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Osmotic Oedometer Using Sodium Chloride Solution and Reverse Osmosis Membrane

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ABSTRACT

There are two suction application techniques in laboratory testing of unsaturated soils: (1) the axis-translation technique in which pore-air pressure is elevated above atmospheric pressure and pore-water pressure is at an atmospheric or a small positive value to give a matric suction and (2) using salt solutions. Salt solutions can be used to control the relative humidity of the air surrounding the soil specimen in the vapor equilibrium technique or as an osmotic suction applied through a semi-permeable membrane in the osmotic technique. The salt solution in the vapor equilibrium technique applies a total suction, whereas the salt solution in the osmotic technique induces a matric suction on the soil specimen. Unlike the axis-translation technique and vapor equilibrium technique, the osmotic technique does not require a sealed chamber, but it is not as popular as the axis-translation technique and vapor equilibrium technique because the commonly used poly(ethylene glycol) solution and cellulosic membrane are susceptible to degradation during long-duration tests. This paper investigates the osmotic technique using sodium chloride solutions and a reverse osmosis membrane in a conventional oedometer. The performance of the updated osmotic oedometer was evaluated using kaolin–bentonite specimens. A kaolin–bentonite specimen was first mechanically consolidated, and thereafter the water within the base of the oedometer was replaced with sodium chloride solution. The results show that osmotic technique causes the soil specimen to be compressed further. However, the measured matric suction of the soil specimen at equilibrium is less than the applied suction. The difference is attributed to the membrane resistance effect. The updated osmotic oedometer is attractive, as it eliminates the drawbacks of the previous osmotic oedometer, and it can theoretically apply matric suction as high as 5,000 kPa.

Keywords

osmotic technique, matric suction, oedometer, axis translation, sodium chloride solution, reverse osmosis membrane

Introduction

Research has shown that suction exists in unsaturated and expansive soils because of both capillary and adsorption forces (Philip 1977; Zhou and Sheng 2016). The experimental study of unsaturated and expansive soils is more difficult than saturated soils because it is hard to measure soil suction. Soil suction is required for describing the mechanical properties of unsaturated soils. Matric and osmotic suctions are the two main components of soil suction (Krahn and Fredlund 1972; Fredlund, Rahardjo, and Fredlund 2012).

Several devices have been employed to measure suction: tensiometers, psychrometers, the null-type axis-translation apparatus, filter paper, thermal conductivity sensor, and electrical conductivity sensor (Leong, Tripathy, and Rahardjo 2003). However, these devices have a limited range of suction measurement, latency, and stability issues during measurement (Leong et al. 2007). As a result, most researchers have adopted the use of suction control methods to characterize unsaturated soils.

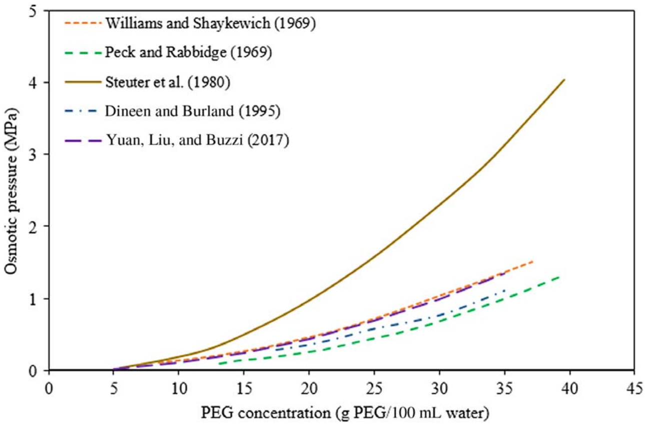
There are two methods of suction control and application in laboratory testing of unsaturated soils. One method uses the axis-translation method in which an air pressure u_a (pore-air pressure) is applied to the specimen while maintaining the pore-water pressure, u_w, at atmospheric pressure or a small positive pressure via a high air entry (HAE) ceramic disk. The matric suction, s, is given as the difference between pore-air and pore-water pressures, i.e., $u_a - u_w$. This method is usually used for unsaturated soil characterization for soil suctions between 0 and 1,500 kPa (Fredlund and Rahardjo 1993). The axis-translation technique has been applied in geotechnical testing using triaxial apparatus (Ho and Fredlund 1982; Rahardjo et al. 1995; Thu, Rahardjo, and Leong 2006; Goh, Rahardjo, and Leong 2014), direct shear apparatus (Gan, Fredlund, and Rahardjo 1988; Nam et al. 2011; Chen et al. 2013; Tang, Borden, and Gabr 2018), and oedometer (Matyas and Radhakrishna 1968; Kassiff and Shalom 1971; Delage, Vicol, and de Silva 1992; Delage and Cui 2008a; Nowamooz and Masrouri 2008; Ajdari, Monghassem, and Reza Lari 2016; Derfouf et al. 2020). The other method uses salt solutions. The salt solutions can be used to control the relative humidity of the enclosed air environment surrounding the soil specimen in the vapor equilibrium technique or as an osmotic pressure through a semipermeable membrane in the osmotic technique. The osmotic technique was developed by biologists (Lagerwerff, Ogata, and Eagle 1961) and introduced to soil science by Zur (1966) and geotechnical engineering by Kassiff and Shalom (1971). The osmotic technique should not be confused with osmotically induced or osmotic consolidation (Barbour and Fredlund 1989; Bulolo and Leong 2019) wherein salt solution replaces the pore water in a saturated soil specimen, causing volume change. An osmotically induced or osmotic consolidation test is usually conducted in an oedometer without the use of a semipermeable membrane (e.g., Di Maio 1996).

The osmotic technique uses a simpler setup, as there is no need for a sealed chamber and air pressure control, as required in the axis-translation technique, or circulation of air at a constant relative humidity, as used in the vapor equilibration technique. The salt solution in the vapor equilibration technique applies a total suction, whereas the salt solutions in the osmotic technique induce a matric suction in the soil specimen. In addition to that, the pore-water pressure is negative, and it reproduces the natural pore-water condition in soils (Delage and Cui 2008a), unlike the axis-translation technique.

