Engineering Geology 312 (2023) 106938

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Technical note

Use of osmotic tensiometers in the determination of soil-water characteristic curves

Hengshuo Liu [a,b], Harianto Rahardjo [c,*], Alfrendo Satyanaga [d], Hejun Du [e]

[a] Environmental Process Modelling Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Cleantech Loop, 637141, Singapore
[b] Interdisciplinary Graduate School, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[c] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[d] Department of Civil and Environmental Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Kabanbay Batyr Avenue, 53, Nur-Sultan 010000, Kazakhstan
[e] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

ARTICLE INFO

Keywords:
Osmotic tensiometer
High suction measurement
Temperature calibration
Flory-Huggins polymer theories
Soil-water characteristic curve

ABSTRACT

Soil-water characteristic curve (SWCC) correlates the water content of a soil to its soil suction, which is a very important property of unsaturated soils. Osmotic tensiometers (OTs) have shown their capability in high soil suction measurement. This study tried to use OT combined with a pressure plate and WP4C dewpoint potentiometer to determine the SWCC of a residual soil. Three OTs with different measuring ranges (900 kPa, 1200 kPa, 2300 kPa) were prepared for soil suction measurement. The temperature effect on the pressure variations of OTs was illustrated based on Flory-Huggins polymer theories and an appropriate calibration equation was proposed to eliminate the temperature effect on the accuracy of soil suction measurement using OT. The OT showed a fast response in soil suction measurement and the equilibrium can be established in 10–15 min during SWCC measurement. Comparison of the SWCC data obtained from the pressure plate, OT, and WP4C dewpoint potentiometer proves that the OT had good performance in the determination of SWCC, especially for the transition zone (i.e., 10–1500 kPa suction range), by providing more data points to define the SWCC in a shorter period. The results show that the usage of OT will shorten the time required for the determination of SWCC and could be considered as a new and reliable technique in SWCC measurement.

1. Introduction

Soil-water characteristic curve (SWCC) is an important property of unsaturated soils, correlating the water content of a soil to the soil suction (Fredlund and Rahardjo, 1993; Rahardjo et al., 2019). SWCC is extensively used in the study of unsaturated soil properties such as permeability and shear strength and the modelling of water flow in unsaturated soil zones (Fredlund et al., 2012; Zhai et al., 2018; Li et al., 2019; Mercer et al., 2019).

Different techniques such as Tempe cell, pressure plate, osmotic control, centrifuge, and WP4C dewpoint potentiometer have been applied to measure the SWCC of unsaturated soils (Delage et al., 1998; Fredlund et al., 2012; Rahardjo et al., 2018; Rahardjo et al., 2019). The SWCC measuring ranges of these techniques are shown in Fig. 1. Among these techniques, Tempe cell and pressure plate are the traditional methods for SWCC measurement on soil specimens with suction lower than 1500 kPa. When placing the soil specimen in Tempe cell or pressure plate, the soil suction is controlled using the axis-translation technique and the water content corresponding to the controlled suction is measured when an equilibrium of soil suction within the soil specimen was established (Fredlund et al., 2012). However, the low permeability of unsaturated soil specimens and the high air-entry ceramic disk make this method weeks to be finished since the time for the equilibrium of soil suction is quite long. Alternatively, the centrifuge method is much faster than the pressure plate in the measurement of SWCC (Rahardjo et al., 2018). However, the centrifuge can only measure SWCC at a lower suction range and a high-speed centrifuge machine is required to realize a higher measuring range. The WP4C dewpoint potentiometer measures the total suction of the soil specimen and this equipment is more suitable for the SWCC measurement at a high suction range (usually higher than 1500 kPa). Salt solution with certain molarity can be used to establish a constant suction environment. The soil suction can be controlled in such

* Corresponding author at: Block N1-01b-36, 50 Nanyang Avenue, 639798, Singapore.
E-mail address: chrahardjo@ntu.edu.sg (H. Rahardjo).

https://doi.org/10.1016/j.enggeo.2022.106938
Received 31 May 2022; Received in revised form 23 August 2022; Accepted 17 November 2022
Available online 24 November 2022

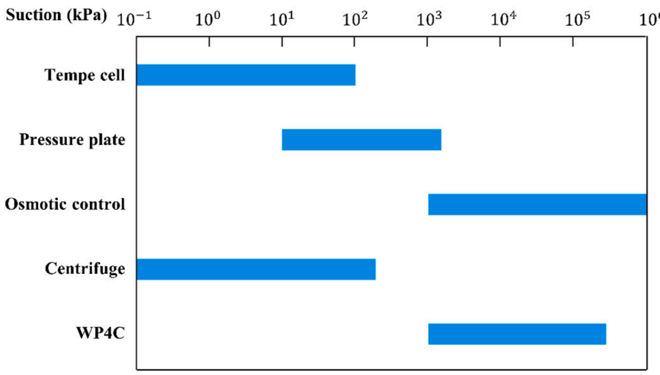

Fig. 1. SWCC measuring ranges of different techniques (Fredlund et al., 2012; Rahardjo et al., 2019).

an environment and the SWCC can be measured after determining the water content of the soil specimen (Rahardjo et al., 2019). This method is appropriate for the SWCC measurement at a high soil suction range.

Recently, high-capacity tensiometers (HCTs) have been proposed for SWCC measurement (Lourenço et al., 2011; Toll et al., 2013; Li et al., 2019; le Roux and Jacobsz, 2021). HCTs have a higher suction measuring range than conventional tensiometers by pre-pressurizing the water inside the tensiometer to avoid cavitation (Ridley and Burland, 1993; Guan and Fredlund, 1997). When using HCTs to measure SWCC, the suction of soil specimen was altered continuously or discretely (i.e., in stages) (Lourenço et al., 2007; Lourenço et al., 2011; Toll et al., 2013). The mass loss of soil specimen was measured using balance to obtain the water content while the soil suction was measured using HCT. The SWCC of the soil can then be established by combining the data of water content and soil suction. It was also reported that the SWCCs obtained following the continuous drying procedures were consistent with those obtained with the discrete drying procedures (Boso et al., 2005; Lourenço et al., 2011).

