Geotechnical Testing Journal

doi:10.1520/GTJ20230387 available online at www.astm.org

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Reliability of Chilled-Mirror Hygrometer (WP4C) for Soil Total Suction Measurement

Reference

Y. Lu, H. Abuel-Naga, E.-C. Leong, and Z. Shang, "Reliability of Chilled-Mirror Hygrometer (WP4C) for Soil Total Suction Measurement," *Geotechnical Testing Journal* https://doi.org/10.1520/GTJ20230387

ABSTRACT

The WP4C chilled-mirror dew-point hygrometer is widely used for measuring soil total suction. This study aimed to evaluate its reliability in determining total soil suction through the vapor equilibrium technique. Results showed offsets between WP4C measurements of soil specimens and its corresponding vapor equilibrium saline solution, particularly for suctions below 10 MPa. This difference can be attributed to the difference in vapor diffusion behavior because of the presence of both liquid and solid evaporation surfaces in the soil case, as opposed to just a liquid surface in the saline solution case. To address this issue, the study modified the WP4C sample cups to present varying solution surface areas to the WP4C, representing varying volumetric water contents of the soil. The results reveal that the total suction measurement increases as the surface area decreases for a specific salt solution. This outcome was used to develop a new WP4C correction equation based on solution surface area. The proposed correction equation was validated through experiments and literature data, showing that it significantly improves the measurement precision of the WP4C.

Keywords

chilled-mirror hygrometer, WP4C, soil suction, water retention curve

Manuscript received April 24, 2023; accepted for publication September 12, 2023; published online November 20, 2023.

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Introduction

Total soil suction, also referred to as soil water potential, is a crucial factor in engineering problems involving unsaturated soils. It is the sum of matric suction and osmotic suction, and its importance has been widely recognized in geotechnical engineering and soil science. Total soil suction has been thoroughly researched, with numerous studies highlighting its significance in various applications (Leong, He, and Rahardjo 2002; Leong, Abuel-Naga, and Lu 2018; Beddoe, Take, and Rowe 2011; Al Rashid et al. 2018; Leong and Abuel-Naga 2018; Lu, Abuel-Naga, and Leong 2020).

There are a variety of suction measurement devices available, each with its own advantages and disadvantages (Leong and Wijaya 2023). For example, the tensiometer measures matric suction in the range of 0 to 90 kPa, whereas the null-type axis translation device can measure matric suction up to 1,500 kPa. The filter paper can measure both matric and total suction in the range of 1 kPa to 1,000 MPa. The thermocouple psychrometer measures total suction in the range of 100 to 8,000 kPa, and the chilled-mirror hygrometer measures total suction in the range of 1,000 kPa to 450 MPa.

Reliable and fast suction measurements are essential in geotechnical engineering and soil science, as they help to understand the water content and water potential of unsaturated soils. In this regard, the chilled-mirror dew-point hygrometer has become a popular choice because of its ability to provide quick measurements at high suctions (e.g., minutes to hours for WP4 all models, days for the filter paper, weeks for the vapor equilibrium technique [VET]). This device measures the relative humidity of a soil specimen in a confined space and then converts the measurement to total suction. It is also listed as Method D in ASTM D6836, *Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge*, which is used to determine the water retention curve on a drying path (ASTM D6836-02, 2010).

However, high relative humidity (>99 %) can pose challenges for accurate suction measurements as the measurement process is generally more difficult because of the variations in vapor diffusion equilibration in unsaturated soils (McCartney and Alsherif 2015; Ng et al. 2020). Despite this, the importance of soil suction and the need for reliable and fast measurements make it an important area of research in geotechnical engineering and soil science.

The WP4 series (all models) of chilled-mirror hygrometers is widely used in geotechnical engineering (Leong, Tripathy, and Rahardjo 2003; Cardoso et al. 2007; Ali et al. 2014; Ferrari et al. 2014; Seiphoori, Ferrari, and Laloui 2014; Lu et al. 2018; Lu, Abuel-Naga, and Bouazza 2017). The WP4 is considered a primary standard for relative humidity measurement (Leong, Tripathy, and Rahardjo 2003). The latest model, WP4C, has a range of 0 to 300 MPa and is specified with resolution of ±50 kPa from 0 to 5 MPa and ±1 % between 5 to 300 MPa, which is an improvement from the earlier model WP4T (±100 kPa from 0 to 10 MPa and ±1 % between 10 to 300 MPa). However, the WP4T/WP4C has not always been found to provide correct total suction readings (Leong, Tripathy, and Rahardjo 2003; Leong et al. 2007; Petry and Jiang 2004; Cardoso et al. 2007; Suits et al. 2007; Mabirzi and Bulut 2009; Mantri and Bulut 2014; Wei and Miller 2019). In this article, the WP4C and earlier models will be referred to simply as WP4 unless specific model identification is needed. The precision of the WP4 is comparable to other chilled-mirror hygrometers, with measurement accuracy dependent on sample size, material surface area, air space above the sample, suction range, and temperature (Lewicki et al. 1978). The accuracy of the WP4 has been evaluated by multiple researchers (Gee et al. 1992; Leong, Tripathy, and Rahardjo 2003; Leong et al. 2007; Petry and Jiang 2004; Cardoso et al. 2007; Le et al. 2008; Mabirzi and Bulut 2009; Ebrahimi-Birang and Fredlund 2016). The WP4 is known to produce either similar or higher total suctions compared to other relative humidity measuring devices (Mabirzi and Bulut 2009; Ebrahimi-Birang and Fredlund 2016), and it produces higher suctions than the vapor equilibrium method at comparable water content (Cardoso et al. 2007; Le et al. 2008). Furthermore, the WP4 shows higher total suctions than the filter paper method (Petry and Jiang 2004; Suits et al. 2007; Mabirzi and Bulut 2009), and it shows higher suctions than independent measurements of matric and osmotic suctions (Leong, Tripathy, and Rahardjo 2003; Leon et al. 2007). However, data from Klein et al. (2010) suggests that the WP4 may have issues measuring suctions below 1.0 MPa. Gee et al. (1992) and Mantri and Bulut (2014) also suggested that suction measurements below 300–400 kPa may be beyond the WP4's capability. The WP4's precision is influenced by random errors (e.g., soil structure variability) and systematic errors (e.g., the assumption that a porous material has the same evaporation surface area as a liquid). Although random errors cannot be fully eliminated, it is possible to correct systematic errors. Therefore, this article aims to propose a correction curve to improve the WP4's precision in the suction range of 0–10 MPa, where the WP4 has a specified resolution of ±100 kPa. Experimental work will be performed to demonstrate WP4's limitations and to introduce the correction curve. The proposed correction curve will be verified with test results from this study and datasets from the literature.

Operation of WP4C

The operation of the WP4C is simpler compared to other testing methods. The soil specimen is placed in a sample cup (38 mm in diameter and 11 mm in height), filled to the halfway mark, and positioned in the WP4C's sample drawer for vapor diffusion equilibrium (Decagon Devices, Inc. 2003). The sample drawer compartment has an infrared thermometer to measure the soil specimen's temperature and a cooled surface (chilled-mirror), which condenses (dew-point) and is detected by an optical sensor. The dew-point and specimen temperature are used to determine relative humidity, and total suction is calculated based on Kelvin's equation as follows:

$$\psi_t = -\frac{RT}{v_{w0}\omega_V}\ln(R_h) \tag{1}$$

where ψ_t is the total suction (kPa); R is the gas constant (8.31432 J/(mol K)); T is the absolute temperature ($T = (273.16 + t$°C) K); v_{w0} is the specific volume of water ($1/\rho_W$ m^3/kg); ω_V is the molecular mass of water vapor (18.016 kg/kmol); R_h is the relative humidity.

