sustainability

MDPI

Article

Measurement of Soil–Water Characteristic Curve of Vegetative Soil Using Polymer-Based Tensiometer for Maintaining Environmental Sustainability

Widjojo Adi Prakoso [1], Abdul Halim Hamdany [1,*], Martin Wijaya [2], Rabbani Isya Ramadhan [1], Aldo Wirastana Adinegara [1], Alfrendo Satyanaga [3,*], Glenn Adriel Adiguna [2] and Jong Kim [3]

[1] Department of Civil Engineering, Universitas Indonesia, Depok 16424, Indonesia; wprakoso@eng.ui.ac.id (W.A.P.); rabbani.isya@ui.ac.id (R.I.R.); aldo.wirastana@ui.ac.id (A.W.A.)
[2] Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung 40141, Indonesia; mwijaya@unpar.ac.id (M.W.); glenn.adiguna@unpar.ac.id (G.A.A.)
[3] Department of Civil and Environmental Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Kabanbay Batyr 53, Astana 010000, Kazakhstan; jong.kim@nu.edu.kz
* Correspondence: abdul.halim04@office.ui.ac.id (A.H.H.); alfrendo.satyanaga@nu.edu.kz (A.S.)

Abstract: The interaction between moisture content and soil suction is commonly represented by a soil–water characteristic curve (SWCC). The direct measurement of water content can be easily achieved, but it usually requires a destructive method where the soil sample needs to be oven-dried. Hence, indirect measurement is commonly employed for monitoring purposes. The limitation of this approach is the variability in water content at the wilting point, particularly for plants in different types of soil. While the moisture content at the wilting point varies greatly, suction at the wilting point is typically around 1500 kPa despite varying slightly depending on the type of plant. However, suction measurement using a normal tensiometer is limited to 100 kPa due to cavitation. Hence, it is not sufficient to cover up to the wilting point. The focus of this paper is the establishment of a polymer-based tensiometer utilizing a 15 bar ceramic disc for the measurement of high suction. The suitability of the polymer-based tensiometer in measuring the soil suction of vegetative soil is conducted by performing a soil–water characteristic curve test on vegetative soil. The SWCC produced from the polymer-based tensiometer is verified using SWCC produced from a centrifuge test. The results show that the SWCCs from both polymer-based tensiometer and centrifuge tests are comparable. Hence, suction measurement using a polymer-based tensiometer is deemed reliable. This advancement in suction measurement technology is crucial for improving irrigation practices, optimizing water use, and enhancing agricultural productivity, which in turn contributes to environmental sustainability by minimizing water waste and ensuring efficient soil management.

Keywords: vegetative soils; SWCC; polymer; tensiometer; environment sustainability

check for updates

Received: 12 September 2024
Revised: 7 December 2024
Accepted: 10 December 2024
Published: 31 December 2024

Citation: Prakoso, W.A.; Hamdany, A.H.; Wijaya, M.; Ramadhan, R.I.; Adinegara, A.W.; Satyanaga, A.; Adiguna, G.A.; Kim, J. Measurement of Soil–Water Characteristic Curve of Vegetative Soil Using Polymer-Based Tensiometer for Maintaining Environmental Sustainability. *Sustainability* **2025**, *17*, 218. https://doi.org/10.3390/su17010218

1. Introduction

One of the pieces of evidence for climate change is an increase in global mean surface temperature (GMST), which leads to warmer days and nights and higher precipitation events in some regions, but drought in other regions [1,2]. As a result, drought-induced mortality (DIM) increases [2,3]. DIM is triggered by water limitations, which can be due to a lack of precipitation or an increase in evaporation [4] and causes plants to lose their hydraulic conductivity, which is usually measured as a percent loss of conductivity (PLC) [5]. In severe drought scenarios, it becomes necessary to observe the PLC in plants.

However, PLC monitoring at a large scale is impractical [2]. The prolonged drought season caused by climate change makes the soil become unsaturated, and, hence, moisture measurement or soil suction measurement appears to be more practical, especially when the monitoring is to be conducted on a larger scale. Effective soil suction measurement can provide valuable insights for managing water resources and mitigating the impacts of drought, contributing to environmental sustainability by enabling more precise agricultural practices, promoting water conservation, and supporting the resilience of ecosystems in the face of climate change.

One of the most important properties for understanding and predicting the behavior of unsaturated soils is the soil–water characteristic curve (SWCC). The SWCC is a curve of the interaction between soil suction and moisture content. SWCC describes the amount of water that can be retained in the soil at a certain soil suction value. The amount of water in the soil can be expressed in terms of weight (gravimetric water content), volume (volumetric water content), or degree of saturation [6]. In unsaturated soil mechanics, the volumetric water content is commonly used to plot the SWCC (SWCC-θ_w). The volumetric water content directly represents the volume of water per volume of soil, which is important for understanding how water flows through the soil. SWCCs with the saturation-based degree (SWCC-Sr) are also important to understanding the behavior of unsaturated soil, which is directly connected to critical engineering properties like strength, volume change, and hydraulic conductivity. The SWCC-Sr is used to determine the air-entry value (AEV), which indicates the point at which soil begins to desaturate, leading to changes in soil strength. The SWCC can be generated by conducting either a drying or wetting process on the sample [7]. The behavior of soil during cycles of wetting and drying is not always the same, resulting in differences between the drying and wetting curves [8,9]. The suction and water content measured in the field are generally between the drying and wetting curves. The zone between the drying and wetting curve is called the scanning curve. Scanning curves are used to represent intermediate pathways between the main drying and wetting curves.