Compared with HCTs, osmotic tensiometers (OTs) can measure a high soil suction by using polymer to increase the osmotic pressure of the water inside the tensiometer (Bocking and Fredlund, 1979; Bakker et al., 2007; Liu et al., 2022a; Liu et al., 2022b). This increase in the osmotic water pressure is regarded as the measuring range of the OT. Cross-linked super water-absorbent polymers have been proved to be suitable for the development of OTs (Biesheuvel et al., 2000; Liu et al., 2022b). Compared with HCTs, the preparation procedure of OT is simpler and the pre-pressurization of water inside the tensiometer is not required. However, the accuracy of high soil suction measurement using OT may be influenced by pressure decay and temperature variation, which hinder the wide application of OTs.

In this study, three OTs were prepared for high suction measurement in the determination of SWCC. The pressure variations of OTs and the ambient temperature were monitored for temperature calibration based on Flory-Huggins polymer theories. Three techniques including pressure plate, OT, and WP4C dewpoint potentiometer were combined to measure the complete SWCC of a residual soil from Jurong formation, Singapore. When measuring SWCC using OT and WP4C, the soil specimen was placed in a container suitable for WP4C measurement and the suction of the soil specimen was controlled by the discrete drying procedures (Lourenço et al., 2011). The experimental data from the pressure plate, OT, and WP4C dewpoint potentiometer were combined and best-fitted using Fredlund and Xing eq. (1994) to determine the SWCC of the soil and the performance of these techniques in SWCC measurement was evaluated.

2. Material and methods

2.1. Preparation of OTs

The prototype and the photo of OT used in this study are shown in Fig. 2. The pressure transducer had a measuring range up to 25bar. The crosslinked sodium polyacrylate (NaPA) with a 10% degree of crosslinking was used for the preparation of OT because of its good performance in the previous study (Liu et al., 2022b).

Three OTs were prepared and their basic information is listed in Table 1. Referring to the relationship between the mass of dry polymer filled in OT and the corresponding pressure of OT shown in Fig. 3, different masses of dry polymer were filled into the polymer chamber of the OT to prepare OT with different measuring ranges. The 15-bar ceramic disk was used for the three OTs. The use of a 15-bar ceramic disk can help to avoid the potential water loss from the saturated ceramic disk during the soil suction measurement as the soil suction is lower than the air-entry value (AEV) of the ceramic disk (Fredlund et al., 2012; Ridley, 2015). The detailed preparation procedure of OTs followed that of the previous study (Liu et al., 2022b). After the preparation of OT, it was placed in distilled water for pressure observation. Water flowed into the polymer chamber of the OT to wet the dry polymer. The polymer absorbed water to form soft hydrogels and gradually filled up the chamber, leading to a build-up of the osmotic pressure of water. The changes in water pressure and the ambient temperature were recorded by the transducer and the integrated temperature sensor inside the transducer, respectively. All the three OTs were kept in distilled water throughout the study unless they were used for soil suction measurement for a certain time interval. In this study, the time interval for suction measurement was less than one hour.

2.2. Measurement of SWCC

2.2.1. Soil materials

The soil used in this study is an undisturbed residual soil collected from Jurong formation, Singapore, following ASTM D1587–00 (2007) e1. Fig. 4 and Table 2 show the grain size distribution and the index properties of the soil, respectively.

2.2.2. SWCC measurement by the pressure plate

The SWCC of the residual soil at a lower suction range was measured using a 5-bar pressure plate. The procedure for the SWCC measurement using the pressure plate followed ASTM D6836–16. One soil specimen with a dimension of 70 mm in diameter and 30 mm in height was prepared. The specimen was contained within a retaining ring and placed on a saturated ceramic disk inside the pressure plate for saturation.

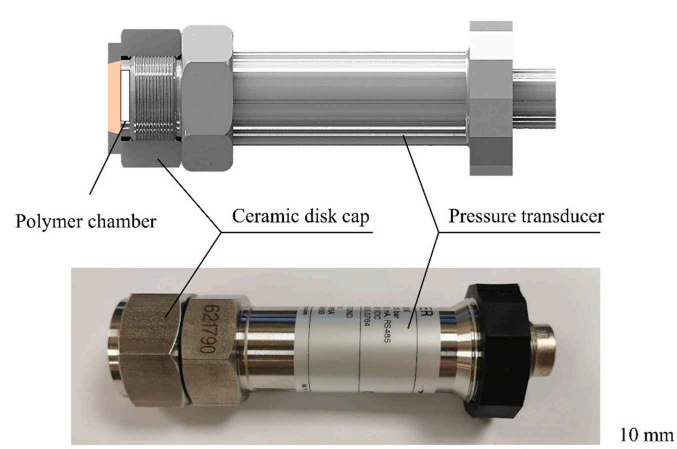

Fig. 2. Prototype and photo of the OT.

Table 1
Basic information of prepared OTs.

