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THE AXIS-TRANSLATION AND OSMOTIC TECHNIQUES IN SHEAR TESTING OF UNSATURATED SOILS: A COMPARISON

CHARLES W. W. NG[i], YUJUN CUI[ii], RUI CHEN[iii] and PIERRE DELAGE[iv]

ABSTRACT

Matric suction in the laboratory testing of an unsaturated specimen is usually controlled by the axis-translation technique or the osmotic technique. To investigate possible differences in the axis-translation and osmotic techniques in shear testing of unsaturated soils, three series of unsaturated triaxial shear tests were conducted on a compacted expansive clay with an initial degree of saturation of 82%. Two of these series were performed using the axis-translation and osmotic techniques at HKUST. Another series was performed using the osmotic technique at ENPC. In the series using the axis-translation technique, the single-stage testing procedure was compared with the multi-stage testing procedure and these two testing methods were found to provide consistent shear strength information. The consistency of the results from the osmotic technique at HKUST and ENPC demonstrated the reliability of the osmotic technique. Based on the extended Mohr-Coulomb shear strength formulation, comparison of the results using the axis-translation technique and the osmotic technique showed that there was no difference in determining the internal friction angle, ϕ'. However, the values of ϕ^b in the test series using the axis-translation technique were slightly larger than those in the test series using the osmotic technique by 3°–4°.

Key words: axis-translation technique, expansive soil, high degree of saturation, osmotic technique, shear strength (**IGC**: D6)

INTRODUCTION

Suction plays a significant role in unsaturated soils. To study unsaturated soil behavior in laboratory and field tests, suction control or suction measurement is an essential issue. Generally, suction in unsaturated soils can be divided into matric suction and osmotic suction. Matric suction, (u_a-u_w), is defined as the difference between pore air pressure, u_a, and pore water pressure, u_w. The effect of matric suction on unsaturated soil behavior is of greatest concern. Therefore, hereafter, the term ''suction'' is simply taken to mean matric suction. The axis-translation technique (Hilf, 1956) and the osmotic technique (Zur, 1966) are generally used to control suction in laboratory testing of unsaturated soils.

Hilf (1956) introduced the axis-translation technique of elevating the pore air pressure, u_a, to increase the pore water pressure, u_w, to be positive, preventing cavitations in water drainage systems. The total stress, σ, is increased with the air pressure by the same amount to maintain net stress $(\sigma-u_a)$ unchanged. Subsequently, this method has been widely used to measure or control matric suction in unsaturated soil testing. The majority of experimental results about unsaturated soils have been obtained by the application of the axis-translation technique. The validity of the axis-translation technique is based on an assumption of two independent stress state variables (i.e. net stress $(\sigma-u_a)$ and matric suction (u_a-u_w)) for unsaturated soils (Coleman, 1962; Fredlund and Morgenstern, 1977). As far as the authors are aware, only limited experimental evidence is available in the literature to support this validity. Bishop and Blight (1963) investigated the effect of the axis-translation technique on measured shear strength by conducting unconfined triaxial compression tests on compacted Selset clay and compacted Talybont clay. They found that the measured shear strength was not affected by the application of the axis-translation technique. However, the authors did not provide complete information about the specimen characteristics, especially the degree of saturation, which is regarded as an indicator of the continuity of the air phase in unsaturated soils. Therefore, consideration should be given to the state of the air phase in unsaturated soils when using these experiments to verify the axis-translation technique. The null tests by Fredlund and Morgenstern (1977) confirmed the validity of the axis-translation

i) Professor, Dept. of Civil Engineering, Hong Kong Univ. of Science and Technology, Clear Water Bay, Kowloon, Hong Kong (cecwwng@ust.hk).
ii) Professor, Ecole Nationale des Ponts et Chaussees, CERMES, France.
iii) PhD student, Dept. of Civil Engineering, Hong Kong Univ. of Science and Technology, Hong Kong.
iv) Professor, Ecole Nationale des Ponts et Chaussees, CERMES, France.
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technique at a high degree of saturation (ranging from 0.833 to 0.95 with one exception of 0.759), when air phase is believed to be occluded (Juca and Frydman, 1996). The null tests by Tarantino and Mongiovi (2000a) verified the axis-translation technique for the case when the air phase is continuous. The analysis by Bocking and Fredlund (1980), however, suggested that the axis-translation technique is no longer valid when the air phase in an unsaturated soil is occluded. Thus, the validity of the axis-translation technique is controversial for the case when the air phase is occluded. Furthermore, since cavitation of pore water is hindered in the axis-translation technique, elevation of pore air pressure may alter the desaturation mechanism of soils (Dineen and Burland, 1995). It is thus essential to understand whether experimental results obtained from the axis-translation technique can be extrapolated to interpret behaviour of unsaturated soils under atmospheric conditions in the field.

An alternative suction control method is the osmotic technique. Delage et al. (1998) reported that this technique was initially developed by biologists (Lagerwerff et al., 1961) and then adopted by soil scientists (Zur, 1966). In geotechnical testing, this technique was successfully adapted in an oedometer (Kassif and Ben Shalom, 1971; Delage et al., 1992; Dineen and Burland, 1995), a hollow cylinder triaxial apparatus (Komornik et al., 1980) and a standard triaxial apparatus (Delage et al., 1987; Cui and Delage, 1996).

