brunette–Emmett–Teller N_2 adsorption (BET) method [5, 8]. The total specific surface area of the bentonite was measured using the ethylene glycol monoethyl ether (EGME) method [9]. The external specific surface area of the bentonite and sand used was 69 and 0.25 m^2/g, respectively. The total specific surface area of the bentonite was 651 m^2/g. The cation exchange capacity (CEC) of the bentonite was 49 meq/100 g [15], with Ca^{2+} and Mg^{2+} as the main exchangeable cations present in the bentonite.

Compacted specimens were prepared in the laboratory either from mixtures of sand and bentonite in equal proportion by mass (i.e., 50 % sand and 50 % bentonite or stated herein as 50/50 bentonite–sand mixture) or only from bentonite (i.e., 100 % bentonite). The specimens prepared had a diameter of 50 mm and a height of 20 mm. Compacted 50/50 bentonite–sand mixture specimens were prepared by following a special sample preparation technique proposed by Gesellschaft für Anlagen und Reaktorsicherheit (GRS)mbH, Braunschweig. The preparation technique was meant to produce specimens with conditions similar to those used in the Sondershausen project. In this case, mixtures of 50/50 bentonite–sand were statically compacted in a compaction mold similar to the swelling pressure cell used by [15] to achieve a targeted dry density of 2.0 Mg/m^3. The initial water content of bentonite–sand mixtures was 11 %.

After the compaction process was completed, the specimens were subsequently allowed to equilibrate with water vapor in a desiccator containing aqueous solution of KCl at 22 °C (±0.2 °C) for several months. The vapor space above the solution corresponds to a total suction of 22,700 kPa. Therefore, the specimens after equilibration were considered to have a total suction of 22,700 kPa. Compacted specimens with 100 % bentonite content were prepared by compacting cured bentonite–water mixtures with water content varying between 19 and 21 %. No special treatment procedure was adopted for these specimens as that occurred for bentonite–sand mixture specimens. The initial total suctions of the heavily compacted bentonite specimens were measured using a chilled-mirror hygrometer [21], and the values ranged between 15,000 and 21,000 kPa.

In total, 13 specimens were tested (eight specimens for 50/50 bentonite–sand mixture and five specimens for 100 % bentonite). The initial compaction conditions and the corresponding initial total suctions of the specimens are presented in Table 1.

4 Experimental program

In this study, multi-step suction-controlled constant-volume swelling pressure tests were performed using both the VET and the ATT. In the multi-step swelling pressure tests, the compacted specimens were hydrated by reducing suction in a stepwise manner.

Table 1 Initial conditions of the specimens tested

Specimen no.	Bentonite content, B (%)	Initial compaction conditions[a]		Initial total suction (kPa)[b]
		Water content, w (%)	Dry density, ρ_d (Mg/m^3)	
50B-1	50	9.0	2.056	22,700
50B-2	50	9.3	2.038	22,700
50B-3	50	9.1	2.042	22,700
50B-4	50	9.3	2.005	22,700
50B-5	50	9.1	2.052	22,700
50B-6	50	9.5	2.050	22,700
50B-7	50	9.4	2.058	22,700
50B-8	50	9.4	2.065	22,700
100B-1	100	21.1	1.582	15,243
100B-2	100	19.9	1.568	20,508
100B-3	100	21.1	1.582	15,243
100B-4	100	19.5	1.600	18,268
100B-5	100	19.5	1.599	18,268

[a] Compaction conditions immediately after the compaction process

[b] Compacted 50/50 bentonite–sand mixture specimens were equilibrated in desiccators containing saturated KCl solution (suction = 22,700 kPa); for others, as-compacted suctions