Numbering of OT	Air-entry value of ceramic disk	Polymer chamber volume (cm^3)	Type of polymer	Polymer mass (g)
OT-1	15-bar	0.18	NaPA	0.023
OT-2	15-bar	0.18	NaPA	0.025
OT-3	15-bar	0.18	NaPA	0.032

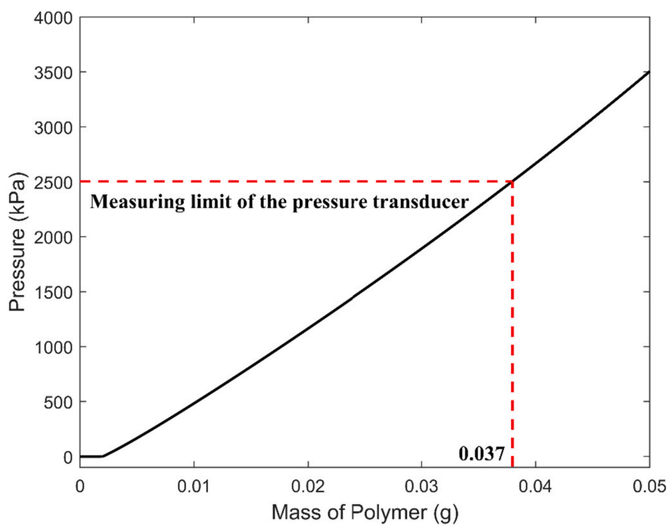

Fig. 3. Relationship between the mass of dry polymer filled in OT and the corresponding pressure of OT. (The curve was determined following the method proposed by Liu et al. (2022a).)

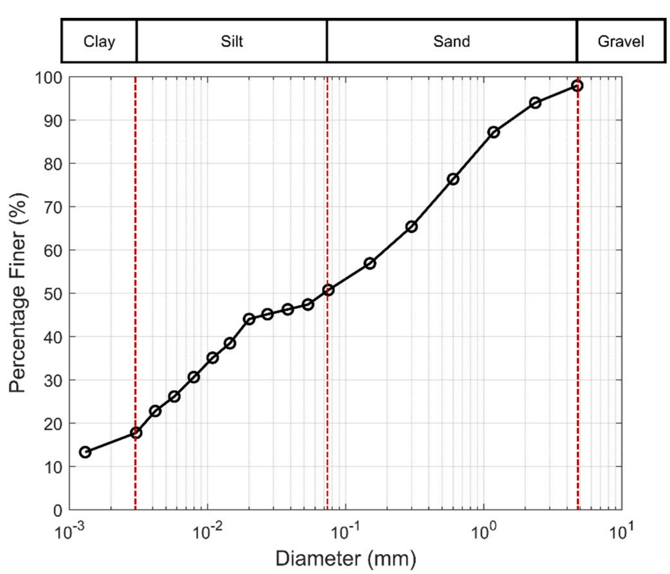

Fig. 4. Grain size distribution of the soil following the procedure explained in ASTM D422–63 (2002).

Then, the soil suction was controlled at 20, 80, 200, and 400 kPa based on the axis-translation technique (Fredlund et al., 2012). The mass of the soil specimen at equilibrium was recorded. When an equilibrium of soil suction at 400 kPa was reached, the soil specimen was placed in the oven for drying to determine the mass of dry solids, which was used for back-calculation of the water content at different stages of suction.

Table 2
Index properties of the soil.

Index properties	ASTM standard	Values
Specific gravity	ASTM D854–02, 2002	2.74
Sand (%)	ASTM D422–63, 2002	49
Silt (%)	ASTM D422–63, 2002	31
Clay (%)	ASTM D422–63, 2002	20
Liquid limit (%)	ASTM D4318–00, 2000	29
Plastic limit (%)	ASTM D4318–00, 2000	18
USCS classification	ASTM D2487–00, 2000	CL

2.2.3. SWCC measurement by OT and WP4C dewpoint potentiometer

Before using OT and WP4C dewpoint potentiometer to measure the SWCC of soil specimens, the soil specimen was prepared following ASTM D6836–16. The soil specimen with a dimension of 70-mm diameter and 30-mm height was contained within a retaining ring and placed on a saturated ceramic disk inside the pressure plate for saturation. Then, the saturated specimen was trimmed and placed in a container (40 mm in diameter and 10 mm in height) for SWCC measurement. Two soil specimens with a dimension of 40 mm in diameter and 5 mm in height were prepared in this manner.

The procedures for SWCC measurement using OT and WP4C dewpoint potentiometer were illustrated in Fig. 5. The SWCC measurement started with zero suction and then the suction of the soil specimen increased following the drying process. At each stage shown in Fig. 5, the soil specimen was firstly dried in the atmosphere for one hour. Then, the soil specimen was covered with a lid for one day to ensure water equalization within the soil specimen and thus an equilibrium of soil suction within the soil specimen can be established. The suction of the soil specimen was then measured using OT. During soil suction measurement, the change in pressure of the OT was observed from the computer and the measurement stopped when the change became negligible, indicating that equilibrium of the suction between the water inside the OT and the soil-water was reached. The measurement usually lasted for one hour. The soil specimen was covered with plastic wrap to avoid moisture loss during suction measurement. The mass of the soil specimen was weighed by an electronic balance after the suction measurement. The same soil specimen underwent similar stages several times to obtain enough data points to define the SWCC until the suction measuring limit (i.e., 1500 kPa) was reached. When the suction of the soil specimen exceeded 1500 kPa, the OT was replaced by the WP4C dewpoint potentiometer for soil suction measurement at each stage. The WP4C presented the result of suction measurement directly on the screen of the equipment. Similar to SWCC measurement using OT, the stages were repeated several times corresponding to the number of data points defining the SWCC until the suction measuring limit (around 100 MPa) of the WP4C dewpoint potentiometer was reached. Finally, the soil specimen was placed in the oven for drying to obtain the mass of dry soil solids, which was used to back-calculate the water content at different stages of suction measurement. In the end, for one soil specimen after a number of *n* stages was performed, a number of *n* data points can be obtained to determine the SWCC.

The experimental data from pressure plate, OT, and WP4C were combined and best-fitted using the Fredlund and Xing (1994) equation as shown in Eq. (1) to determine the SWCC of the soil.

$$w(\psi) = C(\psi) \bullet \frac{w_s}{\left\{ln\left(e + \left(\frac{\psi}{a}\right)^n\right)\right\}^m} = \left(1 - \frac{ln\left(1 + \frac{\psi}{\psi_r}\right)}{ln\left(1 + \frac{10^6}{\psi_r}\right)}\right) \bullet \frac{w_s}{\left\{ln\left(e + \left(\frac{\psi}{a}\right)^n\right)\right\}^m} \tag{1}$$

where $w(\psi)$ is the best-fitted water content; $C(\psi)$ is the correction factor; w_s is the saturated gravimetric water content; ψ is the matric suction; ψ_r is the parameter related to residual suction; and a, n, m are fitting parameters.