The axis-translation technique and vapor equilibration technique require the soil specimen to be placed in a sealed chamber. Although the osmotic technique does not require a sealed chamber to conduct the test, it is not as popular as the axis-translation technique and the vapor equilibration technique because of degradation of the salt solution and membrane used in the osmotic technique. The common salt solution used in the osmotic technique is an aqueous solution of poly(ethylene glycol) (PEG) (a polymer-based solute), which has several molecular weights and may break down during long-duration tests (McGary 1960; Thill, Schirman, and Appleby 1979; Delage and Cui 2008a; Ulbricht, Jordan, and Luxenhofer 2014). The calibration curves given for a particular molecular weight PEG solution are also shown to be different for different researchers. This is illustrated for PEG 20,000 solution in **figure 1**. Possible causes of the degradation of the PEG solution include oxidative degradation in the presence of air (Han, Kim, and Kwon 1995), degradation associated with interactions of molecules of PEG with the semipermeable membrane used and with expelled ions from the pore fluid of soil-water systems

FIG. 1

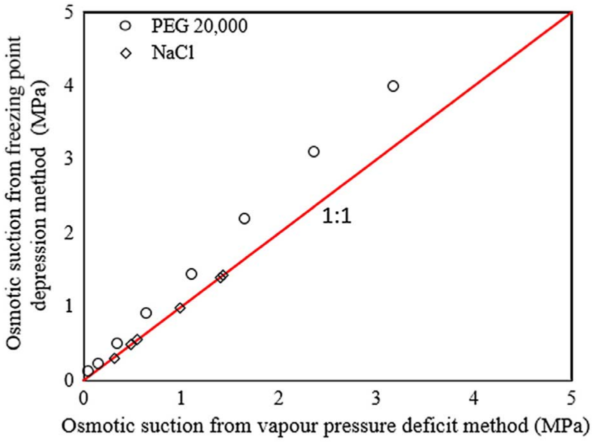
Calibration curves for PEG 20,000 solution from different researchers.



(Tripathy, Tadza, and Thomas 2011), and degradation by soil microorganisms (Haines and Alexander 1975) that could pass through the cellulotic membrane. Inorganic solutes (e.g., sodium chloride [NaCl]), on the other hand, have advantages of being more readily available and inexpensive as compared with polymer-based solutes (e.g., PEG). The polymer-based solutes are characterized by a low osmotic driving force (Klaysom et al. 2013). Unlike NaCl solution, the PEG solution consists of molecules with a range of molecular weights. For example, PEG 20,000 solution consists of molecules of molecular weights ranging from 15,000 to 20,000 (Williams and Shaykewich 1969; Steuter, Mozafar, and Goodin 1981; Delage and Cui 2008a). The hydrodynamic diameter of the PEG molecule also changes with the concentration (Michel and Kaufman 1973; Minagawa et al. 1994). In addition, regardless of the technique used to measure osmotic pressure (either vapor point deficit method or freezing point depression method), the NaCl solution gives the same value but not the PEG solution (fig. 2). The semipermeable membrane commonly used in the osmotic technique together with the PEG solution is a cellulotic membrane that is prone to degradation during tests. Zur (1966) reported the difficulty encountered because of microbial decomposition of the cellulotic membrane when in contact with soil despite the use of biocides and disinfectants. Tadza et al. (2016) reported that the addition of penicillin was not effective in removing the cellulose acetate degrading microbes and proposed using 70 % ethanol to prevent cross contamination. Sterilization of the soil eliminates the problem, but it destroys the structure of the soil. Similar degradation of the cellulotic

FIG. 2

Comparison of osmotic suction for PEG and NaCl solution using two different measurement methods (data from Kiyosawa 2003).



membrane has been reported by Delage, Vicol, and de Silva (1992), Delage and Cui (2008a), and Ng, Zhou, and Leung (2015). Cellulotic membranes are susceptible to bacteria attacks in a long-duration test (Slatter et al. 2000; Monroy et al. 2007). Tripathy, Tadza, and Thomas (2011) mentioned that cellulotic membranes are also known to be vulnerable to mechanical strain according to the membrane manufacturer. In addition, Tripathy, Tadza, and Thomas (2011) found that some alteration of the pore size of the cellulotic membrane occurs during tests using the osmotic technique, leading to leakage of some PEG molecules through the membrane. The problem is more serious at higher applied suctions. Suraj de Silva (1987) proposed that the cellulotic membrane be changed after 6 days but used the semipermeable membrane up to 10 days in tests. Slatter et al. (2000) and Monroy et al. (2007) recommended the use of a polyether sulphonated synthetic (PES) membrane as opposed to cellulotic dialysis membranes for longer testing times. The PES membrane was only tested for suctions below 1,000 kPa, although there are no data to suggest that the membrane did not perform well at suctions greater than 1,000 kPa. However, Delage and Cui (2008b) mentioned that cellulotic membranes are still being used because of the low permeability of the PES membrane. With recent advances in desalination technology, more robust and durable semipermeable membranes are now readily available. For example, a reverse osmosis (RO) membrane can operate within a wide range of pH (2 to 11) and temperatures up to 45°C and can perform over several years (DuPont 2020). Monroy et al. (2007) further concluded that the osmotic technique can be used to perform long-duration tests with the correct choice of membrane and salt solution.

It is generally assumed in the osmotic technique that the matric suction of the soil specimen at equilibrium is equal to the applied osmotic suction, as the head losses due to the membrane resistance are negligible (e.g., Delage and Cui 2008a). Tarantino and Mongiovi (2000) and Marcial (2003) found difficulty in applying suction greater than 1,000 kPa in the osmotic technique using PEG solutions and a cellulotic membrane. The actual matric suction measured across the semipermeable membrane by Dineen (1997), Dineen and Burland (1995), and Peck and Rabbidge (1969) showed differences from the osmotic suction of the PEG solution measured using a psychrometer by Williams and Shaykewich (1969), as shown in **figure 1**. Similar measurements conducted by Yuan, Liu, and Buzzi (2017) using a PES membrane instead of cellulotic membrane showed that there is a difference in the osmotic suction depending on the molecular weight of the PEG solution, especially at high suctions. To date, except for Dineen (1997), there is very little work in the literature that shows independent matric suction measurements conducted on soil specimens after the application of the osmotic technique. So far, the osmotic technique has only been applied using PEG solutions, and no literature exists on the use of inorganic solutes and RO membranes in the osmotic technique. The advantages accrued to inorganic solutes and RO membranes are therefore worth investigating in the osmotic technique to address the challenges associated with the use of PEG solution and cellulotic membranes.

This paper investigates the osmotic technique with the use of NaCl solutions and RO membrane in a conventional oedometer to induce matric suction in a soil specimen under a normal load. In addition, independent matric suction measurements conducted on the specimens after the test are reported and discussed in the paper.

Test Setup and Procedures

OSMOTIC OEDOMETER

The osmotic technique is an alternative method of inducing matric suction in a soil specimen by the use of a semipermeable membrane and a salt solution. Ideally, only water molecules can pass through the membrane. Water from the soil specimen diffuses through the membrane by osmosis because of the osmotic gradient created by the NaCl solution on the opposite side of the membrane. This induces matric suction in the soil. The increase in the salt solution concentration (increase in osmotic pressure) increases the matric suction of the soil specimen. The principle is the same as when PEG solutions were used (e.g., Kassiff and Shalom 1971; Tarantino and Mongiovi 2000; Monroy et al. 2007; Delage and Cui 2008a). The osmotic oedometer was initially used by Kassiff and Shalom (1971), wherein a semipermeable cellulotic membrane was added to a conventional oedometer cell to seal the top and bottom faces of the specimen. Free access of the osmotic solution to the membrane was through ducts in the top cap and the base of the cell. The osmotic solution was fed from a burette and was changed daily to ensure constant concentration. Delage, Vicol, and de Silva (1992) modified the setup to circulate the solution using a reservoir and a pump. The water exchange was measured by a graduated capillary tube connected to the reservoir by observing the meniscus of the solution in the tube. A schematic of the setup is shown in **figure 3**.