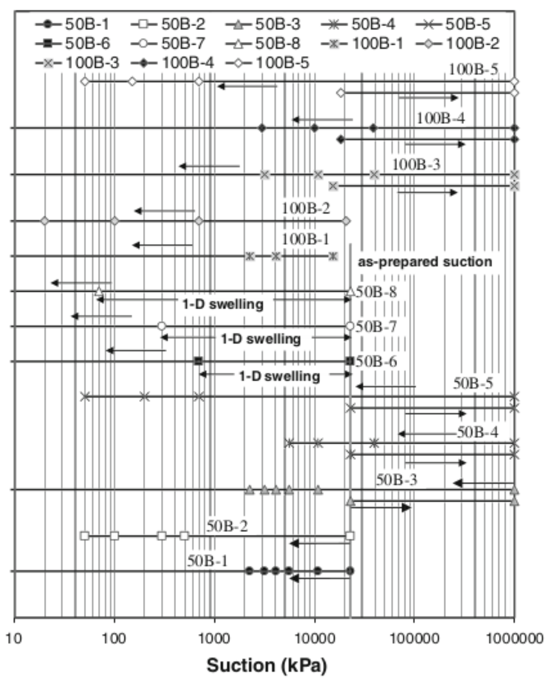

Fig. 1 Suction paths followed in the swelling pressure tests

The suction paths followed by the specimens (Table 1) are shown in Fig. 1. Specimen 50B-1 was subjected to a stepwise wetting process using the VET, whereas suction reduction for specimen 5OB-2 was carried out using the ATT. Specimens 50B-3, 50B-4, and 50B-5 were firstly oven-dried, followed by stepwise wetting by reducing suction. The VET was used for the former two specimens, whereas the ATT was used for the latter. Specimens 50B-6 to 50B-8 were equilibrated to suctions of 700, 300, and 70 kPa, respectively, in a pressure plate apparatus [20]. In this case, stainless steel rings were used to confine the specimens such that swelling of the specimens during suction equilibration took place one-dimensionally. Compacted specimens of bentonite were either wetted from their as-compacted conditions (specimens 100B-1 and 100B-2) or firstly oven-dried and then wetted by reducing suction (specimens 100B-3, 100B-4, and 100B-5). The VET was used for reducing suction of specimens 100B-1, 100B-3, and 100B-4, whereas the ATT was used for specimens 100B-2 and 100B-5. Specimens 50B-1, 50B-3, 50B-6, 50B-7, 50B-8, and all specimens except 100B-5 prepared from the bentonite were hydrated with distilled and de-aired water after the last applied suction steps were completed in order to determine the saturated swelling pressures. The methods adopted during pre-treatment of the specimens and specimen conditions prior to the swelling pressure tests plus the techniques adopted during the swelling pressure tests are summarized in Table 2.

4.1 Equipment used

The tests were carried out using several devices developed at the Technical University of Catalonia, Barcelona (or UPC), Spain (see [28]). The device used is also known as the UPC-isochoric cell. The cell mainly consisted of an exchangeable pedestal, a threaded top part with a top cap and a load cell. The pedestal used for the tests using the VET had a corrosion-resistant porous disk, whereas that used in the tests using the ATT was designed to have a high-air-entry ceramic disk (i.e., with 1,500 kPa air-entry value) seated, flushed, and glued on the base pedestal. Similarly, the top cap had a corrosion-resistant metal porous disk. The cell was equipped with an Erlenmeyer flask and an air pump to circulate water vapor at the top and bottom boundaries of specimens during the tests in which suction is controlled using the VET.

The diameter of the specimen ring was 50 mm and a height of 20 mm. Prior to the swelling pressure tests, the cells were verified for their deformability as induced by the development of swelling pressures. The cells without any specimen were subjected to an increasing and decreasing air pressure, and the vertical deformations of the cells were measured using a precision dial gauge with a least count of 0.001 mm. The deformations of the systems used were utilized to apply corrections to the experimental data.

Table 2 Pre-treatment methods adopted, specimen conditions prior to swelling pressure tests, and techniques adopted during swelling pressure tests

Specimen no.	Set no.	Pre-treatment prior to swelling pressure test[a]	Average specimen conditions prior to swelling pressure test[b]			Techniques used during swelling pressure test[c]
			w_b (%)	ρ_{db} (Mg/m^3)	Total suction test (kPa)	
50B-1	1	None	18.2	1.678	22,700	VET → water circulation
50B-2	1	None	18.2	1.678	22,700	ATT
50B-3	2	Oven-dried	0	1.701	1,000,000	VET → water circulation
50B-4	2	Oven-dried	0	1.701	1,000,000	VET
50B-5	2	Oven-dried	0	1.701	1,000,000	ATT
50B-6	–	1D swelling	–	–	700	Water circulation
50B-7	–	1D swelling	–	–	300	Water circulation
50B-8	–	1D swelling	–	–	70	Water circulation
100B-1	3	None	20.5	1.570	15,243	VET → water circulation
100B-2	3	None	20.5	1.570	20,508	ATT
100B-3	4	Oven-dried	0	1.716	1,000,000	VET → water circulation
100B-4	5	Oven-dried	0	1.664	1,000,000	VET → water circulation
100B-5	5	Oven-dried	0	1.664	1,000,000	ATT