The phenomenon of osmosis is observed whenever a solvent and a solution are separated by a semi-permeable membrane, which only allows diffusion of solvent molecules (i.e., water molecules in this case). In the osmotic technique, suction control in a soil specimen is based on the principle of osmosis. The soil specimen is placed on a cellulotic semi-permeable membrane. Beneath the membrane, a solution is circulated. The membrane is permeable to water and ions in the soil but impermeable to large solute molecules and soil particles (Zur, 1966). This results in a difference in solute concentration between the specimen and the solution, leading to a difference in osmotic potential across the membrane. Osmotic potential of the solution causes drainage of the soil specimen and the potential is finally balanced by the negative pore water pressure in the specimen. According to Zur (1966), an analysis of water energy on both sides of a membrane can prove that matric suction in a soil specimen is equal to osmotic pressure (osmotic potential) of the solution in equilibrium. When the osmotic pressure of the solution is greater than the suction in the specimen, water is drawn from the soil into the solution, increasing the suction in the specimen to achieve equilibrium.

To produce a solution for soil testing, polyethylene glycol (PEG) is the most commonly used solute because of its safety and simplicity. The value of osmotic pressure depends on the concentration of the solution: the higher the concentration, the higher the osmotic pressure. The maximum value of osmotic pressure for a PEG solution was reported to be above 10 MPa (Delage et al., 1998). Since the air pressure around a soil specimen remains atmospheric, field stress path is better simulated by using the osmotic technique.

Since the applied matric suction in the osmotic technique is equal to the osmotic pressure of a PEG solution, calibration between the osmotic pressure and the concentration of the PEG solution is essential. However, the relationship between the osmotic pressure and the concentration of the PEG solution has been found to be significantly affected by the calibration method (Dineen and Burland, 1995; Slatter et al., 2000). Thus, Dineen and Burland (1995) suggested the necessity for direct measurement of the negative pore water pressure in soil specimens when using the osmotic technique. Furthermore, an evaluation of the performance of three different semi-permeable membranes by Tarantino and Mongiovi (2000b) indicated that all membranes experienced a chemical breakdown when the osmotic pressure of PEG solution exceeded a threshold value, which was found to depend on the type of membrane. Beyond this value, solute molecules were no longer retained by the semi-permeable membrane and passed into the soil specimen, with a reduction of the concentration gradient and a resulting decay in the soil suction.

If unsaturated soil behavior is governed by two independent stress variables, i.e., net normal stress $(\sigma - u_a)$ and suction $(u_a - u_w)$, not by component stresses, there should be no difference in the test results obtained from the axis-translation and osmotic techniques under the same applied net stress and suction. However, there has been sparse experimental comparison of these two techniques especially in terms of shear testing. Zur (1966) found that for a sandy loam, the gravimetric soil water characteristic curve (SWCC) obtained by using these two techniques showed a good agreement, although for a clay, the equilibrium water content obtained when using the axis-translation technique was higher than that obtained when using the osmotic technique under the same applied nominal suction. Zur related this observed difference to the test duration, suggesting that duration of two days was not sufficient for suction equilibrium in the axis-translation technique. When the test duration for the suction equilibrium was extended to three days, a better agreement was achieved. However, Williams and Shaykewich (1969) found that even when the suction equilibrium duration was extended to more than 10 days in the axis-translation technique, the equilibrium water content obtained by using the axis-translation technique was still slightly higher than that obtained by using the osmotic technique for a clay. As far as the authors of this paper were aware, the comparison between these two techniques in terms of shear testing had not been investigated, despite the importance of shear strength in engineering practice. It is therefore necessary to investigate any differences in the axis-translation and osmotic techniques in shear testing of unsaturated soils.

To investigate the difference in the axis-translation and osmotic techniques in shear testing of unsaturated soils, a collaborative research project was conducted at the Hong

Kong University of Science and Technology (HKUST) and Ecole Nationale des Ponts et Chaussees, Paris (ENPC). In this project, three series of unsaturated triaxial shear tests were conducted on a compacted expansive soil with an initial degree of saturation of 82%. Two of these series were performed using the axis-translation technique and the osmotic technique at HKUST. Another series was performed using the osmotic technique at ENPC and the results were firstly presented by Mao et al. (2002). In the series using the axis-translation technique, the single-stage testing procedure and the multi-stage testing procedure were compared to investigate the influence of these two testing methods on shear testing for unsaturated soils. The multi-stage testing procedure used by Kenney and Watson (1961) for saturated soils were adopted to maximize shear strength information from one specimen at a constant suction. In addition, this testing procedure assisted in eliminating the effect of soil variability between specimens. In both series using the osmotic technique at HKUST and ENPC, test results were compared to study the reliability of the osmotic technique. The test results using the axis-translation technique and the osmotic technique were compared in an attempt to identify any differences in the axis-translation and osmotic techniques in shear testing of expansive soils at high degrees of saturation.

TESTING EQUIPMENT

At HKUST, two different testing systems with the application of the axis-translation technique and the osmotic technique were used to conduct triaxial shear tests on the unsaturated expansive soil (Ng and Menzies, 2007).

In the system using the axis-translation technique, a triaxial apparatus equipped with two water pressure controllers and two pneumatic controllers was used. Suction was applied to a specimen through one water pressure controller and one air pressure controller. Pore water pressure was applied at the base of the specimen through a ceramic disc with an air entry value of 500 kPa. Pore air pressure was applied at the top of the specimen through a sintered copper filter. A double-cell measurement system was used to measure the total volume change of the specimen. The working principle of the measuring system is to record changes in differential pressure between a reference pressure and pressure inside an inner cell due to changes in water level caused by volume change in the specimen using an accurate differential pressure transducer. Details of this testing system are described by Ng et al. (2002).

The system using the osmotic technique at HKUST is similar to that used at ENPC except that there was no direct measurement of total volume changes during testing on the specimens at HKUST. However, dimensions of the specimens tested at HKUST were measured after shearing and then volume changes were back-calculated. In the application of the osmotic technique, suction was applied to a specimen through two pieces of semi-permeable membrane, which were kept in contact with the top and bottom surfaces of the specimen. Details of the triaxial testing system using the osmotic technique are described by Cui and Delage (1996).