The setup was further modified by Dineen and Burland (1995) to include a suction probe at the top of the specimen to measure suction during the experiment and an electronic balance to measure the mass of water exchange between the soil and the PEG solution. In both modifications (Delage, Vicol, and de Silva 1992; Dineen and Burland 1995), for accurate measurement of the volume and mass of water exchange, it was assumed that there is no water loss because of leakages and evaporation. As a result, any water exchange between the soil and the osmotic solution is captured by the capillary tube or the balance.

The osmotic oedometer used in this study (**fig. 4**) is modified from a conventional oedometer. The modification consists of the addition of an RO membrane, a peristaltic pump and NaCl solution reservoir. The peristaltic pump is GOSO brand model AB11 with a DC power input of up to 12 V. The pump flow range is 0.1–100 mL/min with a speed range between 0.1 and 100 r/min equipped with a pump tubing of 2.5 by 4.7 mm inside to outside diameters. The pump flow rate depends on the power supply with a full flow rate at the full voltage supply of 12 V. **Figure 5** shows a calibration setup of the peristaltic pump rate for the setup. The voltage supplied to the peristaltic pump was adjusted such that the outflow rate from the reservoir is the same as the inflow rate into the reservoir. This is done by ensuring that the meniscus level in the calibration tube is at the same level as the top of the porous stone and the membrane is not lifted from the porous stone. The NaCl solution has to flow through the porous stone as the inlet and outlet are on diametrical opposite sides of the porous stone. The flow is ensured to be at a constant velocity by the peristaltic pump. The setup was further checked by positioning a steel dummy specimen of the same dimensions as the soil specimen on top of the membrane to ensure that the application of the specimen would not cause a variation in the flow rates. This system allows a matric suction to be applied to the soil specimen under a given vertical stress. If the volume or mass measurement device is added to the setup, it can be used to determine the soil-water characteristic curve (SWCC) of a soil specimen under specified vertical stress by changing the concentration of the salt solution after each equilibrium point. Equilibrium was assumed to have occurred when the deformation of the soil specimen was less than the resolution of the linear variable differential transformer (0.01 mm) over 6 h.

The RO membrane used is a DOW Filmtec SW30HR, which allows water molecules to pass freely but not dissolved salts, inorganic molecules, or organic molecules with a molecular weight greater than 100 (DuPont 2020).

FIG. 3

Schematic drawing of typical osmotic oedometer using PEG solution.

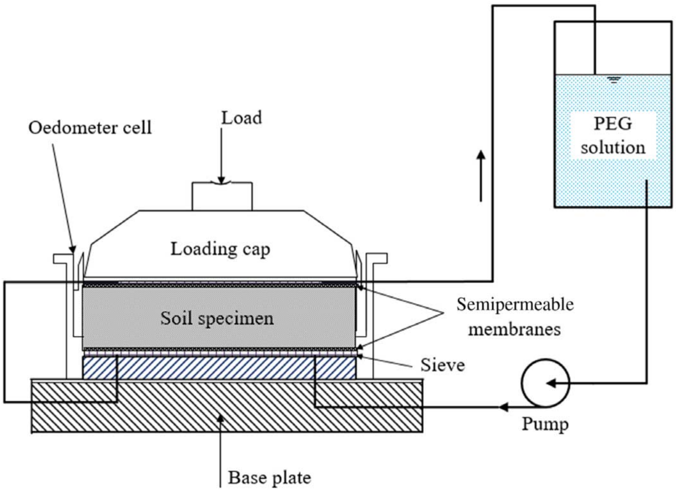


FIG. 4

Schematic drawing of updated osmotic oedometer.

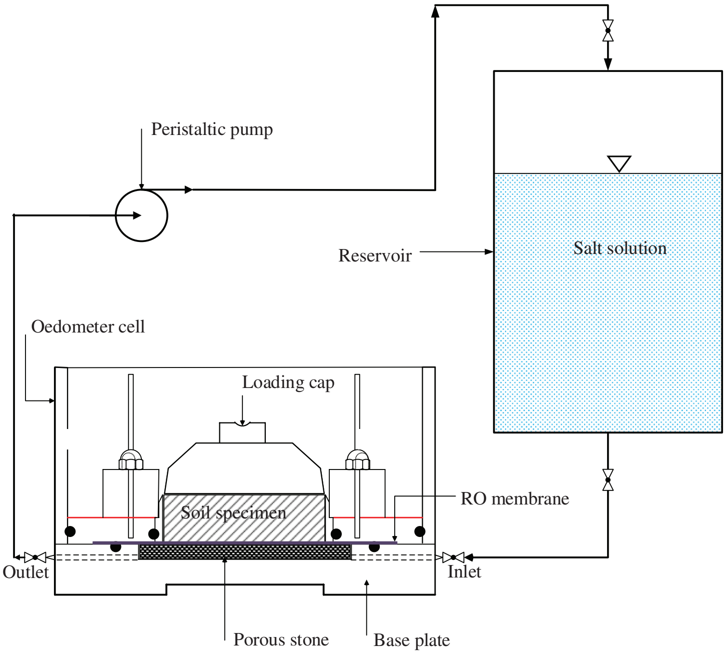
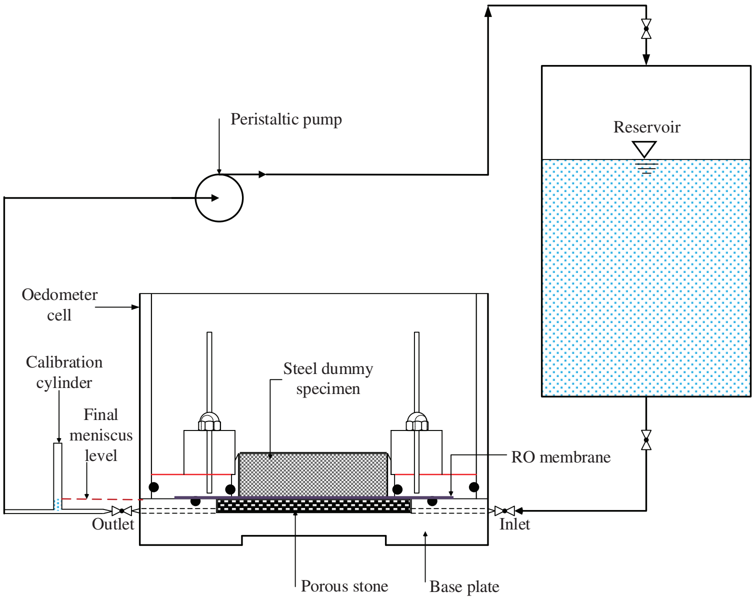


FIG. 5

Calibration of peristaltic pump to circulate salt solution through base of oedometer.