[a] 1D swelling tests were carried out in a pressure plate under controlled applied air pressures; others, as indicated

[b] Water content and dry density values of bentonite fractions (i.e., w_b and ρ_{db}) are based on bulk density, water content, and sand content after the pre-treatment stage; suctions based on the pre-treatment considered

[c] Water circulation method was used to instantly saturate the specimen by circulating distilled and de-aired water at bottom and top boundaries of specimens

4.2 Experimental procedure

The tests using the VET were carried out following the test arrangement as shown in Fig. 2, whereas the tests using the ATT were performed in the test setup as shown in Fig. 3. During a wetting test using the VET, the total suction of the specimen tested was reduced by inducing a relative humidity corresponding to a total suction which was lower than the total suction of the specimens. Pre-determined relative humidities were generated using saturated and molal solutions of sodium chloride (NaCl). The relative humidity of the vapor space above a salt solution is related to total suction and can be calculated using Kelvin's equation [11].

$$s_t = \frac{-RT}{M_w(1/\rho_w)}\ln(RH) \quad (1)$$

where s_t is the total suction, R is the universal gas constant (i.e., 8.31432 J/mol K), T is the absolute measured temperature in K, M_w is the molecular weight of water (i.e., 18.016 kg/kmol), ρ_w is the unit weight of water in kg/m^3 and is a function of T, and RH is the measured relative humidity defined as (u_v/u_{vo}), where u_v is the partial pressure of the pore water vapor in the specimen and u_{vo} is the saturation pressure of the water vapor over a flat surface of water at the same temperature.

Temperature fluctuations during the tests involving the VET may significantly influence the test results. Rapid temperature fluctuations in the room where tests are conducted induce a temperature gradient that may in turn cause condensation of water vapor on the specimens. The effect of temperature is quite significant for applied suctions less than 2,000 kPa [1]. Therefore, the minimum applied suction considered in this study when using the VET was 2,000 kPa. The water vapor above the salt solution in the Erlenmeyer flask was circulated at the bottom and top boundaries of the specimen using an air pump. The setup was placed in a styrofoam box which could maintain a constant temperature to ±0.5 °C in a temperature-controlled room. The purpose of the temperature sensor used in the test using the VET (Fig. 2) was to monitor the temperature of the chamber inside the styrofoam box. In the event where the temperature inside the styrofoam box increased rapidly, the air pump was made redundant and was turned back on after the temperature decreased to the reference value.

The tests using the ATT were carried out in the constant-volume cells. However, the porous disks were replaced by high-air-entry ceramic disks (Fig. 3). Predetermined air pressures were applied from the top of the cell, whereas the bottom of the cell was connected to a distilled and de-aired water supply. Flushing was performed regularly to remove air bubbles that were collected in the water compartment as a result of air diffusion through the soil specimen and the saturated ceramic disk. The amount of diffused air bubbles collected in the water