The osmotic technique in this study employed Spectra/Por® 2 Regenerated Cellulose dialysis membranes with a value of 12 000-14 000 Daltons MWCO (Molecular Weight Cut Off). The corresponding PEG had a value of 20 000 Daltons molecular weight.

CALIBRATION OF THE PEG SOLUTION

Calibration of the PEG solution can be carried out with a psychrometer (Williams and Shaykewich, 1969), an osmotic tensiometer (Peck and Rabbidge, 1969), an Imperial College (IC) suction probe (Dineen and Burland, 1995) or an osmotic pressure cell (Slatter et al., 2000). All these methods employ a semi-permeable membrane except the method using the psychrometer.

In the method using the psychrometer, the relative humidity of the air space above the PEG solution is measured (Williams and Shaykewich, 1969) and then the osmotic pressure, π, is determined from the Kelvin's law as follows:

$$\pi = \frac{RT}{Mg} \ln \frac{P}{P_o} \tag{1}$$

where R is the constant of perfect gases; T is the absolute temperature; M is the molar mass of water; g is the gravity acceleration; P/P_o is the relative humidity, equal to the partial water vapor pressure, P, divided by the saturated water vapor pressure, P_o. This method requires a strictly controlled constant temperature environment. To achieve an accuracy of 10 kPa, the constant temperature must be maintained within ± 0.001°C (Krahn and Fredlund, 1972).

Delage et al. (1998) summarized calibration results from Williams and Shaykewich (1969) using a psychrometer and found that these results fit the following parabolic relation:

$$\pi = 11000C^2 \tag{2}$$

where the osmotic pressure, π, is calibrated by a psychrometer, expressed in kPa; and C is the concentration of the PEG solution (g PEG/g water). The fitted results are shown in Fig. 1. It can be seen that Eq. (2), proposed by Delage et al. (1998), fits the data calibrated by using a psychrometer. Delage et al. also concluded that this equation does not depend on the nature of the PEG (i.e., different molecular weights).

The results calibrated by using an IC suction probe (Dineen and Burland, 1995) are also included in Fig. 1. In this method, a semi-permeable membrane is placed between the probe and the PEG solution and then a negative pressure is measured by the probe, which should be equal to the osmotic pressure of the PEG solution across the membrane. As shown in Fig. 1, the osmotic pressure calibrated by using the IC suction probe is significantly lower than that calibrated by using a psychrometer. This observation suggests that the relationship between the os-

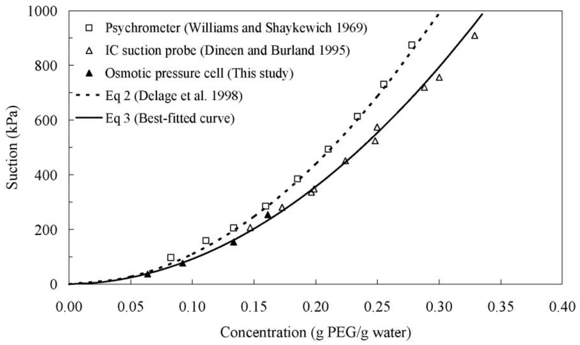

Fig. 1. Calibration results for PEG solution

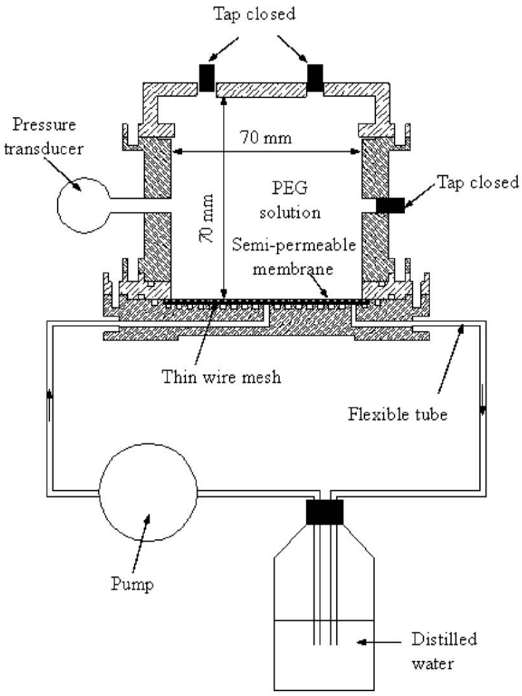

Fig. 2. Schematic diagram showing the calibration of a PEG solution in an osmotic pressure cell

motic pressure and the concentration of the PEG solution is significantly affected by the calibration method.

In this study, an osmotic pressure cell for calibration of the PEG solution was developed at HKUST as shown schematically in Fig. 2. This cell is similar to that used by Slatter et al. (2000) and includes a cylindrical chamber made of stainless steel for maintaining a constant volume of the PEG solution. During calibration, this chamber is filled with the PEG solution. A semi-permeable membrane is placed at the bottom of the chamber and supported by a thin wire mesh. Below this mesh, distilled water is circulated by a peristaltic pump. The PEG solution in the chamber has the potential to draw water through the semi-permeable membrane and then the solution pressure in the chamber, which is monitored by a pore pressure transducer with an accuracy of 2.5 kPa, will increase due to the volume restraint imposed by the stainless steel housing. Eventually, an equilibrium solu-

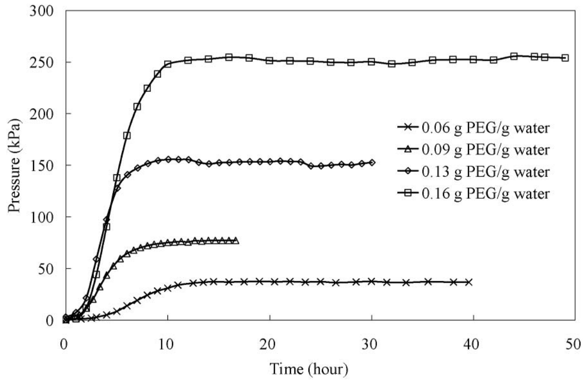

Fig. 3. Response of the pressure transducer during calibration of a PEG solution at different concentrations

tion pressure is reached and it should be equal to the osmotic pressure of the PEG solution across the membrane (Slatter et al., 2000). The calibration of the PEG solution was performed under a room temperature of 20 ± 1°C.