The RO membrane has a minimum salt rejection of 99.6 % and is a thin film composite membrane consisting of 3 layers: a polyester support web, which provides the major structural support and is made to provide a hard and smooth surface with no loose fiber, a microporous polysulfone interlayer that is cast onto the surface of the polyester support web to provide a substrate for the salt barrier layer because the web is too porous and irregular, and the salt barrier layer consisting of an ultrathin layer of polyamide. The microporous polysulfone interlayer provides strong support for the ultrathin polyamide barrier, which is about 2,000 Å (0.0002 mm) thick to withstand high pressures. For RO membranes, the ultrathin polyamide barrier is relatively thick and enhances the membrane resistance to both mechanical stresses and chemical degradation. The membrane also has some short-term resistance to chlorine attack. The membrane can operate within a wide range of pH (2–11) and temperatures up to 45°C and can perform over several years (DuPont 2020).

SOIL SPECIMEN

For evaluation of the updated osmotic oedometer, a soil mixture of bentonite-kaolin in proportions of 30–70 % (KB30) by dry mass was used. The bentonite in the soil mixture makes the soil more compressible and thus enables volume changes to be more clearly observed. The basic properties for the kaolin, bentonite, and KB30 are summarized in **Table 1**. The grain size distributions are shown in **figure 6**.

The soil specimens were obtained by consolidating a slurry of KB30 in a tank (300 mm in diameter) under a vertical pressure of 125 kPa. This vertical pressure was chosen so that a firm specimen could be obtained from the consolidated sample. The settlement was observed regularly until there was no more settlement for a week. After consolidation, the sample was extruded from the consolidation tank and cut into blocks of 70 by 70 by 50 mm. The blocks were wrapped with three to five layers of cling wrap followed by two layers of aluminum foil, waxed, and placed into the humidity cabinet for later use.

SALT SOLUTION

Laboratory-grade NaCl was used to prepare the salt solutions for the study. Different concentrations of NaCl solutions were prepared as shown in **Table 2** to give osmotic suctions of 500, 1,000, 2,000, 5,000, and 10,000 kPa. The concentration of NaCl solution was based on the osmotic suction defined in terms of the molarity of the salt

TABLE 1

Basic soil properties

	Soil Type		
Soil Properties	Kaolin	Bentonite	KB30
Specific gravity, G_s	2.66	2.60	2.63
Liquid limit, %	49	210	135
Plastic limit, %	34	44	40
Plasticity index, %	15	166	38
USCS classification	ML	CH	MH

Note: CH = clay high plasticity; MH = silt high plasticity; ML = silt low plasticity; USCS = Unified Soil Classification System.

FIG. 6

Grain size distribution of the soil used in the study.

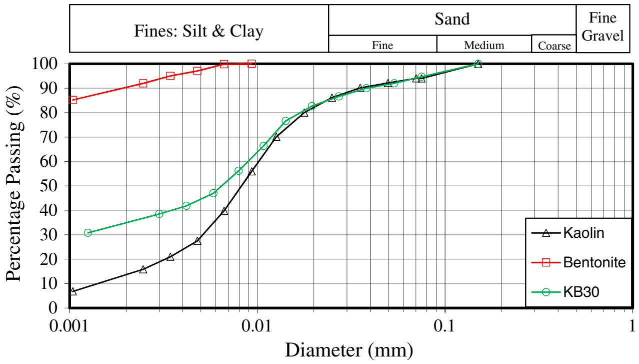


TABLE 2

Concentrations and measured osmotic suctions of NaCl solutions before and after the test

NaCl Solution / Concentration, g/L of Water	Target Osmotic Suction, kPa	Measured Osmotic Suction before Test, kPa	Measured Osmotic Suction after Test, kPa	Difference in Measured Osmotic Suction after the Test, %
6.17	500	496	502	1.15
12.62	1,000	991	996	0.51
25.01	2,000	1,934	1,938	0.21
62.51	5,000	5,032	5,034	0.04
123.457	10,000	9,960	9,963	0.03

solution through the use of the van't Hoff equation (United States Department of Agriculture 1954; Campbell 1985).

The osmotic suction of the NaCl solution used was checked using electrical conductivity meters and chilled mirror dew-point device (WP4) (Leong, Tripathy, and Rahardjo 2003; Leong et al. 2007) to ensure that the target osmotic suction was achieved. Two electrical conductivity meters, Horiba 173 and Horiba ES-12, were used. The Horiba 173 is a portable compact electrical conductivity meter with a measurement range of 0–19.9 mS/cm and accuracy of ±2 % full scale. The Horiba ES-12 electrical conductivity meter has a measurement range of 0–199.9 mS/cm and an accuracy of 0.5 % full scale. The Horiba B-173 has the advantage over the Horiba ES-12 conductivity meter, as it can measure the electrical conductivity using a single drop of fluid (~1 mL). The osmotic pressure π was estimated using equation (1) (Leong et al. 2007):

$$\pi = p_a\left(0.31EC^{1.15}\right) \tag{1}$$

where p_a is the atmospheric pressure (=101.325 kPa) and EC is the electrical conductivity in mS/cm. The WP4 measures the relative humidity (RH) in the air space above the sample in a sealed environment under constant temperature conditions. Details of the WP4 can be found in Leong, Tripathy, and Rahardjo (2003). When measuring the relative humidity because of a salt solution, the osmotic suction can be obtained using equation (2):

$$\pi = \psi = -\frac{\mathrm{RT}}{v_{w0}\omega_v}\ln(RH) \tag{2}$$

where ψ is total suction (kPa), R is the universal (molar) gas constant (i.e., 8.31432 J/[mol K]), T is absolute temperature (i.e., $T = [273.16 + t°\mathrm{C}]$ [K]), t is temperature in °C, v_{w0} is specific volume of water or the inverse of the density of water (i.e., $[1/\rho_w]$ [m^3/kg]), ρ_w is density of water (i.e., 998 kg/m^3 at $t = 20°\mathrm{C}$), and ω_v is molecular mass of water vapor (i.e., 18.016 kg/kmol).