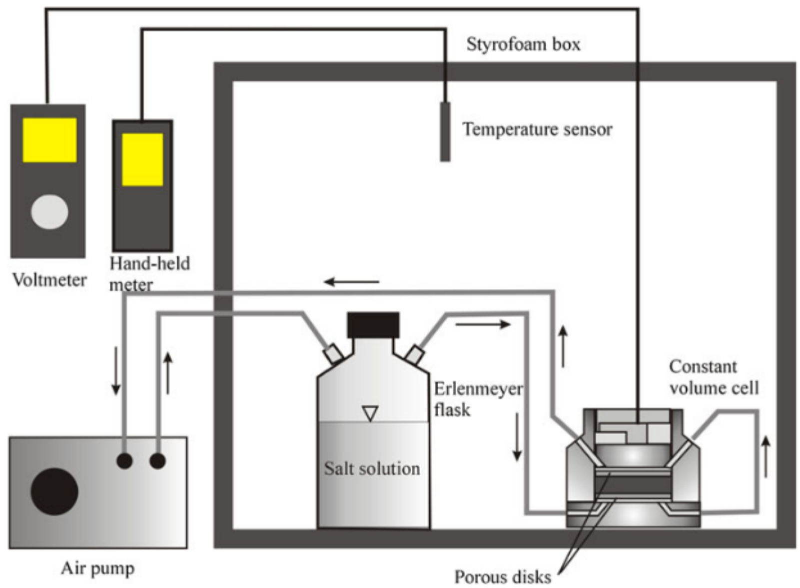

Fig. 2 Setup for the multi-step swelling pressure test using the VET

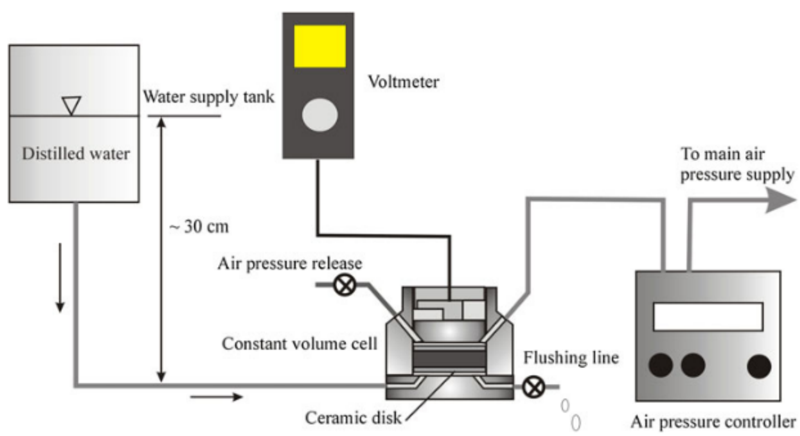

Fig. 3 Setup for the multi-step swelling pressure test using the ATT

compartment below a ceramic disk is a function of water pressure applied to the water compartment [11]. Since the applied water pressure in the water compartment was about 30 cm water column or about 3.0 kPa, frequent flushing was required in order to maintain the water phase continuity between the ceramic disk and the water compartment. After the pre-treatment process, specimens 50B-3 to 50B-5 and specimens 100B-4 to 100B-5 had diameters less than the diameter of the specimen ring since these specimens were oven-dried prior to the swelling pressure tests. Stiff plastic sheets were used to fill the gaps between the specimens and the annular spaces between the specimen rings and the specimens in order to minimize the radial expansions of the specimens.

During the tests using both the VET and the ATT, the swelling pressures of the specimens and the changes in the mass of the cells were monitored. The water content of the specimens during the tests was calculated by determining the initial mass of the specimen, the mass of the specimen at any pre-determined elapsed time, and the mass of the cell used. A precision weighing balance with a resolution of 0.01 g was used for all mass measurements. The swelling pressures were calculated based on the readings of the load cells which in turn were monitored using a precision microvoltmeter with an accuracy of 0.001 μV. Note that voltmeter readings were calibrated against known applied loads prior to using them in actual tests.

4.3 Presentation of test results

Two assumptions were made in the analyses of the experimental data: (1) no dilution of ions occurred during the swelling pressure tests where liquid water was in direct contact with the specimens; therefore, the test results using the VET can be considered comparable with those obtained using the ATT. (2) Suction applied to the specimen when tested under an applied load is merely an equilibrium water potential of the specimen in the system. The consequence of the latter assumption is that suction and swelling pressure can be considered as separate variables. At the end of swelling pressure tests (i.e., a specimen saturated with water or at zero-equilibrium suction), specimens still possess suction since the swelling pressures developed and the unsatisfied suctions (i.e., osmotic suctions) compensate each other, resulting in a zero net water potential. Since the test results using the VET and the ATT were considered together, the terminology 'suction (s)' is used instead of 'matric suction' and 'total suction' in the rest of the paper.