The response of the pressure transducer during calibration is illustrated in Fig. 3 for the PEG solutions at different concentrations. It can be seen that the recorded pressure firstly increases rapidly and then reaches a steady value. This steady value of pressure should be equal to the osmotic pressure across the semi-permeable membrane, which is governed by the concentration of the PEG solution in the chamber. In the triaxial tests using the osmotic technique in this study, the maximum applied suction value (i.e., 165 kPa) was lower than the maximum calibrated value (i.e., 254 kPa).

The results calibrated by using the osmotic pressure cell in this study are also included in Fig. 1. It can be seen that the osmotic pressure calibrated by using the osmotic pressure cell is consistent with that calibrated by using the IC suction probe. Furthermore, they are both lower than the osmotic pressure calibrated by using the psychrometer, similar to the findings of Slatter et al. (2000). The calibrated results involving a semi-permeable membrane (i.e., the calibration results in this study and those of Dineen and Burland, 1995) may be described as follows:

$$\pi = 8632C^2 + 58C \tag{3}$$

It is believed that the main difference between Eq. (2) and Eq. (3) rises from the absence of a semi-permeable membrane when using a psychrometer in the calibration. Since the osmotic technique involves semi-permeable membranes, Eq. (3) is more reasonable than Eq. (2) in determining the applied suction value in the tests using the osmotic technique. Regarding the accuracy of measurement, to achieve an accuracy of 10 kPa for psychrometer, a constant temperature must be maintained within ±0.001°C (Krahn and Fredlund, 1972). Although Williams and Shaykewich (1969) did not present the accuracy of controlled temperature, the accuracy of measurement by psychrometer is believed to be in the order of 10 kPa, which is larger than that (i.e. 2.5 kPa) of the pressure transducer in the osmotic pressure cell. Therefore, Eq. (3)

should be adopted to determine the applied suction value in the triaxial tests using the osmotic technique at HKUST. For the triaxial tests at ENPC, Mao et al. (2002) firstly adopted Eq. (2) to determine the applied suction value. In this study, Eq. (3) was adopted to reinterpret the applied suction value of the triaxial tests using the osmotic technique at ENPC.

TESTING MATERIAL AND SPECIMEN PREPARATION

An expansive soil from Zaoyang, about 400 km far from Wuhan, China, was used in this study. It is composed of 49% clay, 44% silt and 7% sand. It has a liquid limit of 68% and a plastic limit of 29%. The clay fraction is 60% kaolinite, 20–30% montmorillonite and 10–20% illite. According to the USCS classification, the soil can be described as a clay with high plasticity (Wang, 2000).

A drying SWCC of this expansive clay is shown in Fig. 4, which was obtained from four identical specimens under zero vertical stress in a volumetric pressure plate extractor (Wang, 2000). The details about these specimens can be found in Table 1. As shown with a solid line in Fig. 4, the equation of Fredlund and Xing (1994) is used to fit the measured data. The air entry value is obtained by extending the constant slope portion of the curve to intersect with the suction axis at the saturated state. The corresponding value of suction is taken as the air entry suction value of this soil. This estimated air entry value is 60 kPa. The gentle gradient of the SWCC implies a high water storage potential of this expansive soil, which means that this soil can maintain a high degree of saturation within a large range of suction.

Based on consolidation curve measured from oedometer tests at zero suction, Mao et al. (2002) deduced that saturated water permeability of the expansive clay was a function of void ratio. They reported that the deduced saturated water permeability of the clay increased from 1.0×10^{-10} m/s to 1.8×10^{-8} m/s as void ratio increased from 0.61 to 0.93.

For the triaxial tests, the soil was first dried in an oven at a temperature of about 40°C to 50°C, then ground in a mortar with a pestle and passed through a 2 mm sieve. Deaired water was carefully sprayed layer by layer to reach a final water content of 30.3%. After keeping the soil-water mixture in a sealed plastic bag for moisture equalization for 24 hours, the soil was statically compacted in a cylindrical mould of 38 mm in diameter and 76 mm in height. Compaction was performed at a rate of 0.2

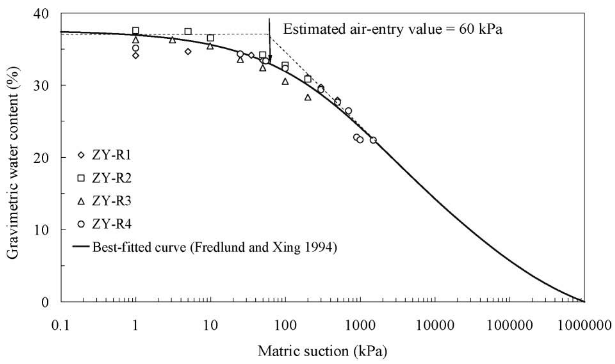

Fig. 4. SWCC of compacted expansive clay

Table 1. Initial characteristics of the specimens for SWCC tests (after Wang, 2000)

Specimen	Dry density (kg/m³)	Water content (%)	Specific volume	Degree of saturation (%)
ZY-R1	1372	31.0	1.99	85.4
ZY-R2	1373	30.3	1.99	83.7
ZY-R3	1372	30.5	1.99	84.1
ZY-R4	1369	31.0	1.99	85.2