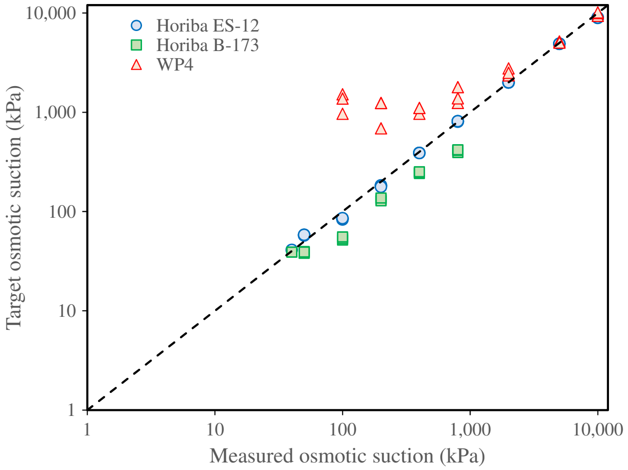
Figure 7 shows a comparison of the target osmotic suctions versus the measured osmotic suctions using the Horiba B-173, Horiba ES-12, and WP4 devices. The reading given by the Horiba ES-12 electrical conductivity meter is the most consistent and reliable, followed by the Horiba B-173 electrical conductivity meter. The WP4 is only reliable for suctions above 1,000 kPa. The osmotic suctions reported in **Table 2** were from the Horiba ES-12 electrical conductivity meter.

TEST PROCEDURES

In this study, the conventional oedometer with a load lever arm ratio of 1:10 was used to conduct the 1-D volume change tests using ASTM D2435/D2435M-11, *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading* (Superseded), for guidance. The soil specimen was cored from the soil blocks prepared earlier using an oedometer ring of 63.5-mm internal diameter and 19-mm height, which has a sharp cutting edge. A thin layer of silicone grease was smeared on the inner surfaces of the oedometer ring before cookie cutting the specimen from the soil block to reduce friction between the specimen and the oedometer

FIG. 7

Comparison between target osmotic suction and measured osmotic suction from electrical conductivity meters and WP4 device.



ring (ASTM D2435/D2435M-11). The soil specimen contained in the oedometer ring was placed in contact with the RO membrane on its bottom. Below the RO membrane is the porous stone. The soil specimen was then inundated in water and consolidated to the specific effective vertical stress of 64 kPa.

At equilibrium with the vertical stress of 64 kPa, the water in the oedometer cell was removed by siphoning, and the NaCl solution contained in the reservoir was circulated through the porous stone under a low-pressure head and returned to the reservoir via a peristaltic pump as shown in **figure 4**. The reservoir contains a large volume of NaCl solution (500 cm^3) compared with the volume of pore water in the soil specimen (about 0.43 cm^3) to ensure that the concentration of the NaCl solution remains almost constant during the test. In the current setup, the suction and volume or mass of the water exchange is not measured during the experiment, but matric suction and water content of the soil specimen were measured at the end of every test. The effect of the osmotic technique was observed by comparing the results with an identical (control) test but with a continuous circulation of distilled water through the base of the oedometer. The tests were performed in an environment where the ambient temperature range is 24°C ± 4°C. To minimize water loss from the soil specimen by evaporation, the top cap of the setup was covered by moist cotton wool. The test procedures were repeated with identical specimens but with a different concentration of NaCl solution.

SUCTION MEASUREMENTS

As mentioned earlier, water flows from the soil specimen through the membrane as a result of the osmotic gradient created by the NaCl solution on the opposite side of the membrane and induces a matric suction in the soil specimen. Independent suction measurements were conducted on the soil specimens after the test. A high-capacity tensiometer (HCT) developed by Wijaya and Leong (2016) was used to measure the matric suctions of the soil specimens after the test. The matric suction was measured by placing the soil specimen in contact with the HAE ceramic disk of the HCT. To improve the contact condition between the soil specimen and the HCT, a kaolin paste with water content between its plastic and liquid limits as suggested by (Oliveira and Marinho 2008) was used. The kaolin paste delays evaporation of the HCT while the specimen is being placed and smooths out any irregularities on the contact surface of the soil specimen. Once the soil specimen is in contact with the HAE ceramic disk, water pressure in the HCT starts to equilibrate with the pore-water pressure in the soil specimen. Measurements were made immediately after the test on both the top and bottom faces of the soil specimens. Thereafter, the soil specimen was wrapped up in 2 layers of cling wrap and a layer of aluminum foil for 24 h to allow moisture equilibration in a humidity cupboard, and the suction measurements with the HCT were repeated on the soil specimen.

To confirm that negligible NaCl passes through the RO membrane into the soil specimen, osmotic suction of the soil specimen was determined by measuring the electrical conductivity (*EC*) of its pore water. Different methods such as mechanical squeezing, dilution, or saturation can be used to extract the pore water (Iyer 1990). In this study, the pore water was extracted from the soil specimen using a mechanical pore fluid squeezer as described in Leong, Tripathy, and Rahardjo (2003). A small amount of the soil was placed into the pore fluid squeezer, a pressure up to 10 MPa was exerted on the soil using a compression machine, and the pore water was collected in a syringe. The electrical conductivity of the pore water was measured using the Horiba B-173 electrical conductivity meter and converted to osmotic suction using equation (1).

Results and Discussion

ELECTRICAL CONDUCTIVITY

One of the biggest challenges faced with the osmotic technique is the leakage of the PEG molecules through the cellulotic membrane during the test. To assess the performance of the NaCl solution and the RO membrane in this respect, a check was conducted using the electrical conductivity measurements of the pore water of the soil specimen and the salt solutions.

Table 2 summarizes the measured osmotic suctions computed using equation (1) from electrical conductivity measurements of the NaCl solution in the reservoir before and at the end of the test. The electrical conductivity measurements were made using the Horiba ES-12 electrical conductivity meter. The variation in osmotic suctions ranged from 0.3 to 1.15 % for the highest to lowest suctions, respectively. This is attributed to experimental error because of the evaporation effects of the NaCl solution in the reservoir over the test duration. Some of the test durations were as long as 3 mo. However, the changes in osmotic suction of the NaCl solutions at the end of the experiment were negligible.

Table 3 presents a summary of the electrical conductivity measurements of the pore water extracted from the soil specimens before and after the test using the Horiba B-173 electrical conductivity meter and the osmotic suction calculated using equation (1). The osmotic suction of the soil specimen before the test was negligible, less than 6.1 kPa. There was a negligible difference in the electrical conductivity values of the pore water before and after the test. The change in osmotic suction of the soil specimens before and after the test ranges from about 0.3 to 16 kPa or 0.03 to 0.16 % of the applied osmotic suction, which is negligible, indicating that the RO membrane has a good salt rejection rate. To further check the possible degradation of the RO membrane over time, a test conducted under an osmotic suction of 5,000 kPa was ran for 3 mo, and there was no change in the deformation curve. A failure in the RO membrane would result in a change in the deformation curve.