Analysis of the test results of the specimens was made based on considering the test results in five different sets (sets 1–5) (see Table 2). Grouping of the test results under various sets was based on two specific criteria prior to the swelling pressure tests: (1) specimen preparation history and (2) bentonite dry density (ρ_{db}) and bentonite–water content (w_b). For specimens prepared from bentonite–sand mixtures, w_b and ρ_{db} values were calculated by assuming that the volume of water added during specimen preparation and the pores belong to the fractions of bentonite in the bentonite–sand mixtures [2]. In the case of specimen prepared from bentonite alone, this assumption is not required. The average ρ_{db} and the corresponding average w_b of the specimens prior to suction reduction in the swelling pressure tests are shown in Table 2.

Specimens having same sample preparation history and similar initial ρ_{db} and w_b were grouped under a set of test results due to the fact that the test results in terms of swelling pressure, water content, and degree of saturation were also found to be very nearly similar. Specimens 50B-1 and 50B-2 had an average ρ_{db} of 1.678 Mg/m^3 and an average w_b of 18.2 %, and both were subjected to a wetting process from their as-compacted state (see Fig. 1). Therefore, these specimens were grouped under set 1 test results. Similarly, specimens 50B-3, 50B-4, and 50B-5 had very similar initial compaction water content and dry density (Table 1). Additionally, these specimens were oven-dried prior to the swelling pressure tests (Fig. 1) and were grouped under set 2. Specimens 100B-1 and 100B-2 were grouped under set 3 (see Tables 1, 2, Fig. 1). Specimens 100B-3 was considered separately under set 4 as compared to specimens 100B-4 and 100B-5 (set 5) due to the fact that although all three specimens were oven-dried prior to the swelling pressure tests (Fig. 1), the latter two had similar initial compaction water content, whereas specimen 100B-3 had higher initial water content and lower initial compaction dry density (see Table 1). This distinction is tenable since initial compaction properties significantly influence the shrinkage behavior of clays [29].

5 Results and discussion

5.1 Swelling pressure development with decreasing suction

Figure 4 shows the suction-controlled constant-volume swelling pressure test results of 10 specimens: five specimens that were prepared from 50/50 bentonite–sand mixtures (i.e., specimens 50B-1 to 50B-5) and others prepared from bentonite (i.e., specimens 100B-1 to 100B-5). Grouping of the specimens in various data sets is shown in the inset of Fig. 4.

It is depicted from Fig. 4 that in case of specimens 50B-1 and 50B-2 (set 1) and specimens 50B-3, 50B-4, and 50B-5 (set 2), development of swelling pressure during the wetting process up to suction of about 2,000 kPa was insignificant, whereas with a further decrease in suction, swelling pressure was found to increase rapidly. At smaller applied suctions, swelling pressure increase was less intense. A similar behavior was also noted for specimens prepared from bentonite alone, but with higher initial water content (i.e., specimens 100B-1 and 100B-2, in data set 3).

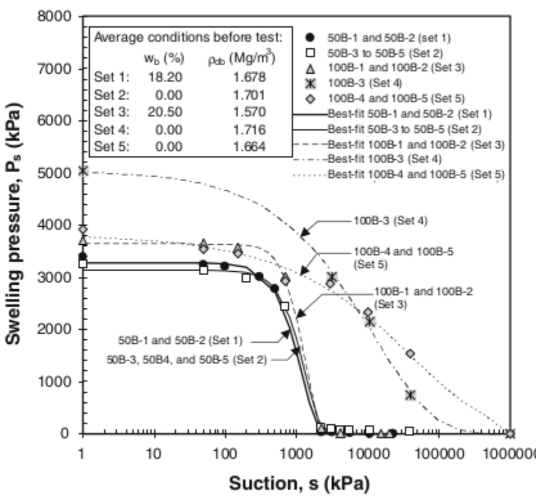

Fig. 4 Swelling pressure development with decreasing suction

Suction reduction caused development of swelling pressures for specimens 100B-3, 100B-4, and 100B-5 (sets 4 and 5) at all applied suctions considered. However, the magnitude of swelling pressure for any applied suction was somewhat different for these specimens.