Table 2. Conditions for the test series using the axis-translation technique at HKUST

ID[a]	Initial state		Suction equalization				Consolidation			Shearing		
	v	w (%)	(u_a-u_w) (kPa)	T (day)	v	w (%)	(σ_3-u_a) (kPa)	v	w (%)	Rate (10^{-5}%/s)	v	w (%)
							25	2.00	30.0		NA	NA
AM1	2.00	30.3	50	NA	2.01	30.5	50	NA	NA	3.07	NA	NA
							100	NA	NA		1.85	28.3
							25	1.97	28.5		NA	NA
AM2	2.01	30.4	100	NA	1.99	28.9	50	NA	NA	3.07	NA	NA
							100	NA	NA		1.82	26.8
AS1	2.03	29.3	50	4	2.03	29.5	100	1.95	28.8		1.84	28.0
AS2	2.02	29.6	100	8	2.00	28.5	50	1.95	27.2		1.84	27.8
AS3	2.00	29.2	100	9	1.98	28.4	100	1.90	27.4	3.07	1.80	26.1
AS4	2.00	29.7	0	6	2.02	37.2	50	1.97	35.7		1.87	31.6
AS5	2.01	29.9	0	6	2.02	37.5	100	1.91	33.2		1.82	30.0

Notes: [a]A = axis-translation, S = single-stage, M = multi-stage; NA = not available.

Table 3. Conditions for the test series using the osmotic technique at HKUST and ENPC

ID[b]	Initial state		Suction equalization				Consolidation			Shearing		
	v	w (%)	(u_a-u_w) (kPa)	T (day)	v	w (%)	(σ_3-u_a) (kPa)	v	w (%)	Rate (10^{-5}%/s)	v	w (%)
OH1	2.01	30.1	43	5	NA	30.2	50	NA	30.0		1.95	29.4
OH2	2.03	30.1	43	6	NA	30.3	100	NA	29.5		1.89	28.6
OH3	1.96	30.5	84	7	NA	29.7	25	NA	29.6	3.07	1.94	29.1
OH4	1.98	30.5	84	7	NA	29.5	100	NA	28.5		1.88	27.8
OH5	2.01	30.1	165	8	NA	27.0	100	NA	26.4		1.86	25.0
OE1	1.99	29.4	0	1	2.05	31.4	50	2.01	NA		1.98	30.7
OE2	2.01	29.6	0	1	2.09	33.9	100	1.95	NA		1.93	30.1
OE3	2.00	29.4	84	6	2.01	29.3	100	1.96	NA	4.39	1.88	28.1
OE4	1.96	27.5	165	10	1.98	28.8	25	1.96	NA		1.93	28.3
OE5	2.04	26.6	165	11	2.05	26.1	50	2.02	NA		1.99	25.4

Notes: [b]O = osmotic, H = HKUST, E = ENPC; NA = not available.

mm/min in three layers to ensure good homogeneity (Cui and Delage, 1996). The final dry density was about 1360 kg/m^3. The soil suction after compaction was measured by a tensiometer on a specimen, showing an initial suction of 62 kPa. The initial characteristics of the specimens are presented in Tables 2 and 3 for the triaxial tests using the axis-translation technique and the osmotic technique, respectively.

TESTING PROGRAM

All the triaxial tests were consolidated drained shear tests. The test series using the axis-translation technique included five single-stage tests and two multi-stage tests (*see* Table 2). In the specimen identification used in Table 2, ''A'' indicates the axis-translation technique, ''S'' indicates the single-stage test and ''M'' indicates the multi-stage test. The applied suction ranged from 0 to 100 kPa and the net confining pressure varied from 25 to 100 kPa. Both series using the osmotic technique were single-stage tests and the testing conditions are presented in Table 3. In the specimen identification used in Table 3, ''O'' indicates the osmotic technique, ''H'' indicates the tests performed at HKUST and ''E'' indicates the tests performed at ENPC. The applied suction ranged from 0 to 165 kPa and the net confining pressure varied from 25 to 100 kPa.

TESTING PROCEDURES

In the test series using the axis-translation technique, a specimen was firstly equalized at a desired suction under a mean net stress of 10 kPa. Suction equalization was terminated when the variation in water content was within 0.05%/day. The duration for this suction equilibrium procedure ranged from 4 to 9 days while the applied suction varied from 0 to 100 kPa (Table 2). Thereafter, the specimen was subjected to isotropic consolidation under constant suction. This stage of the consolidation was terminated when the rate of change in water content was less than 0.05%/day. This stage lasted from 3 to 9 days while the net confining pressure ranged from 25 to 100 kPa. After consolidation, the specimen was sheared at a constant rate under a constant net confining pressure and suction. Two types of shearing procedures, i.e. single-stage shearing and multi-stage shearing, were carried out. In the single-stage shearing procedure, the specimen was sheared directly to failure after the initial consolidation. The multi-stage shearing procedure consisted of three stages. The net confining pressure was varied from one stage to another while the suction remained constant. In each stage of the multi-stage shearing procedure, each shearing commenced from a condition of zero deviator stress, which is called the cyclic loading procedure (Ho and Fredlund, 1982). To ensure that the tests were under drained conditions, shearing was performed at a constant rate of 3.07×10^{-5}%/s. This rate was lower than the shearing rate of 4.39×10^{-5}%/s used at ENPC (Mao et al., 2002), considering that a longer drainage path (i.e., single drainage) was used in the application of the axis-translation technique. For the single-stage shearing, the duration was about eight days and for multi-stage shearing, the duration was about 16 days.