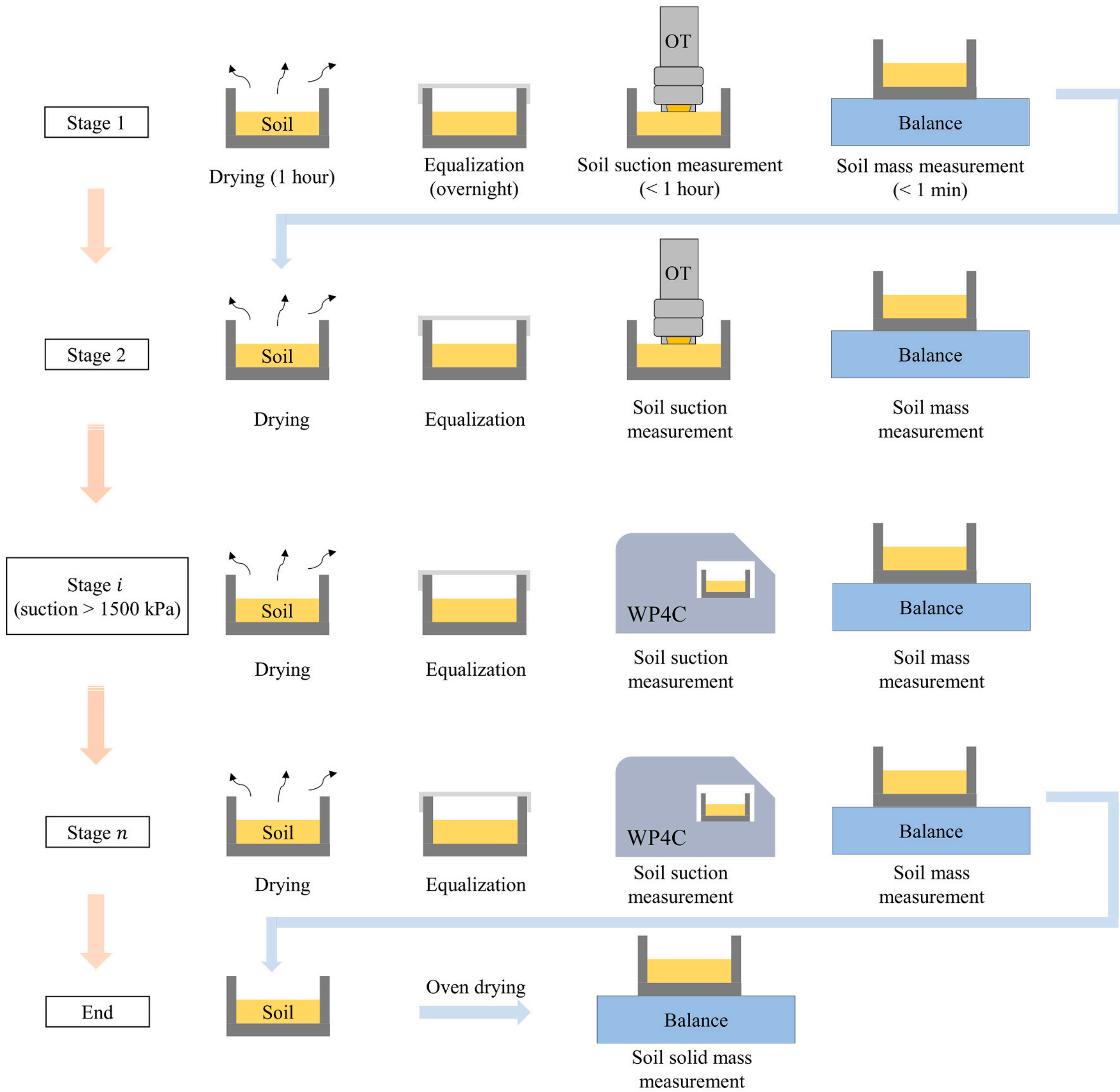

Fig. 5. Schematic diagram of SWCC measurement procedures using OT and WP4C dewpoint potentiometer.

3. Results and discussion

3.1. Pressure decay of OTs

The prepared OTs were kept in distilled water unless they were used for soil suction measurement. The pressure variations of OTs when they were kept in distilled water were observed as shown in Fig. 6. The measuring ranges (i.e., the maximum pressures of OTs) of OT-1, OT-2, and OT-3 are around 900 kPa, 1200 kPa, and 2300 kPa, respectively. However, the measuring ranges of these OTs kept decreasing with time due to the pressure decay of OTs.

In Fig. 6, the pressure decay of OT for a short period (from Day-3 to Day-10) can be regarded as a linear trend and the pressure decay rate was calculated using Eq. (2).

$$k_D = \frac{p_s - p_e}{\Delta t} \quad (2)$$

where k_D is the pressure decay rate of OT; p_s is the pressure of OT at the starting time; p_e is the pressure of OT at the end time; and Δt is the period from Day-3 to Day-10.