Recalling that the development of swelling pressure due to gradual reduction in suction may be accompanied by three consecutive distinct phases in a suction–swelling pressure plot, zone I—a large suction decrease causing a small increase in the swelling pressure, zone II—suction reduction causing a reduction in the swelling pressure, and zone III—suction reduction causing an increase in the swelling pressure, these are specific features applicable to compacted swelling clays [22]. Lloret et al. [22] reported a decrease in swelling pressure at applied suctions between 10.0 and 40.0 MPa in case of a divalent-rich bentonite (LL = 102 %, specific surface = 725 m^2/g, dry density = 1.5 to 1.65 Mg/m^3). In their case, collapse zone (i.e., zone II) occurred between suctions 1.0 and 40.0 MPa. Although three distinct zones can also be distinguished in the test results presented in Fig. 4, in all cases a majority of the swelling pressures were found to be developed in the central zone. A reduction in the swelling pressure was not observed in this study; rather, all specimens exhibited maximum swelling pressures upon saturation with water or when the applied suction was null.

An insignificant development of swelling pressure (between about 0 and 160 kPa) up to an applied suction of 2,000 kPa occurred in case of compacted specimens of bentonite–sand mixtures irrespective of any initial compaction water content (i.e., about 9.0 % or $w_b = 18.2$ % for specimens in set 1 and 0 % for specimens in set 2) and for specimens of bentonite with higher initial water content of 20.5 % (set 3). It is hypothesized that shrinkage of specimens 50B-3, 50B-4, and 50B-5 due to oven drying was prevented by grain-shielding skeleton of the compacted bentonite–sand mixtures. In this case, only the fractions of the bentonite in the specimens underwent shrinkage and attained greater dry densities. However, this was not the case with specimens 50B-1, 50B-2, 100B-1, and 100B-2 those which were subjected to suction decrease from their as-compacted state. Komine and Ogata [19] suggested that swelling upon wetting takes place when the pores in a compacted bentonite–sand mixture are filled with swollen bentonite. This suggests that microstructural swelling was possibly compensated to a great extent due to collapse of macrostructure of these specimens, leading to development of only very small magnitudes of swelling pressure. Later, it will be shown that for these specimens, the water content increase was consistent with a decrease in suction up to an applied suction of 2,000 kPa, indicating that inefficiency of the VET to apply desired suctions may not be solely held responsible for insignificant increase in the swelling pressure. This behavior was not evident for the oven-dried bentonite specimens (i.e., specimens in sets 4 and 5) at large applied suctions in which case the specimens shrank due to oven drying and attained greater dry densities prior to the swelling pressure tests. The swelling pressures exhibited by these heavily compacted bentonite specimens were primarily on account of crystalline swelling that exceeded the collapse of the macrostructure. The development of swelling pressure for all specimens in the central zone (Fig. 4) is attributed to the microstructural swelling of compacted bentonite. An increase in the swelling pressure in the secondary swelling phase was found to be insignificant.

5.2 Constant-volume wetting behavior

Figure 5a and b shows the applied suction versus water content and applied suction versus degree of saturation data for the ten specimens grouped under five sets (i.e., sets 1–5) for which the swelling test results are shown in Fig. 4. Figure 5a and b clearly shows that irrespective of specimen type (50/50 bentonite–sand mixture or 100 % bentonite), the water content and the degree of saturation of the specimens increased with a decrease in the applied suction. The water content of 50/50 bentonite–sand mixture specimens was found to be distinctly lower than that of the specimens prepared from bentonite alone. At any given suction, the difference in the water content between compacted specimens of bentonite and bentonite–sand mixtures is on account of the presence of sand in the latter.

Compacted specimens of the bentonite which were subjected to suction reduction from the oven-dried conditions (sets 4 and 5) showed a rapid increase in the water content, whereas the water content increase was less intense for 50/50 bentonite–sand mixture specimens that had higher initial water content (i.e., sets 1 and 3) and that were oven-dried prior to the tests (i.e., specimens in set 2). The combined influence of dry density and initial water content was manifested on the water uptake by the compacted bentonite specimens. In this case, specimens with higher dry densities absorbed less water and exhibited greater swelling pressures (sets 3, 4, and 5) (see Figs. 4, 5a).