In the series using the osmotic technique at HKUST, suction was equalized by water interchange between the specimen and the PEG solution with a desired concentration under a mean net stress of 10 kPa. After suction equalization, the specimen was consolidated under a constant net confining pressure. The criteria to terminate the suction equalization and consolidation were the same as those adopted in the series using the axis-translation technique. The duration for suction equilibrium ranged from 5 to 11 days in a suction range from 0 to 165 kPa, whereas the duration for consolidation ranged from 3 to 7 days as the net confining pressure varied from 25 to 100 kPa (Table 3). When the consolidation stage was completed, the specimen was sheared to failure at a constant rate of 3.07×10^{-5}%/s under constant net confining pressure and suction. The shearing rate was the same as the one adopted in the tests using the axis-translation technique but it was slower than that adopted in the series using the osmotic technique in ENPC (Mao et al., 2002). In the application of the osmotic technique, the pore air pressure was maintained at atmospheric pressure during the entire triaxial testing. To ensure performance of the semi-permeable membrane, inspection of the membrane was carried out before and after the test following the method described by Tarantino and Mongiovi (2000a). In the inspection, the semi-permeable membranes were firstly clamped on the top cap and the base in the triaxial apparatus, and then a negative water pressure was applied below the membranes. Therefore, possible cracks in the membrane during clamping could be detected by ingress of air through the membranes. All the triaxial tests at HKUST were performed under a temperature of 20 ± 1°C.

In the test series using the osmotic technique at ENPC, the specimens were first wrapped in a semi-permeable membrane and kept in a PEG solution for 5–6 days to reach desired suctions. Then they were put in a triaxial cell for three days to reach equilibrium under desired suctions and confining pressures. Shearing was performed at a constant rate of 4.39×10^{-5}%/s. Details of the test procedures were described by Mao et al. (2002).

EXPERIMENTAL RESULTS

In triaxial space, the stress state for unsaturated soils can be represented by the net major normal stress, (σ_1-u_a), the net minor normal stress, (σ_3-u_a), and the suction, (u_a-u_w), where σ_1 is the major principal stress and σ_3 is minor principal stress. In this paper, the experimental results are presented by using these stress variables.

For simplicity, the extended Mohr-Coulomb shear strength formulation (Fredlund et al., 1978) is used to interpret the shear strength, τ, of the unsaturated soils as follows:

$$\tau=c'+(\sigma-u_a)\tan\phi'+(u_a-u_w)\tan\phi^b \quad (4)$$

where c' is the effective cohesion; ϕ' is the internal friction angle with respect to changes in $(\sigma-u_a)$ when (u_a-u_w) is held constant; ϕ^b is an angle with respect to changes in (u_a-u_w) when $(\sigma-u_a)$ is held constant.

The effect of suction on the shear strength may be regarded as an increase in the apparent cohesion, i.e., $(u_a-u_w)\tan\phi^b$. Therefore, the total cohesion, c, is defined as follows (Fredlund, 1979):

$$c=c'+(u_a-u_w)\tan\phi^b \quad (5)$$

The material parameters, ϕ' and ϕ^b, can be also obtained from stress point envelope and it is more convenient to use stress point envelope to represent the stress state at failure. Therefore, the triaxial test results at failure are presented by the stress point envelope on the s_n versus t plane, where $s_n=[(1/2)(\sigma_1+\sigma_3)-u_a]$ and $t=[(\sigma_1-\sigma_3)/2]$.

Test Results from the Axis-translation Technique

Although multi-stage tests can maximize the shear strength information from one specimen, it may also be useful to verify this shearing method with a single-stage test result. Figure 5 presents the relationships between deviator stress, $(\sigma_1-\sigma_3)$, and axial strain, ε_a, during shearing for one multi-stage test (AM1) and two single-stage tests (AS2 and AS3). These three tests were performed under a suction of 100 kPa. In three stages of the multi-stage test AM1, the net confining pressures were 25 kPa, 50 kPa and 100 kPa. In the single-stage tests AS2 and AS3, the net confining pressures were 50 kPa and 100 kPa, respectively.

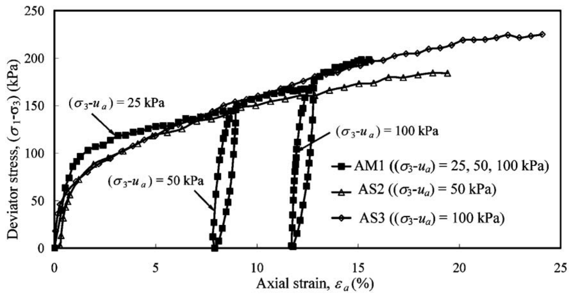

Fig. 5. Stress-strain relationships of single-stage and multi-stage tests using the axis-translation technique at 100 kPa suction

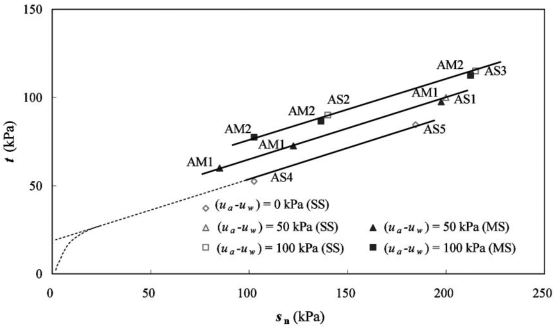

Fig. 6. Comparison of the results obtained from single-stage (SS) and multi-stage (MS) tests using the axis-translation technique

As shown in Fig. 5, the first stage of test AM1 shows a stiffer behavior than do the tests AS2 and AS3 at the start of shearing. However, the stress-strain relationship in the second stage of test AM1 is consistent with that of the single-stage test AS2, which is under the same net confining pressure of 50 kPa. The stress-strain relationship in the third stage of test AM1 is almost identical to that of the single-stage test AS3, which is under the same net confining pressure of 100 kPa. This comparison illustrates that the stress-strain relationships in a multi-stage test at different stages coincide with those of the corresponding single-stage tests, which are under the same suction and net confining pressure.