The WP4C achieves equilibrium in less than 10 min, on average (Leong, Tripathy, and Rahardjo 2003; Campbell, Smith, and Teare 2007; Cardoso et al. 2007). The device has three reading modes: fast, precise, and continuous. The manufacturer recommends the fast mode for low relative humidity soils, the precise mode for high relative humidity soils, and the continuous mode for soils that require a prolonged equilibrium time. Calibrating the WP4C is straightforward based on Decagon Devices, Inc. (2003). The calibration involves adjusting two factors: slope and offset. The slope factor is predetermined in the factory and programmed into the firmware. Users only need to verify and adjust the offset using a standard solution with a known suction (0.5M kCl is recommended), with a standard suction reading of 2.19 MPa at 20°C or 2.22 MPa at 25°C. If the WP4C's reading differs from the standard value by more than ±0.05 MPa, the offset is adjusted to the standard value. This is considered a one-point calibration technique, as no other steps are required by the user.

According to Cardoso et al. (2007), calibrating at different one-point suctions typically lowers the total suction readings from expected levels in saline solutions of varying concentrations. They suggest using equation (2) to correct the measured total suction for this discrepancy. However, equation (2) only accounts for the nonlinearity in the WP4 calibration equation, which cannot be fully represented by the slope and offset programmed in the firmware.

$$\psi = \psi_{WP4} - (\psi_{WP4} - \psi_{\text{cal}})\left(1 - \frac{1}{b}\right) \tag{2}$$

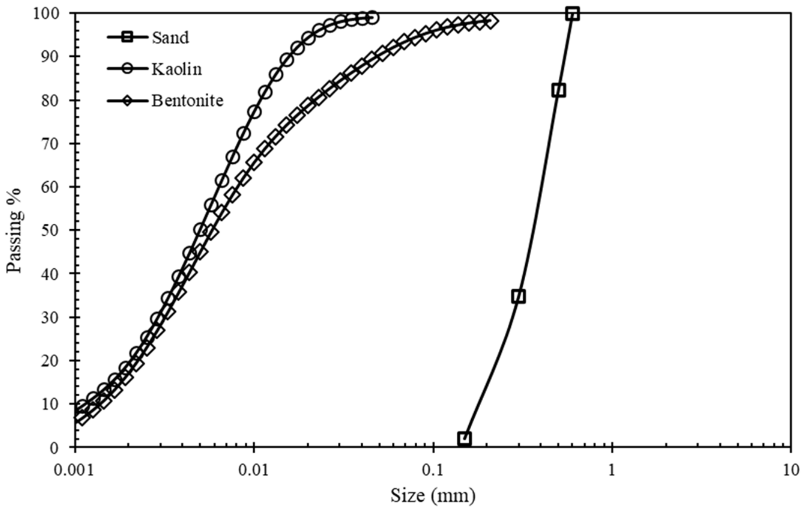
where ψ is the soil total suction (MPa); ψ_{cal} is the calibration point (MPa); ψ_{WP4} is the measured value (MPa); b is the sensitivity coefficient.

Materials and Methods

Different types of reconstituted soil mixtures were prepared in this study using different dry weight percentages of kaolin (K), bentonite (B), and sand mixtures (e.g., K9S1 and B8S2). The number in K/B*S* denotes the fraction of the dry mass of kaolin (K), bentonite (B), and sand (S) to the total dry mass of the soil mixture. The particle size distribution curves of kaolin, bentonite, and sand are shown in **figure 1** (ASTM D6913-04, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*, 2017; ISO 13320-1, 1999). The specific gravity is 2.58 for kaolin, 2.68 for bentonite (both provided by the manufacturer), and 2.65 for sand (ASTM D6913-04, 2017). The liquid and plastic limit for kaolin is 74 % and 32 %, and 503 % and 53 % for bentonite

FIG. 1

Particle size distribution for sand, kaolin, and bentonite.



(ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, 2010). The maximum and minimum void ratio for sand is 0.968 and 0.582, respectively (ASTM D4253, *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*, 2006; ASTM D4254, *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*, 2006). For the VET, NaCl and $CaCl_2$ salt solutions at varying concentrations were employed to control suction levels up to 10 MPa. All experiments in this study were performed at a temperature of 22°C.

Experimental Program

In this study, laboratory work was conducted to evaluate the reliability of the WP4C in measuring total soil suction. A comparison was made between WP4C measurements of soil specimens controlled by the VET and its corresponding saline solution used to control its suction. To investigate the impact of the liquid surface area ratio of the WP4C cup, a testing program was also conducted using modified WP4C cups with varying liquid surface area ratios. WP4C measurements of different salt solutions were taken using the modified cups and compared with their readings obtained using a standard WP4C cup. The testing program was also expanded to evaluate the impact of WP4C measuring time on its suction reading using its continuous reading mode. Additionally, an experiment was conducted to verify the sealing condition of the WP4C cup during the measurement mode. The experimental program will be described in detail in the following section.

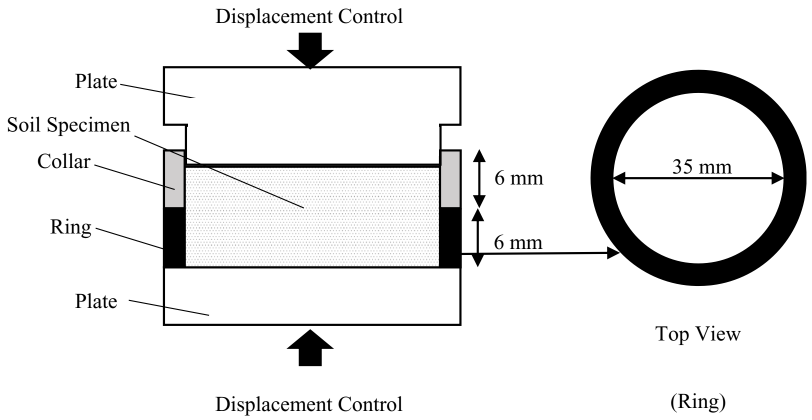
SPECIMEN PREPARATION

The soil was mixed using a mixer and evenly moistened by spraying water from a spray bottle. The target water content for the kaolin and bentonite mixtures was close to the liquid limit. After mixing, the soil mixture was stored in a sealed plastic bag for 24 h to attain moisture equilibrium. A portion of the soil was then statically compressed in a rigid ring with a collar to the target height using a displacement-controlled loading machine, as depicted in figure 2. The soil specimen was allowed to relax for an hour to relieve stress and any elastic rebound. Finally, the soil specimen was extracted from the ring and placed in a WP4C sample cup.

RELIABILITY OF WP4C MEASUREMENTS

The study employed the VET to control the suction of the prepared specimens. This technique relies on the exchange of vapor between the soil specimen and saline solution in the desiccator until they reach relative

FIG. 2 Specimen preparation by static compression.



humidity equilibrium. At this point, the soil has a total suction equal to the suction of the saline solution (Tang and Cui 2005; Pintado, Lloret, and Romero 2009). To prevent condensation in the desiccator at high relative humidity (low suction), the inside of the desiccator lid was oiled and tilted slightly (10°), as shown in **figure 3** (Houston, Houston, and Wagner 1994; Likos and Lu 2002). Upon reaching equilibrium (constant weight), the suction of the soil specimen and its corresponding salt solution were measured using WP4C (precise mode). The final height of the soil specimen was determined with a 0.01-mm resolution laser sensor, as shown in **figure 4**. The study assumed isotropic shrinkage allowing the final volume of the specimen to be estimated where the volumetric water content, θ_w, can be calculated as follows:

$$\theta_w = \frac{V_w}{V} \tag{3}$$

where V_w is the volume of water; V is the total volume of soil specimen.