The influence of dry density on the development of swelling pressure was found to be distinct only at small applied suctions. Consider data sets 4 and 5 that had the same bentonite content and w_b before the swelling pressure tests (see Table 2), but had different ρ_{db}. Figure 5a indicates that the suction–water content curves of both data sets remained similar up to a suction of about 10,000 kPa, whereas the curves diverged at lower applied suctions, indicating the significant effects of dry density on the wetting behavior of the specimens at low suctions.

Figure 5b suggests that the applied suction–degree of saturation curves have similar shape for specimens with the

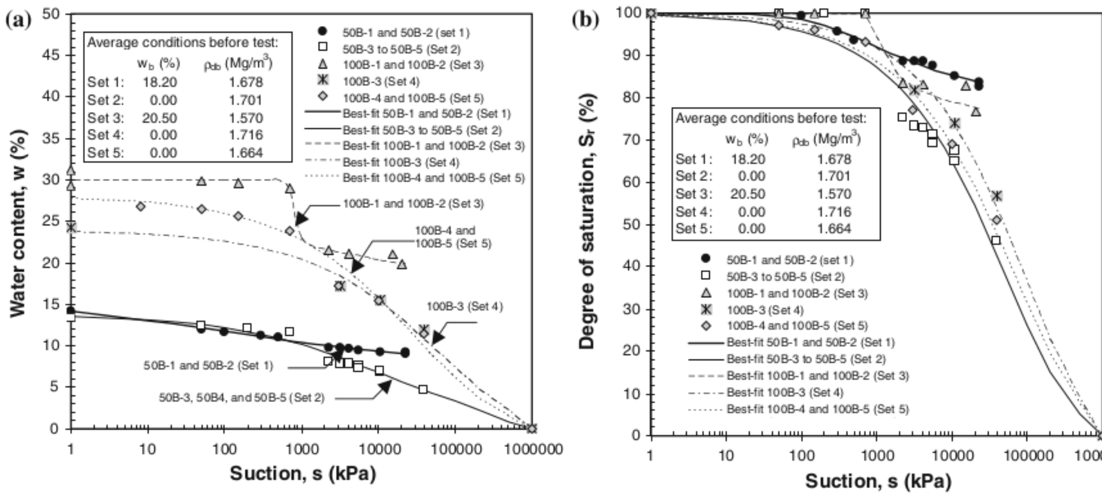

Fig. 5 Constant-volume wetting behavior: **a** suction versus water content and **b** suction versus degree of saturation plots

same initial w_b. For a given suction reduction, an increase in the degree of saturation was found to be influenced by the volume of air-filled pores available in the specimens or the initial degree of saturation of the specimens. A greater increase in the degree of saturation occurred for specimens with larger volume of air-filled pores or smaller degree of saturations as compared to the specimens with a smaller volume of air-filled pores or greater degree of saturation.

5.3 Swelling pressure increment ratio

In order to examine the relationship between initial suction and saturated swelling pressure for 50/50 bentonite–sand mixture specimens, the test results for specimens 50B-1, 50B-3, and 50B-6 to 50B-8 are plotted on a semi-logarithmic plot in Fig. 6. Note that these specimens were saturated with water for determining their saturated swelling pressures.

Figure 6 shows that a similarity between initial suction and saturated swelling pressure may not be tenable for a large range of initial suction. The trend line drawn in Fig. 6 to express the relationship between swelling pressure and initial suction of the specimens is found to be merged with the line of equality below a suction of about 200 kPa. This indicates that below this value of suction (i.e., the threshold suction), a reduction in suction induces an increase in the swelling pressure of the same magnitude. In other words, the swelling pressures were smaller than the initial suctions for specimens with initial suctions greater than about 200 kPa.

In a more general case, the ratio of swelling pressure increment (ΔP_s) and suction reduction (Δs) is formulated in the following equation and is termed herein as the swelling pressure increment ratio (α_p):