DEFORMATION

The vertical deformation was used to determine the suction equilibrium of the soil specimen in the osmotic oedometer. At equilibrium, there is negligible water flow from the soil specimen through the RO membrane, and the experiment was stopped. For this study, the experiment was stopped when the registered deformation was less than 0.01 mm over 6 h.

TABLE 3

Electrical conductivity of pore water extracted from soil specimens before and after the test

Applied Osmotic Suction, kPa	Electrical Conductivity before the Test, mS/cm	Initial Osmotic Suction, kPa	Electrical Conductivity after the Test, mS/cm	Final Osmotic Suction, kPa
500	0.21	5.2	0.23	5.8
1,000	0.23	5.8	0.24	6.1
2,000	0.21	5.2	0.31	7.9
5,000	0.24	6.1	0.41	11.3
10,000	0.23	5.8	0.72	21.5

Figure 8*A* illustrates the vertical deformations of the soil specimens subjected to different osmotic suctions at the base. The figures represent deformations starting from the point of application of the osmotic suction (the deformation under the vertical stress before application of the salt solution is not presented on the graph). For all specimens tested, the deformation under the vertical stress of 64 kPa before application of the osmotic suction was between 0.31 and 0.34 mm. **Figure 8*A*** shows that the equilibration time increases with an increase in applied osmotic suction.

It can be observed that the deformation shows two segments: the first segment starts on the application of the osmotic suction and the second segment starts after a few days of application of osmotic suction. The time to start for the second segment varies with the osmotic suction applied, and it can be observed that the longest duration is reflected in **figure 8*A*** at the lowest applied osmotic suction of 500 kPa. The possible explanation for the small decrease before leveling off in the first segment is attributed to the process of siphoning out the water from the oedometer cell and a delayed response to the applied osmotic suction. To check the hypothesis, an identical experiment was conducted in which the soil specimen was not inundated with water in the oedometer cell at the beginning of the consolidation test and the osmotic suction of 5,000 kPa was applied after the initial consolidation to 64 kPa. The results illustrated in **figure 8*B*** show that there is only one segment that corresponds to the second segment of **figure 8*A***.

Larger deformations were recorded as the applied osmotic suction increased. This is consistent with the results reported by other researchers (Delage, Vicol, and de Silva 1992). The deformations due to the application of the various osmotic suction values shown in **figure 8*A*** are summarized in **Table 4** and **figure 9**. **Figure 9** shows that the deformation increases at a decreasing rate as in the applied osmotic suction in the osmotic technique increases.

FIG. 8

Time-dependent volume change of the specimens with different applied osmotic suctions at the base: (*A*) inundation of specimen with water at the beginning of the consolidation test and under various applied osmotic suctions; (*B*) no inundation of specimen with water at the beginning of the consolidation test and under 5,000 kPa applied osmotic suction.

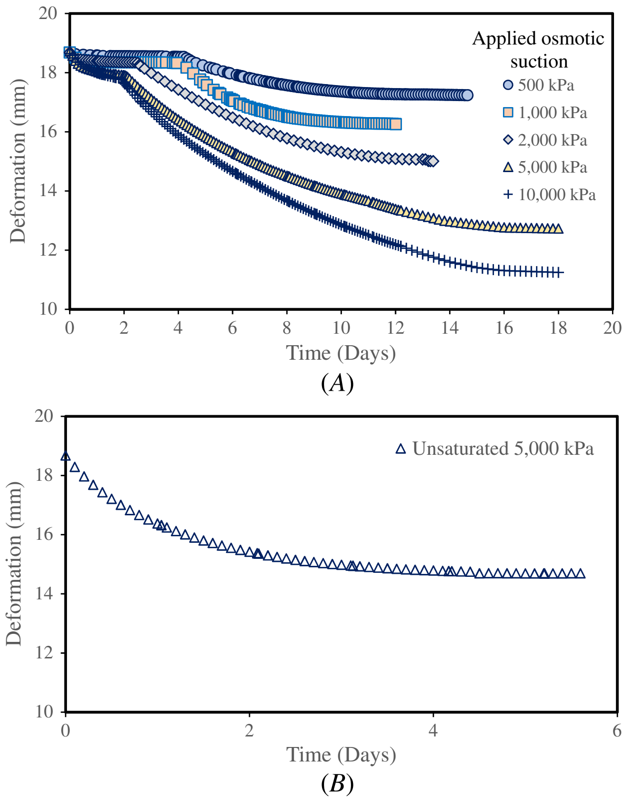


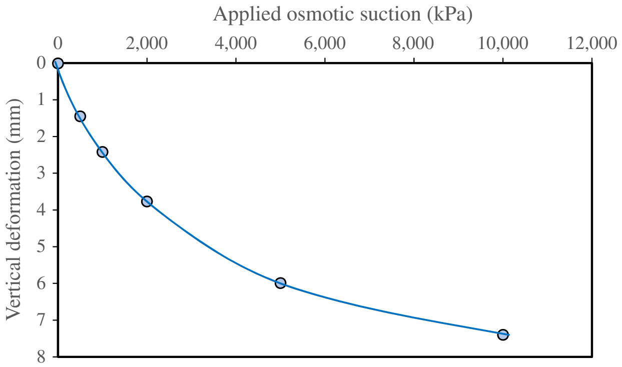
TABLE 4

Deformations due to applied osmotic suctions

Osmotic Suction, kPa	Observed Deformation, mm
500	1.45
1,000	2.42
2,000	3.77
5,000	5.99
10,000	7.40

FIG. 9

Total deformation against applied osmotic suction.



MATRIC SUCTION

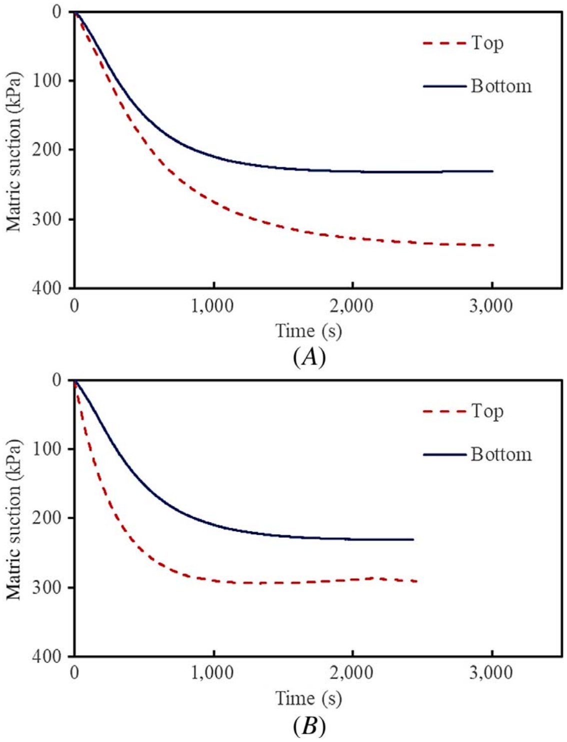
The matric suctions of the soil specimen on the top and bottom faces were measured using an HCT at the end of the test. Typical responses of the HCT are shown in figures 10 and 11 for soil specimens subjected to applied osmotic suctions of 2,000 and 5,000 kPa, respectively. It can be observed that the matric suction recorded at the bottom faces of the specimens is lower than the matric suction recorded at the top faces, showing that there is a pore-water pressure gradient within the soil specimen and that the pore water was subjected to 1-D flow through the bottom of the specimen. Hence, the osmotic technique imposes a matric suction on the bottom of the soil specimen, causing it to consolidate further.