Four identical specimens were prepared for each kaolin mix (K, K9S1, and K8S2) and three for each bentonite mix (B, B9S1, and B8S2). The specimens were placed in a desiccator and equilibrated with a saline solution at a temperature of 22°C, as shown in **figure 3**. Four different NaCl concentrations (0.1 M, 0.15 M, 0.2 M, and 0.4 M) were used for the Kaolin specimens. The bentonite specimens were equilibrated with three different NaCl concentrations (0.5 M, 0.9 M, and 1.4 M).

FIG. 3 Vapor equilibrium technique to prepare the specimen with 10° in the tilt angle to prevent water drop.

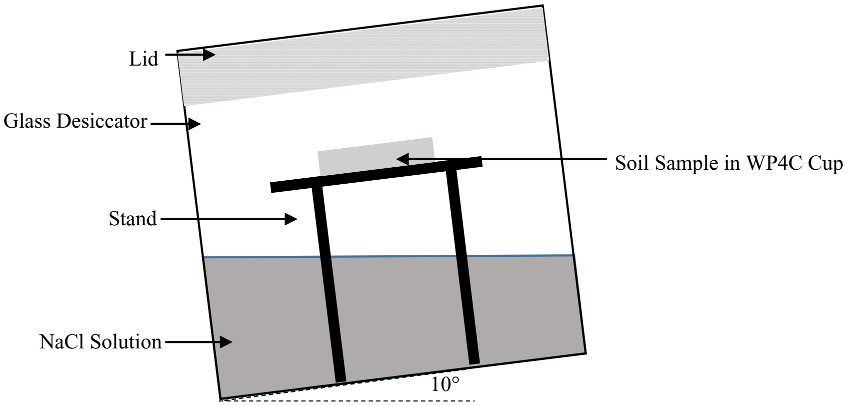
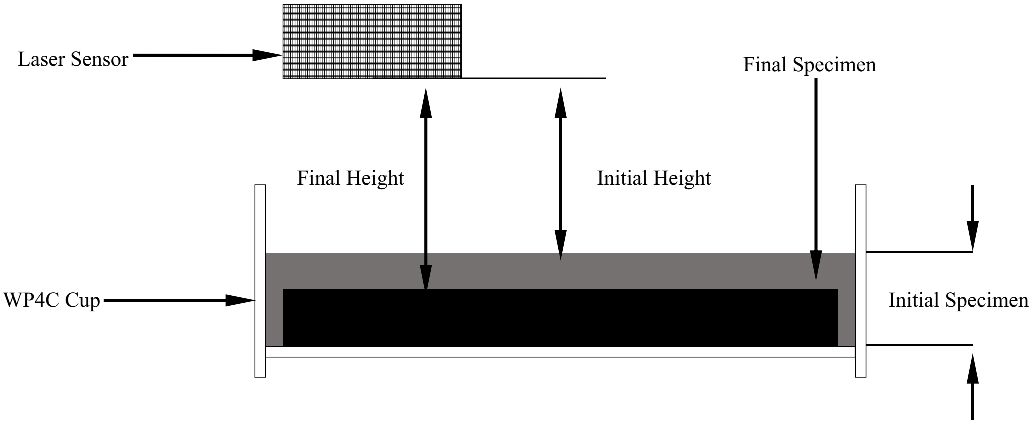


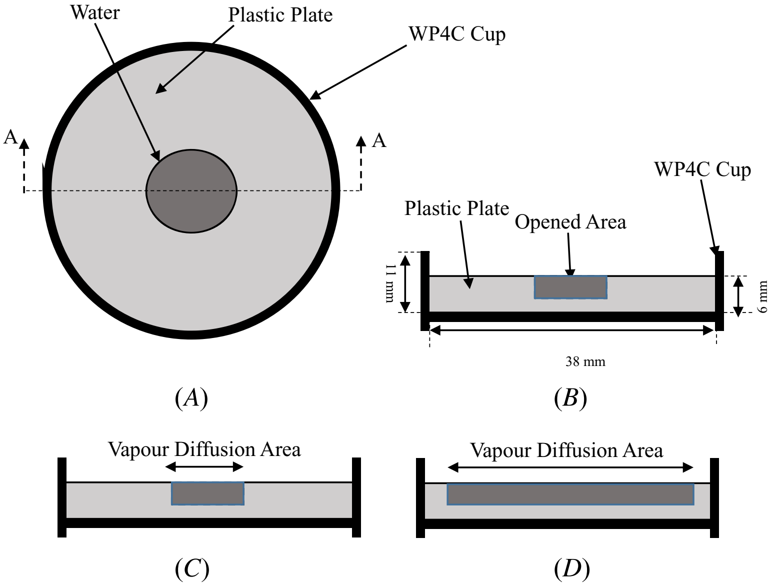
FIG. 4 Laser sensor to measure volume change of the specimen assuming isotropic shrinkage.



EFFECT OF SURFACE LIQUID AREA RATIO ON WP4C READINGS

Leong et al. (2007) noted that if the cross-sectional area of the WP4C sample cup was not fully covered with salt solution, higher total suction readings were obtained. So, it can be hypothesized that an unsaturated soil specimen presents a similar scenario, as the surface of the unsaturated soil comprises solid, air, and water phases. To further investigate the differences in vapor diffusion of a saline solution and an unsaturated soil specimen, the WP4C sample cup was modified, as shown in figure 5. The modified sample cup was fitted with an acrylic disk with a central recess. The area of the recess A_w was varied according to area ratios A_w/A of 0.1, 0.3, 0.5, 0.7, and 0.9, where A is the cross-sectional area of the WP4C sample cup. The recess was filled with a saline solution of various concentrations, and suction measurement was made using the WP4C. The concentrations of the NaCl saline solution included 0.1 M, 0.2 M, 0.3 M, 0.5 M, and 2 M. The WP4C

FIG. 5 Cup used to fill water to assess different vapor diffusion effect: (*A*) top view, (*B*) A-A view, (*C*) small liquid area ratio, and (*D*) large liquid area ratio.



measurements were repeated three times using the precise mode. It should be mentioned that the area ratio A_w/A can represent the volumetric water content of the soil specimen, θ_w.

Test Results

Figure 6 illustrates the typical time required for kaolin (K) specimens to reach equilibrium when exposed to 0.1M and 0.4M NaCl solutions in the desiccator. Both specimens required approximately 35 days to reach equilibrium, which is defined as two consecutive gravimetric water content readings with less than 0.5 % variation over a five-day period. This time frame is in line with findings from other studies using the VET (Tang and Cui 2005; Pintado, Lloret, and Romero 2009). Once all specimens in the desiccator achieved moisture equilibrium, the total suction of the specimens and the corresponding NaCl solutions were measured and plotted in figure 7. The results show that WP4C measured

FIG. 6

Gravimetric water content against day for K (0.1M and 0.4M).