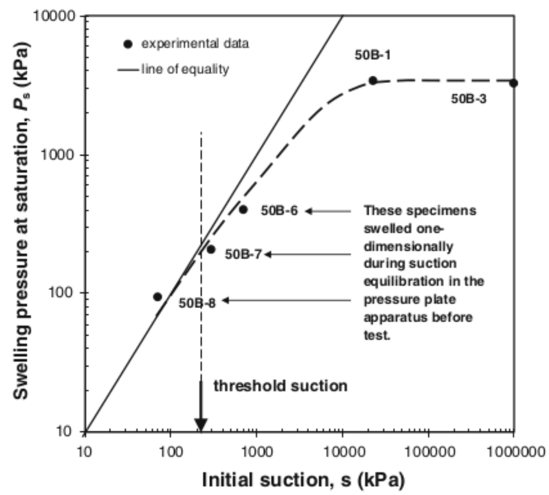

Fig. 6 Swelling pressure versus initial suction for the as-prepared specimens

$$\alpha_p = \frac{\Delta P_s}{\Delta s}. \quad (2)$$

The computed α_p values are shown in Fig. 7 as a function of average (logarithmic) suction. The threshold suction as indicated in the Fig. 7 is defined as an average suction below which the α_p value is equal to unity.

If swelling pressure is regarded as the net stress, a further decrease in suction below the threshold suction will be accompanied by an increase in the net stress of the same magnitude. This fact is in favor of the effective stress concept for unsaturated soils that incorporate suction in their formulation. However, since the specimens below the

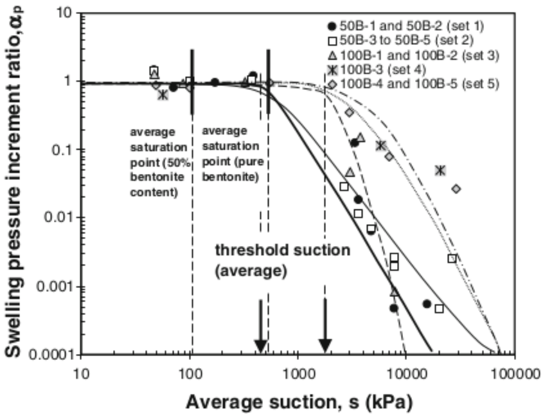

Fig. 7 Swelling pressure increment ratio for all specimens tested in this study

threshold suction were essentially saturated, the incorporation of suction in the effective stress formulation, in this case, is only possible at very high degrees of saturation. In the formulation of effective stress for unsaturated soils, the net stress is summed with suction, resulting in a single-valued effective stress which is considered to be the stress state governing the behavior of unsaturated soils. The effective stress concept incorporating suction in the formulation has been used to describe the behavior of expansive soils at microscopic level [12]. The behavior of expansive soils at microscopic level gets reflected on the behavior of saturated soil since microstructures (i.e., the clay clusters) are considered to be always saturated even at high suctions.

The value of threshold suction for the heavily compacted 50/50 bentonite–sand mixture specimens (i.e., data sets 1 and 2) was found to be about 320 kPa (Fig. 7), regardless of the initial water content and suction of the specimens prior to the tests, which is in a good agreement with the threshold suction determined from Fig. 6. For the heavily compacted bentonite specimens (i.e., data sets 3–5), the threshold suction was found to be about 1,800 kPa (Fig. 7). Based on these results, it is concluded that the magnitude of threshold suction appears to be a function of bentonite content. The average suctions corresponding to full saturation conditions for 50/50 bentonite–sand mixture specimens and those for the 100 % bentonite specimens were found to be about 100 and 520 kPa, respectively (see Fig. 7).

6 Conclusions

Results of an experimental study to establish a relationship between swelling pressure and initial suction for a heavily compacted bentonite–sand mixture and heavily compacted bentonite specimens are presented. Suction-controlled constant-volume swelling pressure tests were carried out on several compacted specimens using both axis-translation and vapor equilibrium techniques. The test results revealed that suction decrease did not contribute to a reduction in the swelling pressure to indicate a collapse of macrostructure of the specimens tested. The maximum swelling pressure of the specimens tested occurred at zero-equilibrium suction and was found to be a function of bentonite dry density. Test results for specimens with same bentonite content and bentonite water content but with different bentonite dry densities indicated that at large applied suctions, the influence of dry density on swelling pressure and water content was insignificant, whereas the effect of higher density at smaller suctions was to produce greater swelling pressure. The development of swelling pressure with decreasing suction for the specimens showed threshold suctions below which a further reduction in suction yields an increase in swelling pressure of the same magnitude. The magnitude of threshold suction was found to be a function of bentonite content in compacted specimens.

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