After measuring the matric suction immediately after the test, the soil specimens were wrapped with two layers of cling wrap and one layer of aluminum foil and kept in an air-tight zip lock bag in a humidity cupboard for 24 h for moisture equilibration. Thereafter, the matric suctions were again measured for both the top and bottom faces of the soil specimens. The matric suction readings are summarized in Table 5. The matric suctions at the top and bottom faces are closer in value, and the average matric suction is almost equal to the average matric suction of the soil specimen measured immediately after the test. The difference in average matric suctions immediately after the test and 1 day after the test becomes smaller as the applied osmotic suction increases. The matric suction induced by the osmotic technique is the measured matric suction less the measured matric suction of the control test specimen where water in place of NaCl solution was circulated at the base of the oedometer instead. The corrected average matric suctions due solely to osmotic technique are summarized in Table 6. Nevertheless, the measured matric suction of the soil specimen at the end of the test is much less than the applied osmotic suction. Similar results have been reported by researchers using PEG solutions such as Peck and Rabbidge (1969), Delage and Cui (2008a), Slatter et al. (2000), and Zur (1966). The difference in measured matric suction and applied osmotic suction has been reported to be about 20 % (Dineen and Burland 1995).

Figure 12 shows the variation of corrected average matric suction measured after 1-day moisture equilibration with the applied osmotic suction. According to figure 12, the measured matric suction is about 13 %

FIG. 10

Responses of the HCT to soil specimen under applied osmotic suction of 2,000 kPa: (*A*) immediately after test; (*B*) 1-day moisture equilibration after test.



of the applied osmotic suction. The osmotic suction of a saturated NaCl solution was measured to be 38,803 kPa using the WP4 compared with a theoretical value of 38,790–38,972 kPa based on equation (2). According to the relationship in **figure 12**, the expected matric suction of a soil using the osmotic oedometer with a saturated NaCl solution is about 13 % of 38,803 kPa, that is, 5,000 kPa. The lower matric suction is attributed to the membrane resistance effect (Slatter et al. 2000; Tarantino and Mongiovi 2000; Monroy et al. 2007). The membrane resistance effect is a complicated phenomenon and has been a topic of intense research in desalination. It has been attributed to the concentration polarization phenomenon in membrane processes (Tang et al. 2010; Chanukya, Patil, and Rastogi 2013; Klaysom et al. 2013; Rong and Zhang 2018). The concentration polarization phenomenon is more complicated in the RO membrane because of its three-layered structure.

The water flux Q_v through a membrane is driven by a pressure difference across the membrane and can be written as follows (Henkens, Eijsermans, and Smit 1979; Kim and Hoek 2005; Feher 2017; Dominijanni, Guarena, and Manassero 2018):

$$Q_v = L_p\left(\Delta p - \Delta \pi\right) \tag{3}$$

where L_p is the hydraulic permeability, Δp is the hydrostatic pressure, and $\Delta\pi$ is the osmotic pressure. However, equation (3) is modified because of the concentration polarization phenomenon to the following:

$$Q_v = L_p\left(\Delta p - \Delta \pi_{eff}\right) \tag{4}$$

where $\Delta\pi_{eff}$ is the effective osmotic pressure. The ratio of $\Delta\pi_{eff}$ and $\Delta\pi$ is known as the reflection coefficient ω, i.e.,

FIG. 11

Responses of the HCT to soil specimen under applied osmotic suction of 5,000 kPa: (*A*) immediately after test; (*B*) 1-day moisture equilibration after test.

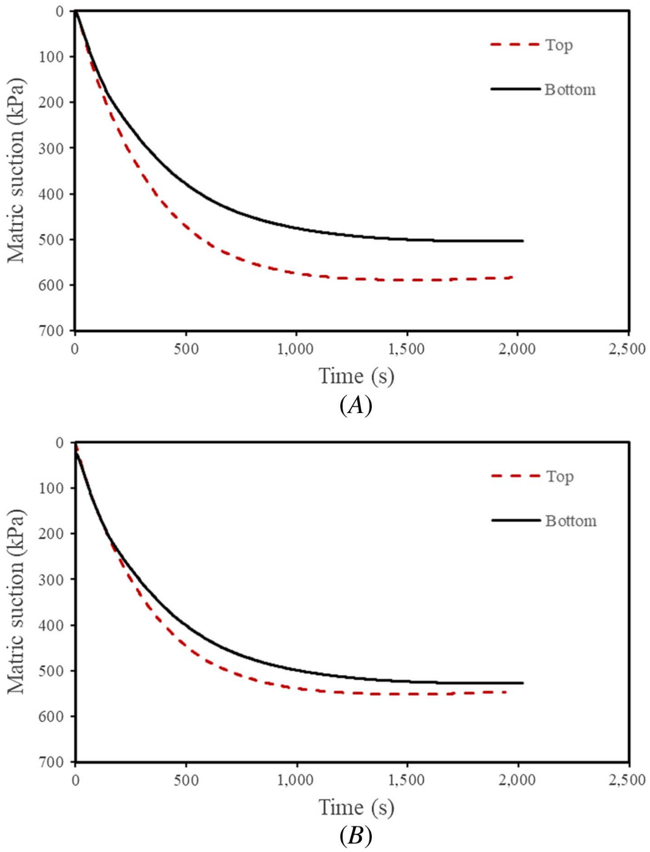


TABLE 5

Matric suctions measured on the top and bottom faces of the specimen immediately after the test and after 1-day moisture equilibration

	Measured Matric Suction, kPa					
	Immediately after the Test			1 Day after the Test		
Osmotic Suction, kPa	Top	Bottom	Average	Top	Bottom	Average
Control	51.6	33.9	42.8	44.6	40.1	42.4
500	185.3	102.3	143.8	107.0	104.2	105.6
1,000	203.2	162.0	182.6	168.7	166.2	167.5
2,000	337.7	231.3	284.5	291.0	231.0	261.0
5,000	782.6	723.5	753.1	738.2	732.1	735.2
10,000	1,422.1	1,201.3	1,311.7	1,318.2[a]	1,305.2	1,305.2