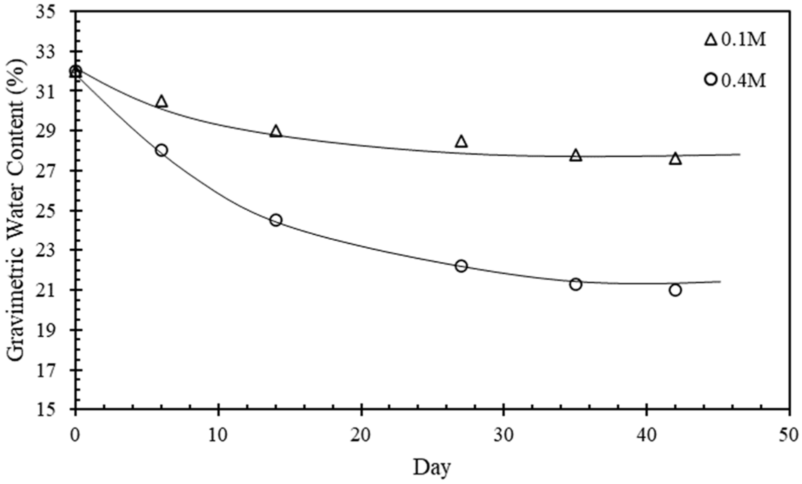
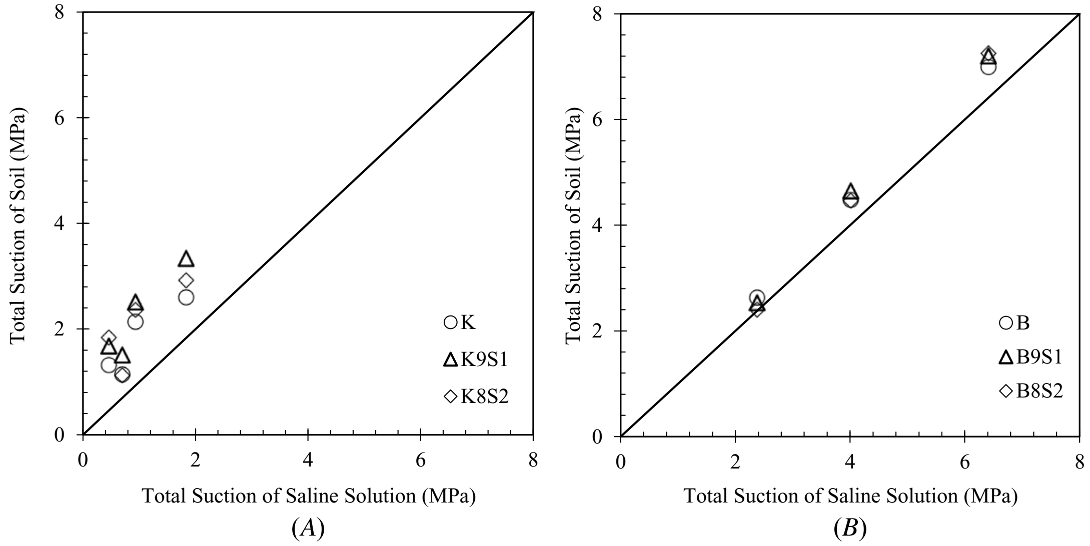


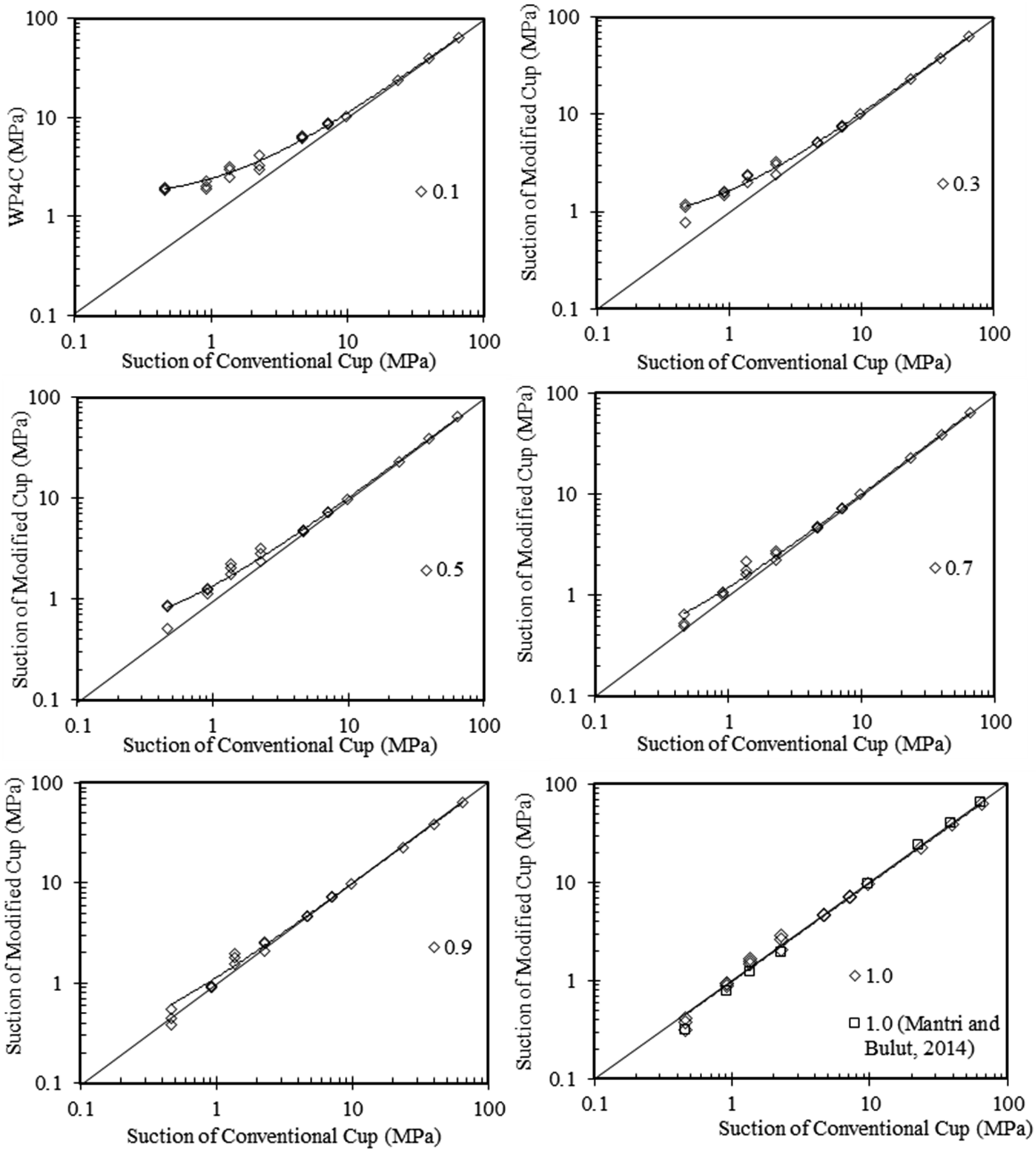
FIG. 7 Total suction of soil specimens and their saline solutions after equilibrium using WP4C: (*A*) kaolin-sand mixture and (*B*) bentonite-sand mixture.



higher suctions for the soil specimens compared to the NaCl solutions they were equilibrated with. This trend has also been reported in other studies (Cardoso et al. 2007; Bulut and Leong 2009; Gubiani et al. 2013; Ferrari et al. 2014; Mantri and Bulut 2014; Ebrahimi-Birang and Fredlund 2016). This variation in suction readings could be attributable to insufficient equilibrium time in the sample chamber when using the precise mode. Evaporation from a partially saturated porous surface is different from the liquid surface case, as the evaporation resistance in the porous surface could delay the evaporation process (Bange 1953; Schlünder 1988; Lehmann et al. 2018).