Based on Eq. (2), the pressure decay rates of OTs from Day-3 to Day-10 were calculated and presented in Table 3. It shows that the OT with a higher measuring range had a higher pressure decay rate k_D. However,

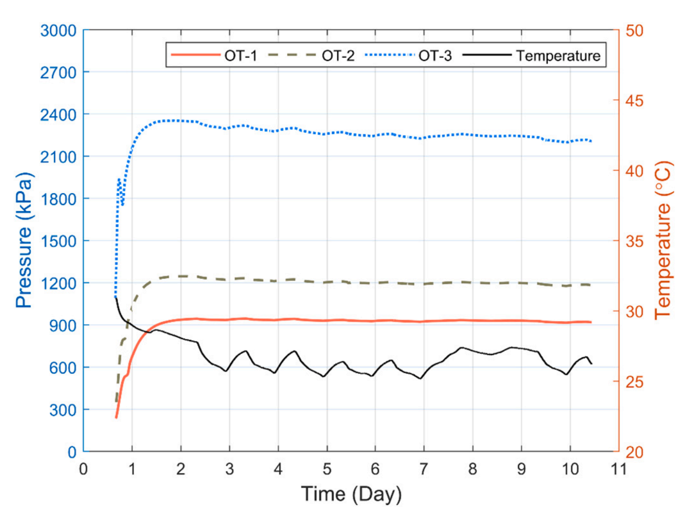

Fig. 6. Pressure variations of OTs. (The soil suction measurement using the OT was conducted at time intervals from Day-3 to Day-10.)

Table 3
Summarized properties of OTs.

Numbering of OTs	Measuring range (kPa)	Pressure decay rate, k_D (kPa/h)	Pressure-temperature parameter, k_T (kPa/°C)	
			Day-3	Day-10
OT-1	900	0.125	6.93	5.65
OT-2	1200	0.262	8.43	8.02
OT-3	2300	0.537	18.05	18.07

the k_D values of all three OTs are lower than 1 kPa/h, suggesting that the pressure decay would not affect the result of high suction measurement significantly because the time for measurement was not long (less than one hour in this study).

3.2. Temperature effect on the pressure variations of OTs

Fig. 6 also shows the pressure fluctuation of OTs due to the change in ambient temperature. This effect can be illustrated using Flory-Huggins polymer theories as described by Eq. (3) (Flory, 1953; Horkay et al., 2000; Wack and Ulbricht, 2009; Ganji et al., 2010).

$$p = p_{\text{mix}} + p_{\text{el}} + p_{\text{ion}} \tag{3}$$

where p is the total osmotic pressure; p_{mix}, p_{el}, and p_{ion} are mixing term, elastic term, and ionic term of the total osmotic pressure, respectively.

The three terms on the right hand side of Eq. (3) yield the total osmotic pressure p as a function of the absolute temperature T as shown in Eq. (4).

$$\begin{aligned} p &= -\frac{RT}{V_1}\left[ln(1-\phi_P)+\phi_P+\chi{\phi_P}^2\right]-\frac{RT}{v_2\overline{M}_c}\left(\phi_P^{\frac{1}{3}}-\frac{\phi_P}{2}\right)+RT\frac{i\phi_P}{V_m} \\ &= RT\left\{-\frac{1}{V_1}\left[ln(1-\phi_P)+\phi_P+\chi{\phi_P}^2\right]-\frac{1}{v_2\overline{M}_c}\left(\phi_P^{\frac{1}{3}}-\frac{\phi_P}{2}\right)+\frac{i\phi_P}{V_m}\right\} \\ &= RT\bullet A \end{aligned} \tag{4}$$

where R is the universal gas constant (8.31432 J/(mol•K)); T is the absolute temperature; V_1 is the molar volume of water; ϕ_P is the volume fraction of polymer; χ is the interaction parameter; v_2 is the specific volume of polymer; $\overline{M}_c$ is the average molecular weight of polymer chains between crosslinks; i is the degree of ionization; V_m is the molar volume of the monomer unit of polymer; A is a combination of terms ($A = -\frac{1}{V_1}\left[ln(1-\phi_P)+\phi_P+\chi{\phi_P}^2\right]-\frac{1}{v_2\overline{M}_c}\left(\phi_P^{\frac{1}{3}}-\frac{\phi_P}{2}\right)+\frac{i\phi_P}{V_m}$).

According to Eq. (4), the pressure-temperature parameter k_T of the OT (i.e., the pressure derivative function of p_{total} over T) can be obtained:

$$k_T = \frac{\partial p}{\partial T} = RA + RT\frac{\partial A}{\partial T} \tag{5}$$

Based on the pressure variations of OTs as shown in Fig. 6, the k_T can be found by plotting the pressure of OT versus the corresponding ambient temperature. In Fig. 7, two time intervals (Day-3 (0–7 am) and Day-10 (0–7 am)) were selected to study the relationship between the pressure of OT-1 and the ambient temperature. These two time intervals were selected because the SWCC measurement using OT was conducted from Day-3 to Day-10. The pressure decay of OT during the time interval was calibrated based on the pressure decay rate k_D listed in Table 3. It can be seen from Fig. 7 that the pressure of OT-1 varied almost linearly with temperature. The k_T was determined by taking the gradient of fitting equation. The k_T values of OT-2 and OT-3 were found using the same method and all the results are shown in Table 3.

Table 3 shows that the OT with a higher measuring range was affected by the ambient temperature more significantly (i.e., a higher k_T). The temperature effect on the pressure variation of OT follows Flory-Huggins polymer theories as shown in Eqs. (4) and (5) in which both p and k_T increase as the value of A becomes higher. The relationship between k_T and p was quantified by plotting the experimental k_T against the corresponding p as shown in Fig. 8. Based on the fitting equation shown in Fig. 8, the pressure variations of OTs were calibrated with the reference temperature of 25 °C using Eq. (6) and the results are presented in Fig. 9. The comparison of Fig. 6 and Fig. 9 shows that the pressure fluctuation of OT caused by the change in ambient temperature can be eliminated effectively using the proposed calibration equation. In addition, Eq. (6) should be suitable for temperature calibration of all OTs filled with the same polymer considering that the determination of k_T as a function of p as shown in Fig. 8 follows Flory-Huggins polymer theories.