The stress points at failure are plotted in Fig. 6. This figure shows that the shear strengths obtained from the single-stage tests are consistent with those obtained from the multi-stage tests under the same suction and net confining pressure (e.g., the differences in shear strength for the specimens AS1, AS2 and AS3 are 2.6%, 4% and 2.2 %, respectively, as compared with the corresponding multi-stage tests).

In this triaxial test series, the internal friction angle, ϕ', ranges from 19.3° to 20.8° in a suction range from 0 to 100 kPa, and the average value is 20.0°. By assuming a constant friction angle of 20°, the failure envelopes for this series fit well with the test results (*see* Fig. 6). The increasing intercepts on the t axis indicate that apparent cohesion increases with suction.

At a saturated state (i.e., zero suction), there appears to be a small intercept of 19.6 kPa (corresponding to cohesion of 20.8 kPa) on the t axis when the failure envelope is extended linearly to the zero value of s_n. To demonstrate whether this apparent intercept is attributed to a true cohesion, a slaking test (GCO, 1988) was performed on a specimen just after specimen compaction. The specimen was immerged in water without applying any stress and it was observed that the specimen disintegrated completely after a few hours. This means that no true cohesion is present in the compacted specimen. Hence, the apparent intercept is likely due to experimental error at low stress range or the failure envelope is curved within the range of small stress (*see* Fig. 6).

Test Results from the Osmotic Technique

The stress points at failure from the tests using the osmotic technique are plotted in Fig. 7. Under the same net confining pressure and suction, tests OH4 and OE3 exhibit similar shear strengths as do tests OH5 and OE6. These tests indicate the consistency of the results from HKUST and ENPC, confirming the reliability of the osmotic technique. The tests at HKUST and ENPC are thus regarded as one test series using the osmotic technique hereafter.

In this test series, the internal friction angle, ϕ', ranges from 19.5° to 20.8° in a suction range from 0 to 165 kPa, and the average value is 20.2°. Again, by assuming a constant friction angle of 20°, the failure envelopes for this series fit well with the test results, as shown in Fig. 7. The increasing intercepts on the t axis indicate that apparent cohesion increases with suction. Similar to the results from using the axis-translation technique, at the saturated state, a small intercept of 19.4 kPa (corresponding to cohesion of 20.6 kPa) appears on the t axis when the failure envelope is extended linearly to the zero value of s_n. Previous analysis indicated that this apparent intercept is likely due to experimental error or the failure envelope is curved within the range of small stress (*see* Fig. 7).

Comparison of Test Results from the Axis-translation and Osmotic Techniques

Both test series using the axis-translation and osmotic techniques can be approximated by an internal friction angle of 20°. This means that there is no difference in determining the internal friction angle when using the axis-translation technique and the osmotic technique for testing this material.

In the view of the results of the slaking test, it is evident that no true cohesion is present in the compacted specimens (i.e., $c' = 0$). In order to calculate apparent cohesion due to suction (i.e., $(u_a - u_w) \tan \phi^b$) using Eq. (5), it is assumed that ''true cohesion'' is not equal to zero for mathematical convenience and so it can be obtained from an intersect on the t axis by extending the stress point failure envelope for zero suction linearly to zero value of s_n. Based on Eq. (5), apparent cohesion at a given suction is obtained by subtracting total cohesion from the true cohesion. The relation between deduced apparent cohesion and suction is shown in Fig. 8(a). For the test series using the axis-translation technique, the relation curve shows a linear increase of shear strength with suction in a suction range from 0 to 100 kPa. For the test series using the osmotic technique, a nonlinear increase of shear strength with suction is observed in a suction range from 0 to 165 kPa. In the test series using the axis-translation technique, apparent cohesion due to suction is consistently larger than that in the test series using the osmotic technique.

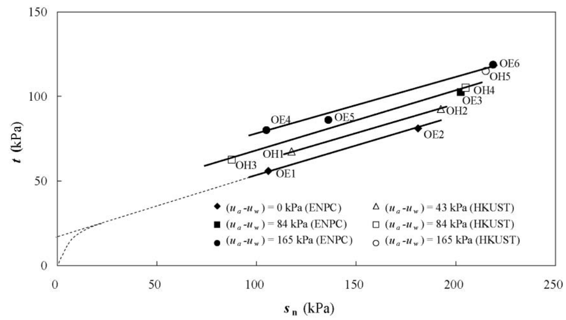

Fig. 7. Results of triaxial tests using the osmotic technique at HKUST and ENPC

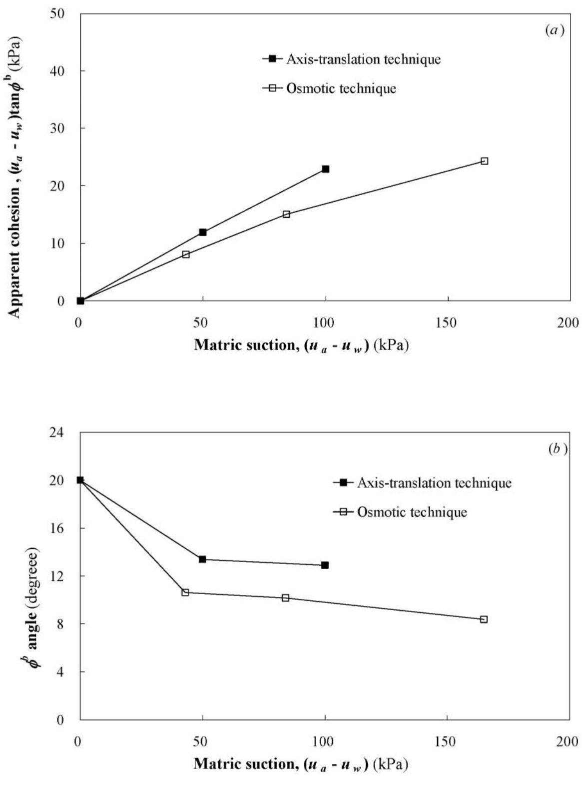

Fig. 8. Suction vs. shear strength: (a) Apparent cohesion due to suction and (b) Variation in ϕ^b angle with suction