The laboratory results on the impact of the liquid area ratio on WP4C readings are presented in **figure 8**. The results show that for a specific NaCl solution, the total suction in the modified sample cup is always higher than the reading in the original cup (actual), and the difference increases as the A_w/A ratio decreases. **Figure 8** also indicates that for total suction values above 10 MPa, the A_w/A ratio has a negligible effect on the WP4 reading.

FIG. 8 Effect of A_w/A ratio on WP4 suction measurements of NaCl saline solutions at different concentrations.

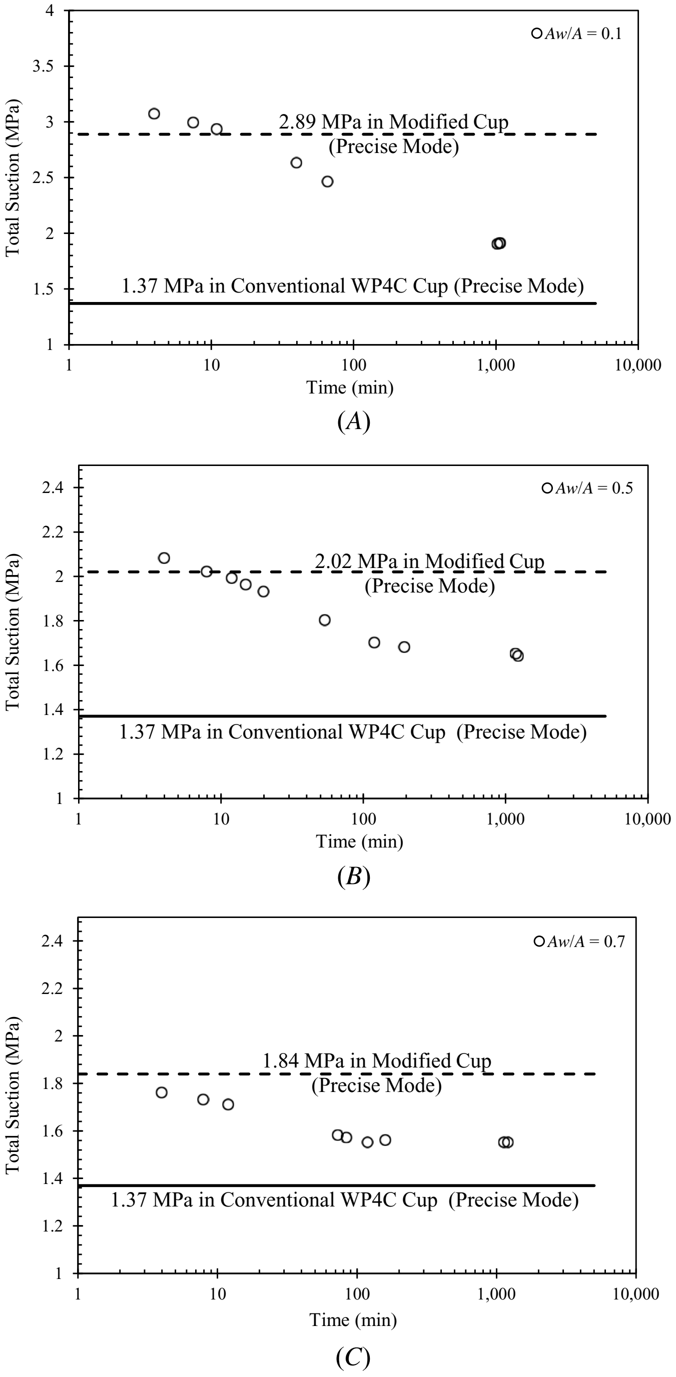


Discussion and Analysis

To investigate the evolution of suction readings over time in the WP4C, the continuous mode of measurement was employed (**fig. 9**). The total suction of the NaCl solution measured using the original WP4 sample cup

FIG. 9

Comparison between continuous and precise mode of WP4 readings for a certain NaCl using conventional WP4C cup and modified cups at A_w/A (0.1, 0.5, and 0.7): (*A*) Aw/A = 0.1, (*B*) Aw/A = 0.5, and (*C*) Aw/A = 0.7.



($A_w/A = 1.0$) in the precise mode was 1.37 MPa. The total suction readings measured using the modified sample cups in both the continuous and precise modes are presented in **figure 9*A*–*C*** for A_w/A values of 0.1, 0.5, and 0.7, respectively. The results show that the precise mode readings of the modified cups overestimated the total suction. However, the continuous mode readings of the modified sample cups showed higher readings at the beginning compared to the precise mode, but then decreased toward the reading of the conventional cup over time. Despite this, the continuous mode readings of the modified cup did not reach the total suction reading of the conventional cup (1.37 MPa) even after 1,000 min. These results suggest that longer measurement time may be necessary when the A_w/A ratio is less than 1.0. Lozano et al. (2008) reported that it takes over 200 min for a silty sand soil with 10 % clay content to reach equilibrium in a sealed environment when subjected to changes in suction. The equilibration time is expected to increase with an increase in clay content. As the results in **figure 9** did not reach equilibrium even after 1,000 min, the sealing condition of the WP4 cup during the measurement mode was investigated.

The WP4 cups were filled with water and a 0.1 M NaCl solution and placed in the WP4C device under the measurement mode for over 1,800 min, and the change in liquid weight was monitored. The results shown in **figure 10** indicate that about 2.6 % of the water weight evaporated per day, whereas the 0.1 M NaCl solution lost about 2.35 % of its weight per day. This imperfect sealing condition could affect the accuracy of suction measurements taken using the continuous mode over long periods. Based on these results, using the continuous mode is not recommended as it does not improve the resolution of WP4C readings and cannot mitigate the impact of the area ratio. Therefore, a general area ratio correction method should be developed to improve the precision of WP4C readings.

CORRECTING WP4C READING FOR EFFECT OF AREA RATIO

The results of the effect of A_w/A on WP4 readings presented in **figure 8** are replotted in **figure 11** and could be mathematically modelled using the following equation:

$$\psi = m(\psi_{WP4})^c \tag{4}$$

where ψ is the actual total suction (conventional cup), ψ_{WP4} is the uncorrected WP4C suction (modified cup), m and c are the correction constants dependent on the area ratio. Equation (4) must satisfy two conditions, $\psi = 0$ at $\psi_{WP4} = 0$, and $\psi = 10$ MPa at $\psi_{WP4} = 10$ MPa. Condition 1 is that the WP4C is able to give readings close to zero suction and condition 2 assumes that suction readings above 10 MPa is not affected by the area ratio. To satisfy these two conditions,

FIG. 10

Monitoring sealing condition of WP4C conventional cup under the continuous reading mode for saline solution.

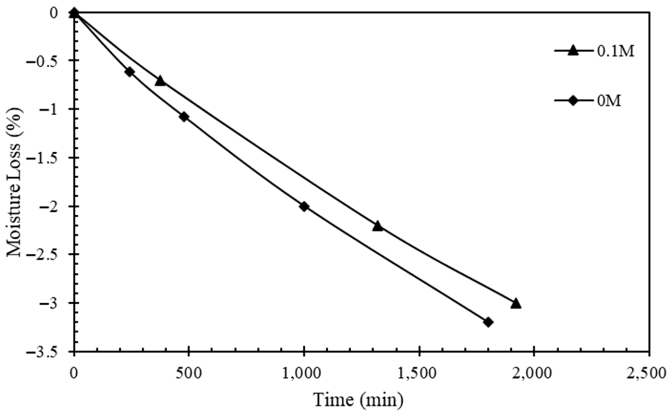


FIG. 11

Difference of suction when using conventional cup and modified cup with various exposed area measuring different molality of saline solutions.