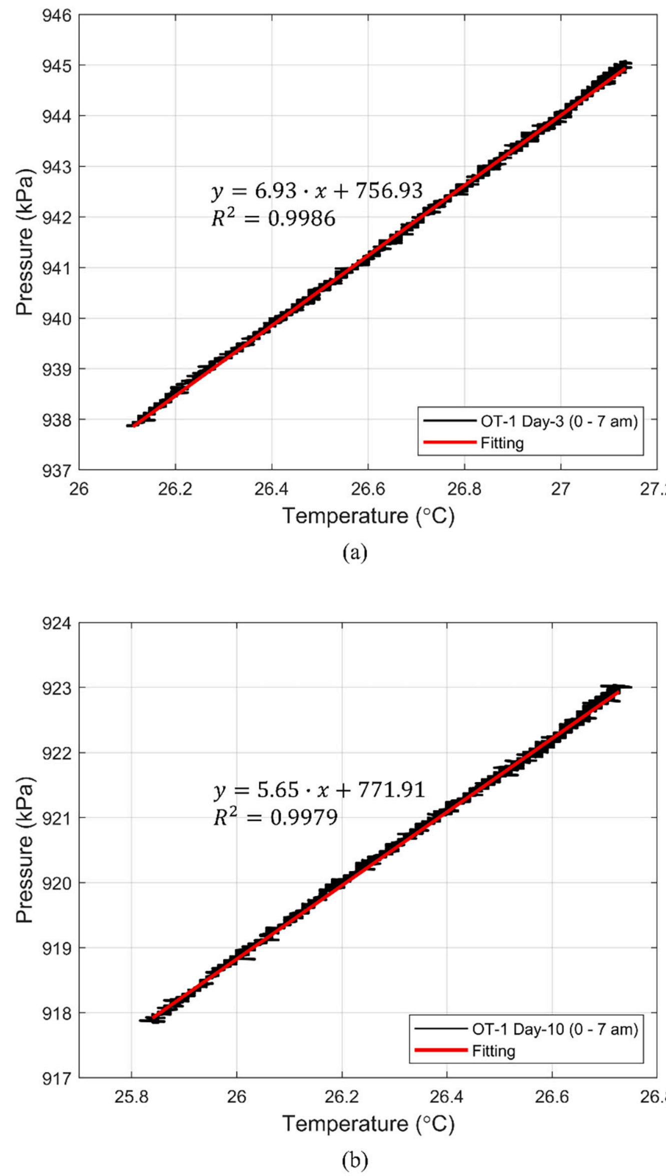

Fig. 7. Relationship between the pressure variation of OT-1 and the ambient temperature at two time intervals: (a) Day-3 (0–7 am); (b) Day-10 (0–7 am).

$$p_{\text{cali}} = p - k_T\bullet(T-T_0) = p - (0.00896\bullet p - 2.285)\bullet(T-T_0) \tag{6}$$

where p_{cali} is the calibrated pressure of the OT; p is the actual total pressure of the OT; k_T is the pressure-temperature parameter; T is the ambient temperature; T_0 is the reference temperature (25 °C in this

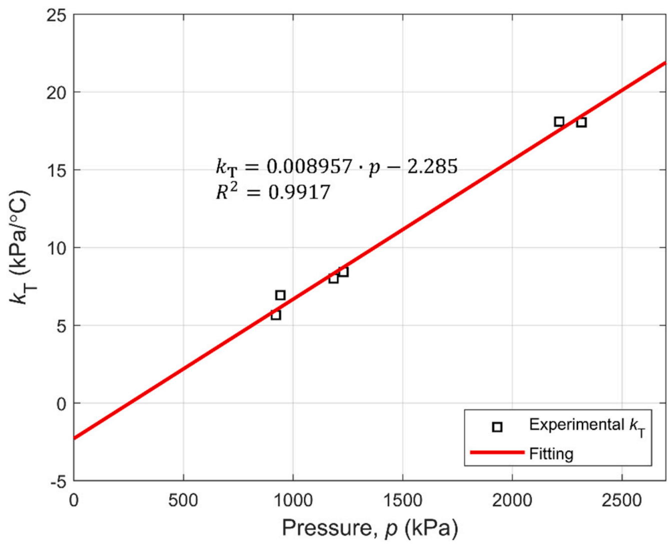

Fig. 8. Pressure-temperature parameter k_T as a function of the pressure of OT.

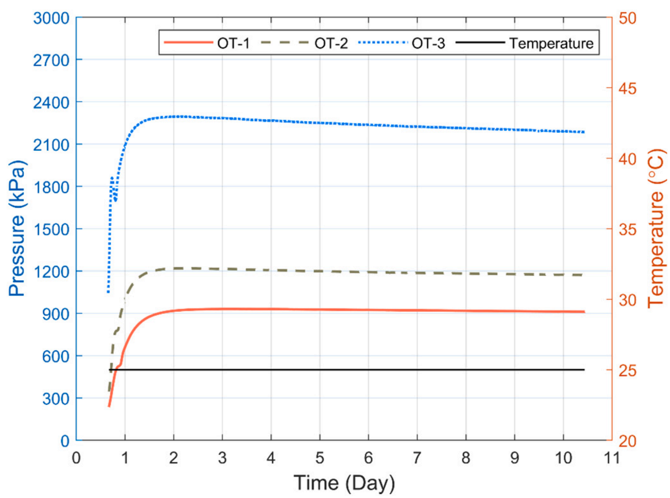

Fig. 9. Calibrated pressure variations of OTs with the reference temperature of 25 °*C*.

study).