Note: [a] Final reading recorded before the HCT cavitated. Hence, this value was ignored in averaging.

$$\omega = \frac{\Delta\pi_{eff}}{\Delta\pi} \tag{5}$$

The symbol ω for reflection coefficient follows that used by Dominijanni, Guarena, and Manassero (2018). In the osmotic oedometer, Δp is given by the matric suction in the soil specimen, and $\Delta\pi$ is given by the osmotic

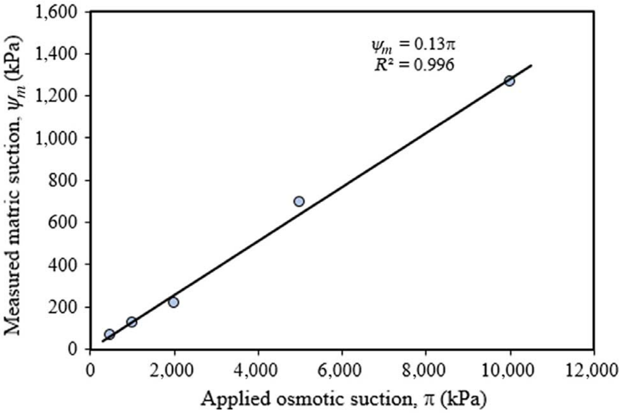
TABLE 6

Corrected average measured matric suctions immediately after the test and after 1-day moisture equilibration

	Corrected Measured Matric Suction, kPa			
	Immediately after the Test		1 Day after the Test	
Osmotic Suction, kPa	Corrected Average	Reduction from Applied Osmotic Suction, %	Corrected Average	Reduction from Applied Osmotic Suction, %
500	101	79.8	63.2	87.4
1,000	139.8	86.0	125.1	87.5
2,000	241.7	87.9	218.6	89.1
5,000	710.3	85.8	692.8	86.1
10,000	1,268.9	87.3	1,262.8	87.4

FIG. 12

Relationship of measured matric suction and applied osmotic suction.



suction of the NaCl solution. At equilibrium, no flow condition prevails, and the matric suction of the specimen is given by $\Delta\pi_{eff}$. **Figure 13** shows the variation of the reflection coefficients from Peck and Rabbidge (1969) ranging from 0.54 to 0.73, Dineen and Burland (1995) ranging from 0.77 to 0.83, Slatter et al. (2000) ranging from 0.6 to 1, Tarantino and Mongiovi (2000) ranging from 0.9 to 0.95, and Yuan, Liu, and Buzzi (2017) ranging from 0.85 to 1.0 for different concentrations of PEG solutions and membranes. This indicates that different osmotic technique

FIG. 13

Reflection coefficients from others.

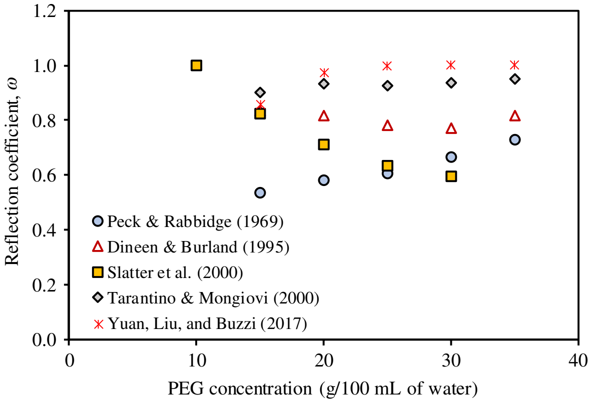
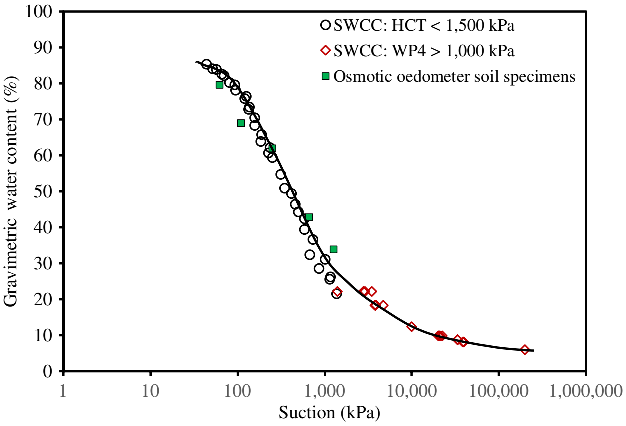


FIG. 14

Drying SWCC for KB30 from HCT and WP4 together with the water content and matric suction of the soil specimens from the osmotic oedometer test.



setups have different reflection coefficients and, as a result, there is a need for independent suction measurement of the soil specimen for verification at the end of the test. For the osmotic oedometer used in this study, ω ranges from 0.11 to 0.14, with an average value of 0.13. The membrane resistance effect in the RO membrane is more than the cellulotic membrane or PES membrane because of its three-layered structure.

Further experimental evidence of ω is obtained from the SWCC of the soil. Figure 14 shows the SWCC of the soil obtained from drying soil specimens in which the matric suction was measured using the HCT for suctions below 1,500 kPa and the WP4 for suctions above 1,000 kPa. The gravimetric water content and the matric suction of the soil specimens from the osmotic oedometer tests are also plotted in figure 14, showing good agreement with the SWCC.

Conclusion

This paper investigated the application of the osmotic technique using NaCl solutions and an RO membrane in a conventional oedometer. Independent matric suction measurement of the soil specimens conducted after the test using an HCT revealed that the matric suction was about 13 % of the applied osmotic suction, that is, the reflection coefficient of the RO membrane is 0.13. The reduction is caused by the membrane resistance effect attributed to concentration polarization in membrane processes. It is expected that the matric suction of the soil specimen as a function of the applied osmotic suction will be different for different combinations of membrane and salt solution in the osmotic technique. Hence, a calibration should be performed on the soil specimen to ascertain the achievable matric suction when applying the osmotic technique. The updated osmotic oedometer is attractive, as it does not have the drawbacks of the previous osmotic oedometer using PEG solution and a cellulotic membrane. In this study, the setup has only been verified for an induced matric suction of up to 1,300 kPa using a NaCl solution with osmotic suction of 10,000 kPa. For a saturated NaCl solution, the osmotic oedometer can theoretically induce a matric suction of up to 5,000 kPa on the soil specimen based on a reflection coefficient of 0.13. A volume or mass measurement device can be added to the setup for the determination of the SWCC of the soil specimen under constant normal stress by changing the concentration of the salt solution after each equilibrium point. Other salt solutions, such as potassium chloride and sodium sulfate, can also be investigated as well as other commercial forward osmosis and RO membranes to see if additional benefits can be derived. The use of other types of membranes (e.g., a microfiltration membrane) with NaCl solution can be investigated in further studies.

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