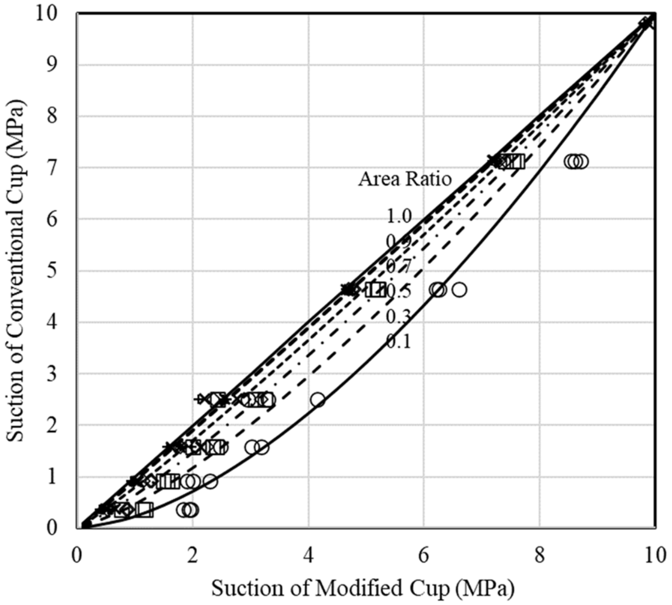
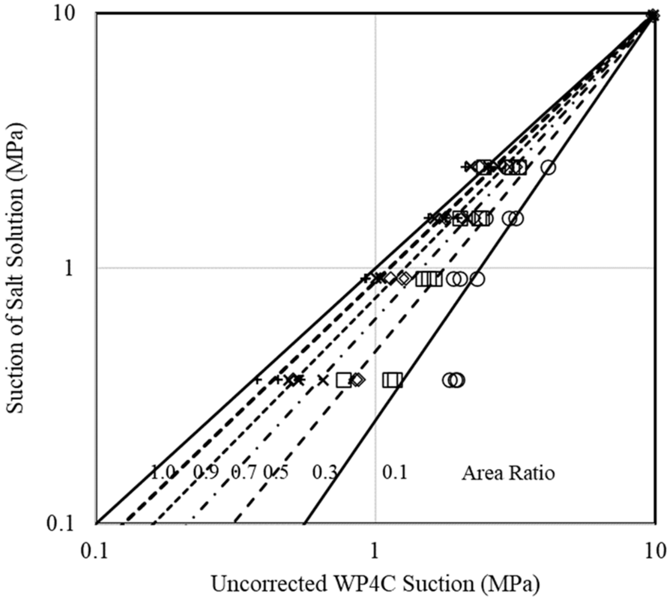


FIG. 12

Replot of **figure 13** on a log-log plot.

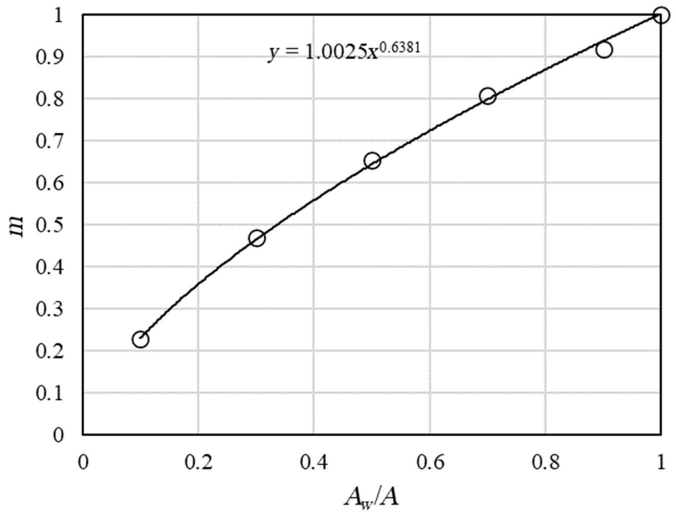


$$c = 1 - \log(m) \tag{5}$$

Hence, only m needs to be determined. **Figure 11** replots on a log-log plot as shown in **figure 12** to display the fitting of equation (5). **Figure 13** shows the variation of m with area ratio. Total suction of saline solution in

FIG. 13

Relationship between m and A_w/A



desiccator (**fig. 3**) was transferred into the sample cup by a syringe and measured using the WP4C. The relationship of m with the area ratio is given by equation (6).

$$m = 0.942\left(\frac{A_w}{A}\right)^{0.5684} = 0.942\theta_w^{0.5684} \tag{6}$$

where θ_w is the volumetric water content. Using equations (2)–(6), the uncorrected WP4C suction can be corrected to give the actual suction.

VALIDATION OF THE PROPOSED CORRECTION CURVES

Table 1 lists some data to get constant m and c, including the data from this study and Leong, Tripathy, and Rahardjo (2003) and Leong et al. (2007) as an example.

Figures 14 and **15** and **Table A.1** compare the WP4C total suction readings of the kaolin and bentonite mixtures from this study with and without the "corrected" results obtained using equations (2)–(6). The results suggest that the proposed correction curves are valid, as they improve the precision of the results. The validity of the proposed WP4C correction method in this study is also supported by multiple datasets from the literature, despite the limitations of the measurement methods used (such as the loss of moisture in the filter paper technique or hydraulic barriers in the pressure plate technique).

Leong, Tripathy, and Rahardjo (2003) measured total, matric, and osmotic suctions of sandstone and mudstone, and found that WP4 readings overestimated total suction by up to 100 % (e.g., 2.5 MPa by WP4 vs. 1.25 MPa actual). However, the errors were significantly reduced after applying the proposed correction in this study, as shown in **figure 16**. Leong et al. (2007) conducted similar tests on kaolin and residual soils, which also showed improved results after correction, as shown in **figure 17**.

Petry and Jiang (2007) compared the WP4 and filter paper readings from seven geotechnical laboratories for three expansive clay soils at three water content-dry unit weight configurations. **Figure 18** showed the data from Petry and Jiang (2007) indicating that WP4 readings were higher. After applying the proposed correction curves, the slope improved to 0.9074, indicating better agreement between the two techniques, as shown in **figure 18**.