3.3. Soil suction measurement by OT

Fig. 10 summarizes all the results of soil suction measurement using OT. The change in the pressure of OT during the measurement was converted to the measured matric suction following the method proposed by Liu et al. (2022b). The pressure decay and the temperature effect on the measurement have been calibrated based on parameters in Table 3 and Eq. (6), respectively. Fig. 10 shows that all OTs had a similar response time once they were placed in contact with the soil specimen for the measurement. The equilibrium of suction between the water inside the OT and the soil-water can be established in 10 to 15 min. However, the time required for equilibrium when measuring a higher soil suction became longer, especially when the soil suction exceeded 1500 kPa. The fast response of the OT and the short equilibrium time indicated that there was mainly water exchange between the soil and the OT along with the water energy transferred between the soil-water and the water inside OT. During the measurement, the ceramic disk kept saturated when the soil suction was lower than the AEV of the ceramic disk of the OT, which ensured the smooth and fast water exchange as

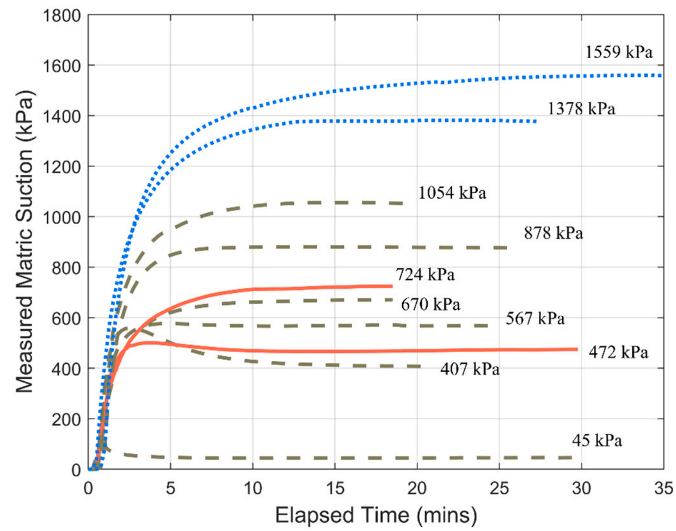

Fig. 10. Results of soil suction measurement using OT. (Different line colors with line styles indicate the corresponding OT in Fig. 9 that was used for soil suction measurement and the number near the line represents the measurement result.)

well as salt movement from soil-water to OT. Finally, the matric suction of the soil was measured at equilibrium.

3.4. Results of SWCC measurement using different techniques

The experimental results of SWCC measurement for the residual soil, whose properties are listed in Table 2, using the pressure plate, OT, and WP4C were combined as shown in Fig. 11. The experimental data obtained by three different techniques were best-fitted using Fredlund and Xing (1994) equation.

Fig. 11 shows that the experimental data from the three techniques showed good agreement with each other at the measuring boundaries of these techniques. Particularly, OT was good at measuring SWCC in the transition zone (i.e., 10–1500 kPa) due to its high suction measuring range and shorter equilibrium time. Compared with the traditional pressure plate that requires weeks for the equilibrium of soil suction within the soil specimen to be established, using OT combined with discrete drying procedures can help to determine the SWCC much faster

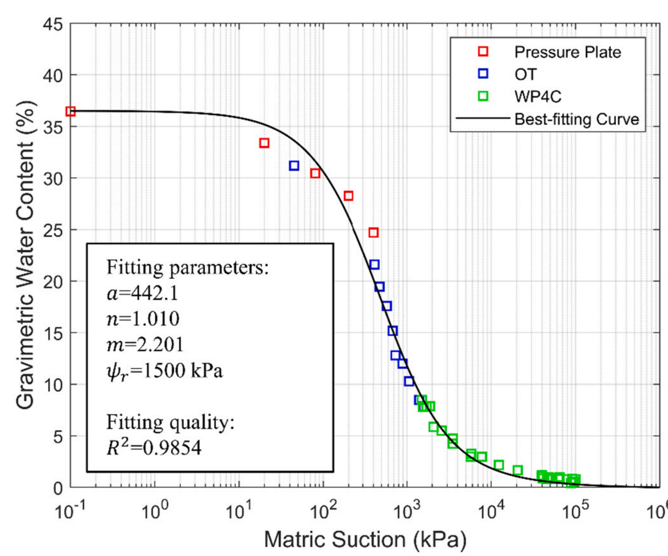

Fig. 11. Combination of SWCC measurements by pressure plate, OT, and WP4C and the best-fitted SWCC curve.

and more accurately as more number of data points can be obtained to define the SWCC. Considering that WP4C cannot measure soil suction accurately at the suction range lower than 1500 kPa due to the error in the conversion from the relative humidity to the total suction, OT can support the determination of SWCC in this suction range. Besides, fewer soil specimens were required in the determination of SWCC using OT since the same soil specimen can be used for OT and WP4C measurement continuously as shown in Fig. 5. As a result, OT could be considered as a new and reliable technique in SWCC measurement.

4. Conclusions

This study used OT combined with a pressure plate and WP4C dewpoint potentiometer to determine the SWCC of a residual soil. Three OTs with different measuring ranges (900 kPa, 1200 kPa, 2300 kPa) were prepared for soil suction measurement. The pressure decay of OTs and the temperature effect on the pressure variations of OTs were studied. The result shows that pressure decay was considered insignificant to the accuracy of soil suction measurement if the measurement can be conducted in a short time (e.g., less than one hour). An appropriate temperature calibration equation based on Flory-Huggins polymer theories was proposed to eliminate the temperature effect on soil suction measurement using OT. Once placing OT in contact with the soil specimen, the OT showed a fast response to soil suction and the equilibrium can be established in 10–15 min. Comparison of the experimental data from the pressure plate, OT, and WP4C dewpoint potentiometer proves that the OT had good performance in the determination of SWCC, especially for the transition zone (i.e., 10–1500 kPa suction range), by providing more data points to define the SWCC in a shorter period. The usage of OT will improve the accuracy and the speed of high soil suction measurement, thus shortening the time required for the determination of SWCC. Further studies should focus on the SWCC measurement of other types of soil as well as the validation of models for SWCC prediction using OT.

CRediT authorship contribution statement

Hengshuo Liu: Conceptualization, Methodology, Writing – original draft, Formal analysis. **Harianto Rahardjo:** Conceptualization, Methodology, Writing – review & editing, Formal analysis, Supervision. **Alfrendo Satyanaga:** Methodology, Writing – review & editing, Formal analysis. **D. Hejun:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors would like to express their thanks for the assistance from the staff from Geotechnics Laboratory, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

References

ASTM D1587–-00, 2007. e1 Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes. ASTM International, West Conshohocken, PA, USA.