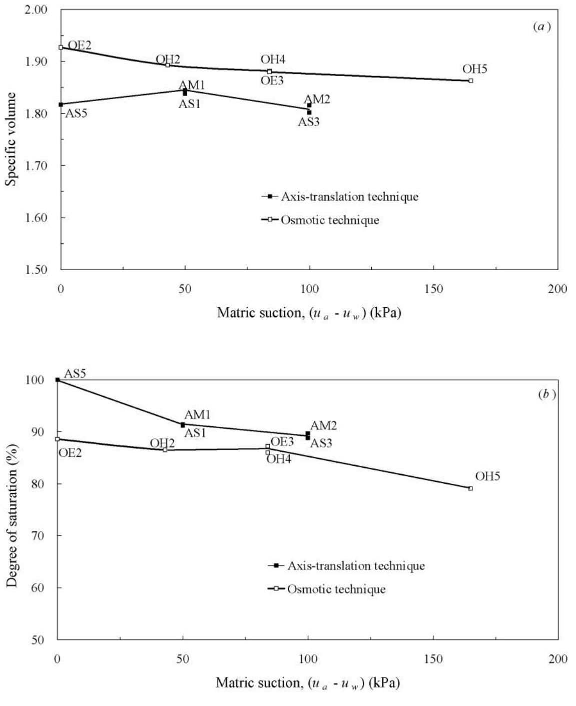

Fig. 9. (a) Specific volume and (b) Degree of saturation at failure in the tests under net confining pressure of 100 kPa

For a given suction, the value of ϕ^b is calculated from ratio of apparent cohesion to the corresponding suction using Eq. (5). For example, the value of tan ϕ^b at suction of 165 kPa using the osmotic technique is obtained by calculating the ratio of apparent cohesion at suction of 165 kPa to the controlled suction value of 165 kPa. At zero suction, ϕ^b may be assumed to be equal to the saturated friction angle, ϕ' (i.e., 20°) as suggested by Gan and Fredlund (1996). It is well recognized that ϕ^b is not a constant (Fredlund et al., 1987) and it is evident that ϕ^b decreases with an increase in suction, as shown in Fig. 8(b). In the test series using the axis-translation technique, ϕ^b is slightly larger than that in the test series using the osmotic technique by 3°–4° when the suction is greater than zero. The larger ϕ^b shows that the tests using the axis-translation technique exhibit a larger suction effect on the shear strength as compared with those using the osmotic technique.

Figure 9(a) shows the specific volume at failure in each test under net confining pressure of 100 kPa. For a given suction, it is observed that the specimens in the test series using the axis-translation technique have lower specific volumes at failure than those tested using the osmotic technique. It is well-understood that a lower specific volume of a saturated soil specimen may result in higher shear strength. On the other hand, however, this may or may not be the case for unsaturated soils.

Figure 9(b) shows the corresponding degree of saturation at failure in the tests under net confining pressure of 100 kPa. The degree of saturation at failure in each test was deduced from measured specific volume and water content at failure (Tables 2 and 3). For a given suction, it can be seen from the figure that the degree of saturation in the specimens tested using the axis-translation technique is higher than that tested using the osmotic technique. According to Wheeler et al. (2003), soil water in voids of an unsaturated soil may be idealized as bulk water within water-filled voids and meniscus water at the inter-particle contacts around air-filled voids of the soil. A soil specimen at a higher degree of saturation will have a larger number of voids filled with bulk water and a smaller number of voids affected by meniscus water than an equivalent specimen at a lower degree of saturation. As a consequence, even if the values of two independent stress state variables (i.e., net stress and suction) and specific volume were the same for the two specimens, they would be expected to show different mechanical behavior, because the inter-particle contact forces transmitted through the soil skeleton would be different in the two cases. Based on the results shown in Fig. 9(b), it may be postulated that the inter-particle contact forces transmitted through the soil skeleton of the soil specimens tested using the axis translation technique may be higher than those in the specimens sheared using the osmotic technique, leading to the measured higher ϕ^b angle using the former than the latter technique.

SUMMARY AND CONCLUSIONS

In the application of the osmotic technique, the applied matric suction is equal to the osmotic pressure of PEG solutions. Therefore, the relationship between the osmotic pressure and the concentration of the PEG solution is important. Different calibration methods lead to different calibrated relationships between the osmotic pressure and the concentration of the PEG solution. The main difference comes from whether or not a semi-permeable membrane is used in calibration.

On the compacted expansive clay used in this study, comparison of the results of single-stage and multi-stage tests indicated that these two testing methods provide consistent shear strength information for unsaturated soils. The consistency of the results from using the osmotic technique at HKUST and ENPC indicated the reliability of the osmotic technique. Based on the extended Mohr-Coulomb shear strength formulation, comparison of the results using the axis-translation technique and the osmotic technique showed that there was no difference in determining the internal friction angle, ϕ'. However, the values of ϕ^b in the test series using the axis-translation technique were slightly larger than those in the test series using the osmotic technique by 3°–4°. The larger values of ϕ^b may be due to lower specific volume and higher inter-particle contact forces (because of higher degree of saturation) transmitted through the soil skeleton of the soil specimens tested using the axis translation technique than those in the specimens sheared using the osmotic technique.

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