TABLE 1

Some data obtained to get constant *m* and *c* from this study and Leong, Tripathy, and Rahardjo (2003) and Leong et al. (2007)

Soils	θ_w	Constant m	Constant c	Reference
K	27.70	0.454	1.343	This study
	27.80	0.455	1.342	
	25.65	0.435	1.362	
	21.26	0.391	1.408	
K9S1	20.24	0.380	1.420	
	21.96	0.398	1.400	
	21.22	0.390	1.409	
	12.16	0.284	1.546	
K8S2	22.73	0.406	1.392	
	25.42	0.433	1.364	
	16.63	0.340	1.469	
	13.59	0.303	1.519	
Mudstone	25.38	0.432	1.364	Leong, Tripathy, and Rahardjo (2003)
	30.07	0.476	1.322	
	35.02	0.519	1.285	
	26.32	0.441	1.355	
	30.20	0.477	1.321	
	34.54	0.515	1.288	
	25.93	0.437	1.359	
	29.91	0.474	1.324	
	34.54	0.515	1.288	
Sandstone	21.94	0.398	1.400	
	27.06	0.448	1.349	
	31.56	0.489	1.311	
	37.28	0.538	1.269	
	22.24	0.401	1.397	
	27.08	0.448	1.348	
	31.76	0.491	1.309	
	37.58	0.540	1.268	
	23.98	0.418	1.378	
	27.67	0.454	1.343	
	32.40	0.496	1.304	
	37.07	0.536	1.271	
Kaolin	26.93	0.447	1.350	Leong et al. (2007)
	29.48	0.471	1.327	
	32.64	0.499	1.302	
	34.43	0.514	1.289	
	36.96	0.535	1.272	
	39.12	0.553	1.258	
Soil A	17.11	0.345	1.462	
	20.79	0.386	1.414	
	26.72	0.445	1.352	
	28.96	0.466	1.332	
	31.86	0.492	1.308	
Soil B	19.01	0.367	1.436	
	23.79	0.417	1.380	
	25.90	0.437	1.359	
	29.12	0.467	1.330	

FIG. 14

Comparison for kaolin mixtures in this study.

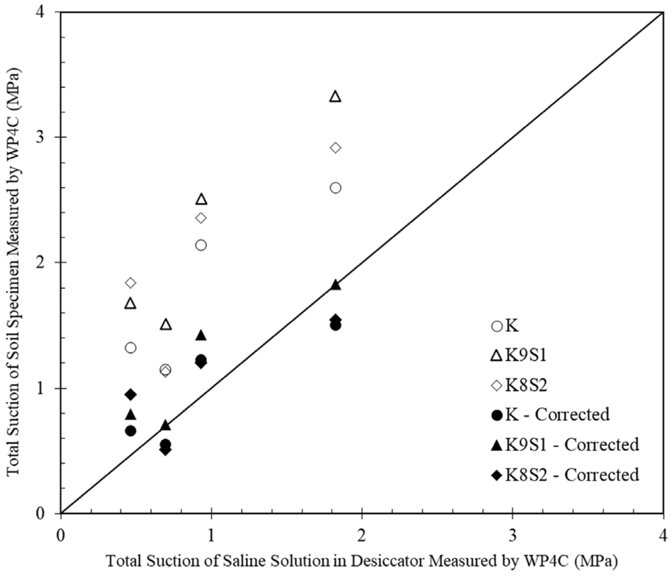


FIG. 15

Comparison for bentonite mixtures in this study.

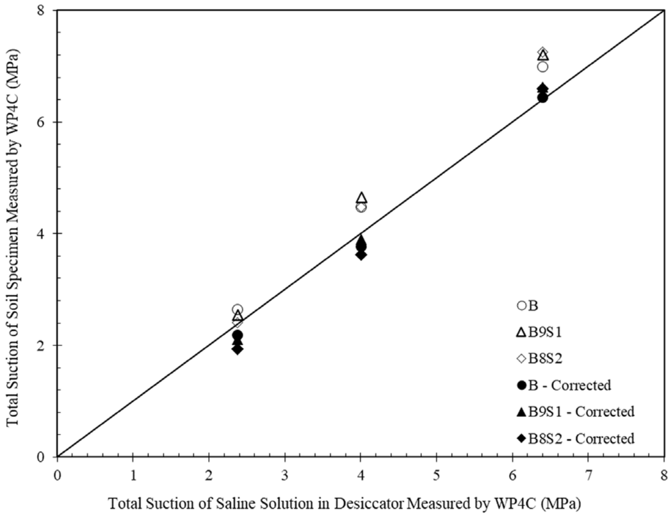


Figure 19 compares suction measurements by WP4, hanging column, and pressure plate for silty sand from Anderson and Stormont (n.d.). The WP4 readings from 100 kPa to 65 MPa are not consistent with the readings from hanging column and pressure plate. However, after applying the proposed correction curves to WP4 readings from 100 kPa to 10 MPa, they align better with hanging column and pressure plate measurements, as shown in **figure 19**.

FIG. 16

Comparisons for sandstone and mudstone residual soils (data from Leong, Tripathy, and Rahardjo 2003).

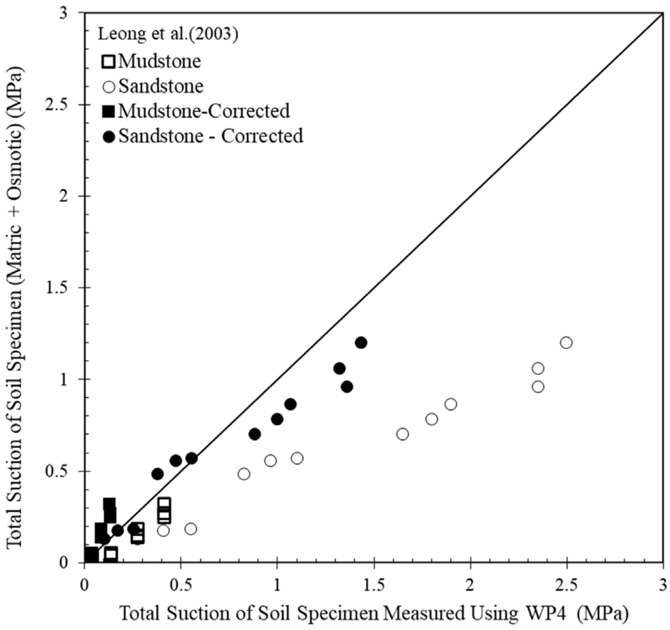


FIG. 17

Comparison for kaolin, residual soils A and B (data from Leong, Tripathy, and Rahardjo 2007).

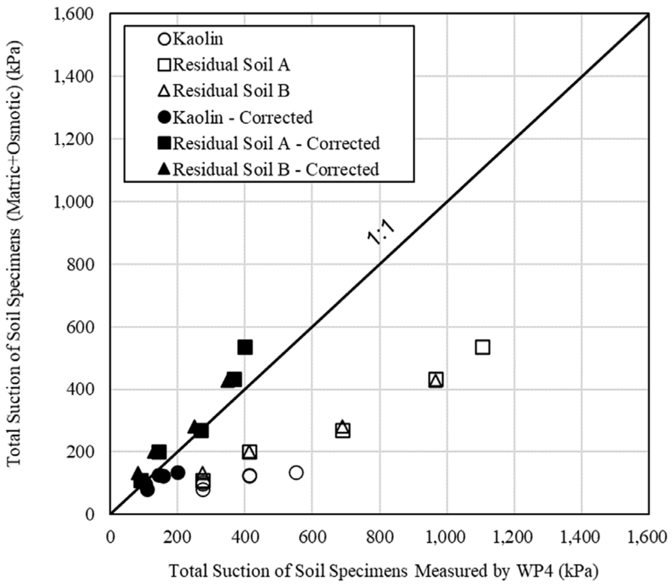


Figure 20 shows a comparison of fly ash suction measurements using WP4, tensiometer, MPS, and equi-tensiometer (Abhijit and Sreedeep 2015). After applying the proposed correction curves, WP4 reading agree better with the other methods.

FIG. 18

Comparison of WP4 and filter paper suction (data from Petry and Jiang 2004).