ASTM D2487–-00, 2000. Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA.

ASTM D422–-63, 2002. Standard Test Method for Particle-Size Analysis of Soils. ASTM International, West Conshohocken, PA, USA.

ASTM D4318–-00, 2000. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, USA.

ASTM D854–-02, 2002. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International, West Conshohocken, PA, USA.

Bakker, G., Van Der Ploeg, M.J., De Rooij, G.H., Hoogendam, C.W., Gooren, H.P.A., Huiskes, C., Koopal, L.K., Kruidhof, H., 2007. New polymer tensiometers: measuring matric pressures down to the wilting point. Vadose Zone J. 6 (1), 196–202.

Biesheuvel, P.M., Van Loon, A.P., Raangs, R., Verweij, H., Dirksen, C., 2000. A prototype osmotic tensiometer with polymeric gel grains. Eur. J. Soil Sci. 51 (2), 355–364.

Bocking, K., Fredlund, D., 1979. Use of the osmotic tensiometer to measure negative pore water pressure. Geotech. Test. J. 2 (1), 3–10.

Boso, M., Romero, E., Tarantino, A., 2005. The use of different suction measurement techniques to determine water retention curves. In: Schanz, T. (Ed.), Unsaturated Soils: Experimental Studies. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 169–181.

Delage, P., Howat, M.D., Cui, Y.J., 1998. The relationship between suction and swelling properties in a heavily compacted unsaturated clay. Eng. Geol. 50 (1), 31–48.

Flory, P.J., 1953. Principles of Polymer Chemistry. Cornell University Press.

Fredlund, D.G., Rahardjo, H., 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons, Inc., New York.

Fredlund, D.G., Xing, A., 1994. Equations for the soil-water characteristic curve. Can. Geotech. J. 31 (4), 521–532.

Fredlund, D.G., Rahardjo, H., Fredlund, M.D., 2012. Unsaturated Soil Mechanics in Engineering Practice. John Wiley & Sons, Inc., New York.

Ganji, F., Vasheghani-Farahani, S., Vasheghani-Farahani, E., 2010. Theoretical description of hydrogel swelling: a review. Iran. Polym. J. 19 (5), 375–398.

Guan, Y., Fredlund, D.G., 1997. Use of the tensile strength of water for the direct measurement of high soil suction. Can. Geotech. J. 34 (4), 604–614.

Horkay, F., Tasaki, I., Basser, P.J., 2000. Osmotic swelling of polyacrylate hydrogels in physiological salt solutions. Biomacromolecules 1 (1), 84–90.

Le Roux, P.F., Jacobsz, S.W., 2021. Performance of the tensiometer method for the determination of soil-water retention curves in various soils. Geotech. Test. J. 44 (4), 1079–1096.

Li, L., Zhang, X., Li, P., 2019. Evaluating a new method for simultaneous measurement of soil water retention and shrinkage curves. Acta Geotech. 14 (4), 1021–1035.

Liu, H., Rahardjo, H., Du, H., Hamdany, A.H., 2022a. Long-term decay of the water pressure in the osmotic tensiometer. J. Rock Mech. Geotech. Eng. https://doi.org/10.1016/j.jrmge.2022.05.005.

Liu, H., Rahardjo, H., Satyanaga, A., Du, H., 2022b. Use of synthesised polymers for the development of new osmotic tensiometers. Geotechnique 1–9. https://doi.org/10.1680/jgeot.21.00108.

Lourenço, S.E., Gallipoli, D., Toll, D., Evans, F., Medero, G., 2007. Determination of the soil water retention curve with tensiometers. In: Schanz, T. (Ed.), Experimental Unsaturated Soil Mechanics. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 95–102.

Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Augarde, C.E., Evans, F.D., 2011. A new procedure for the determination of soil-water retention curves by continuous drying using high-suction tensiometers. Can. Geotech. J. 48 (2), 327–335.

Mercer, K., Rahardjo, H., Satyanaga, A., Geomechanics, A.C.F., 2019. Unsaturated Soils Guidelines - Volume 1: Soil Water Characteristic Curves for Materials Classified According to the Unified Soil Classification System. Australian Centre for Geomechanics.

Rahardjo, H., Nong, X., Lee, D., Leong, E., Fong, Y., 2018. Expedited soil–water characteristic curve tests using combined centrifuge and chilled mirror techniques. Geotech. Test. J. 41 (1), 207–217.

Rahardjo, H., Satyanaga, A., Mohamed, H., Yee Ip, S.C., Shah, R.S., 2019. Comparison of soil–water characteristic curves from conventional testing and combination of small-scale centrifuge and dew point methods. Geotech. Geol. Eng. 37 (2), 659–672.

Ridley, A.M., 2015. Soil suction — what it is and how to successfully measure it. In: Dight, P.M. (Ed.), Proceedings of Ninth International Symposium on Field Measurements in Geomechanics. Australian Centre for Geomechanics, Perth, pp. 27–46.

Ridley, A.M., Burland, J.B., 1993. A new instrument for the measurement of soil moisture suction. Geotechnique 43 (2), 321–324.

Toll, D.G., Lourenço, S.D.N., Mendes, J., 2013. Advances in suction measurements using high suction tensiometers. Eng. Geol. 165, 29–37.

Wack, H., Ulbricht, M., 2009. Effect of synthesis composition on the swelling pressure of polymeric hydrogels. Polymer 50 (9), 2075–2080.

Zhai, Q., Rahardjo, H., Satyanaga, A., 2018. Estimation of air permeability function from soil-water characteristic curve. Can. Geotech. J. 56 (4), 505–513.

Further reading

ASTM D6836–-16, 2016. Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge. ASTM International, West Conshohocken, PA, USA.