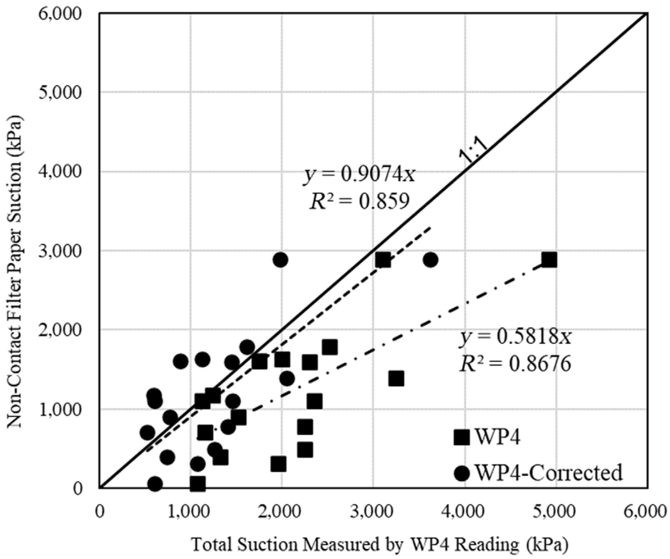


FIG. 19

Comparison of suctions from WP4, hanging column, and pressure plate (data from Anderson and Stormont n.d.).

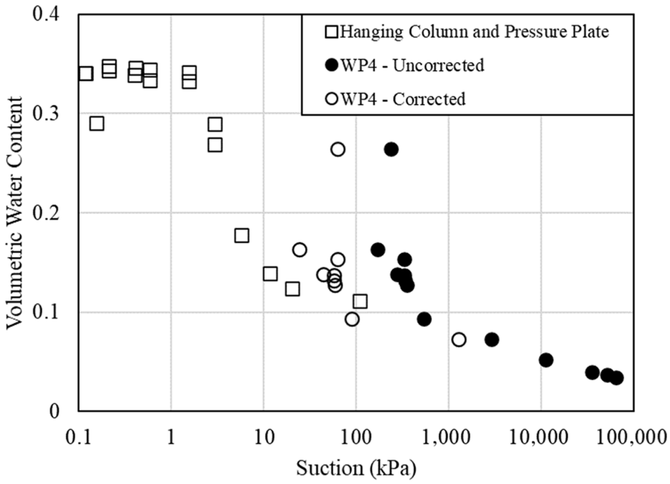


Figure 21 presents WP4 and pressure plate readings for a 1:1 mixture of Metro Mix 902 and all-purpose sand by volume (Nelson, McGinnis, and Daigh 2018). After applying the proposed correction curves to the WP4 readings from 1 to 10 MPa, the WP4 readings agree better with the pressure plate data.

Applying the proposed correction curves to the WP4 suction readings in this study (**figs. 14** and **15**) and those from the literature (**figs. 16–21**) improve the WP4 suction readings from 0 to 10 MPa to align with the other methods. However, the reliability issue remains unresolved for low suction readings as WP4 readings still show limiting values of 300 to 400 kPa, as noted by Gee et al. (1992) and Mantri and Bulut (2014).

FIG. 20

Comparison of suctions from WP4 and other methods (data from Abhijit and Sreedeep 2015).

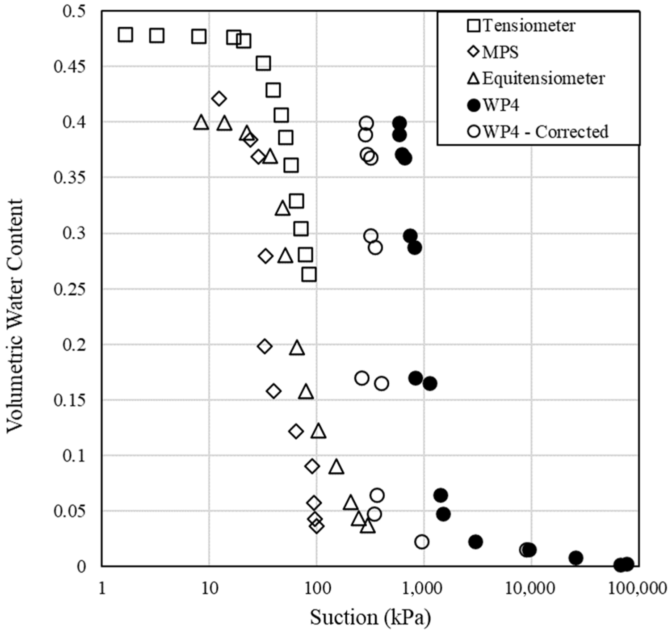
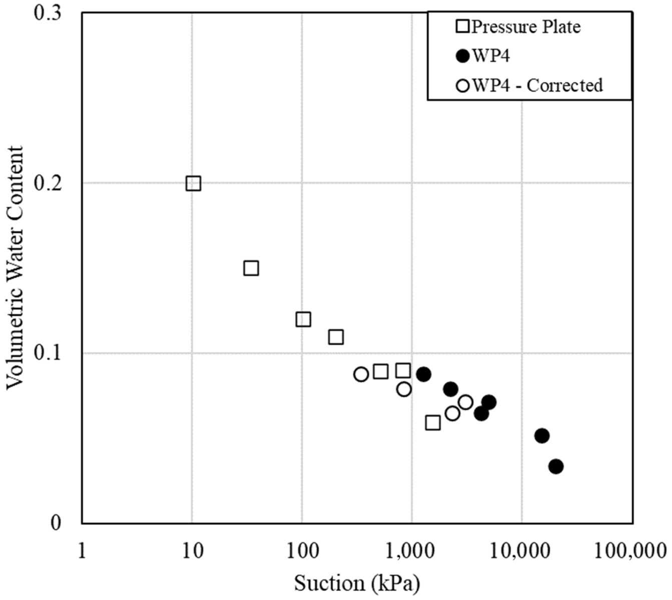


FIG. 21

Comparison of suction from WP4 and pressure plate (data from Nelson, McGinnis, and Daigh 2018).



Conclusions

This study provides valuable insights into the accuracy of WP4C measurements of soil suction in unsaturated soils. The results indicate that WP4 (all models) generally overestimates soil suction, particularly for values below 10 MPa, because of differences in vapor diffusion behavior between a liquid surface and soil surface, which requires longer equilibration time for soil. However, the imperfect sealing of the WP4C cup makes continuous mode equilibration over a prolonged period unreliable. In response, this study proposed a correction method for the precise mode in WP4 (all models) based on soil volumetric water content, which has been validated using literature datasets. Although the proposed method can improve the precision of readings, it does not fully resolve the reliability issues associated with WP4 (all models) soil suction measurements, particularly at low suction levels below 400 kPa.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant Nos. 52108310, 51991393, 5202010500).

Appendix

TABLE A.1

Supplementary data for calculation

Soils	A_w/A, %	Soil Suction from WP4C, MPa	Salt Solution Suction, MPa
K	27.70	1.32	0.46
	27.80	1.15	0.69
	25.65	2.14	0.93
	21.26	2.61	1.82
K9S1	20.24	1.68	0.46
	21.96	1.51	0.70
	21.22	2.51	0.93
	12.16	3.33	1.82
K8S2	22.73	1.84	0.46
	25.42	1.13	0.70
	16.63	2.36	0.93
	13.59	2.92	1.82
B	62.19	2.64	2.38
	46.63	4.48	4.01
	43.89	6.99	6.40
B9S1	63.78	2.54	2.38
	43.68	4.65	4.01
	39.70	7.20	6.40
B8S2	58.94	2.41	2.38
	38.61	4.47	4.01
	34.08	7.25	6.40

Note: The data are given as supplementary data.

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