Soil suction or soil moisture is monitored to prevent the soil from reaching the wilting point (WP), which is the maximum soil suction or minimum moisture content at which the plant will not wilt [10]. Direct measurement of volumetric water content in the field commonly utilizes frequency domain reflectometry (FDR) or time domain reflectometry (TDR) for monitoring purposes [11]. The problem with moisture measurement is that the water content at the wilting point for a plant varies greatly in different types of soil [10]. The other issues are also related to uncertainty due to the hysteresis effect of SWCC [12]. While the moisture content at the wilting point varies greatly, the suction at the wilting point is typically around 1500 kPa [13], despite varying slightly depending on the type of plant. Suction in the soil is typically monitored using a tensiometer. A tensiometer requires constant maintenance due to the generation of water bubbles, which limits the duration of suction measurement and makes it impractical for continuous monitoring over a long period of time. The main drawback of a conventional tensiometer is the limitation of suction measuring range, which is limited to 100 kPa due to cavitation [14]. Hence, it is not sufficient up to the wilting point (WP).

Polymer-based tensiometers (PBTs) have been developed to have the capability to measure the suction up to the plant wilting point (1500 kPa) [15–22]. This technology utilizes the swelling or shrinking of a polymer for suction measurement. The implementation of polymers has served as an alternative solution as it relies on osmotic pressure instead of purely water pressure. The polymer particle is placed into the water chamber to prevent tension in the water due to the presence of positive osmotic pressure, thus eliminating the potential for cavitation. The osmotic pressure generated by polymers can be easily produced without problems related to gas or vapor bubble formation in traditional tensiometers, causing a disruption in the continuous liquid phase between the soil and the reference state [20].

The application of polymer-based tensiometers was first established by Peck and Rabbidge [20] using polyethylene glycol (PEG). The results indicated that the instrument was unable to generate a consistent osmotic pressure and produced unreliable data (zero drifts) for more than 1% of the time due to technological constraints at the time. Bakker, van der Ploeg [23] developed a tensiometer filled with polyethylene glycol and polyvinylpyrrolidone polymer. The research showed that the polymer tensiometer had the capacity to measure a larger range of suction pressure, although a gradual drop in osmotic pressure was observed during long-term continuous operation. Hamdany et al. (2022) [15] investigated PBT (referred as NTU osmotic tensiometer) to conduct field monitoring on soil suction. It was reported that the pressure decay affected the long-term performance of the NTU osmotic tensiometer. Liu et al. (2022) [24] further improved the NTU osmotic tensiometer in order to solve the problem of pressure decay by using the synthesis of polymers such as polyacrylamide (PAM) and sodium polyacrylate (NaPA) with varying degrees of cross-linking through ultraviolet polymerization. From the study, the osmotic tensiometer filled with NaPA had a measuring range above 1000 kPa, but the range continued to decrease due to slow pressure decay. Otherwise, the osmotic tensiometer filled with PAM maintained a consistent measuring range of approximately 400 kPa after a rapid pressure decay process. In Liu et al. (2022) [24], the ceramic disk used in the polymer tensiometer had an air entry value (AEV) of up to 500 kPa.

There is a concern regarding water flow in a ceramic disk when the measured suction is beyond the AEV of the ceramic disk (the ceramic disk becomes unsaturated), especially when the suction measurement range is around the plant wilting point. In this paper, a polymer-based tensiometer is investigated using a 1500 kPa AEV ceramic disk (15 bar disk). The suitability of the PBT in measuring the soil suction of vegetative soil is conducted by performing an SWCC test on vegetative soil. At first, the long-term performance of the polymer-based tensiometer is evaluated by means of an evaporation test. The moisture content of the soil sample is recorded using an automatic weighing balance; hence, the moisture content generated in the laboratory is typically in the form of the gravimetric water content. A shrinkage test is then conducted using a three-dimensional scanner. By measuring the volume changes in the soil, a shrinkage curve can be obtained. SWCC-w is then connected to the shrinkage curve to obtain the SWCC-θ_w and the SWCC-Sr. The SWCC obtained using the polymer-based tensiometer is verified by using the SWCC obtained from the centrifuge test.

2. Materials and Methods

2.1. Preparation of Soil Sample

In this study, commercially available vegetative soil was investigated. Vegetative soil refers to an approved soil mixture (ASM) that consists of a specific mixture of loamy soil, compost, and sand that meets the predetermined standards or specifications for landscaping to effectively help plant growth. The original soil specimen is shown in Figure 1a. Before measurement of the soil water characteristics, the oven-dried soil was compacted to determine the compaction curve of the vegetative soil. The soil specimen was reconstituted (see Figure 1b) to achieve 95% relative compaction using the standard Proctor effort. The reconstituted soil had dimensions of 70 mm in diameter and 95 mm in height.

(**a**) (**b**)

Figure 1. Vegetative soil specimen. (**a**) Original soil. (**b**) Reconstituted soil.

The compaction test was carried out in accordance with ASTM D698-12 [25] utilizing Standard Proctor effort. The compaction curve for the vegetative soil can be seen in Figure 2. The compacted vegetative soil achieved a maximum dry density of approximately 1.69 mg/m^3 at an optimum water content of 17%. The soil specimen was prepared at 95% of the maximum dry density, which was around 1.6 mg/m^3, with a water content of 12%.

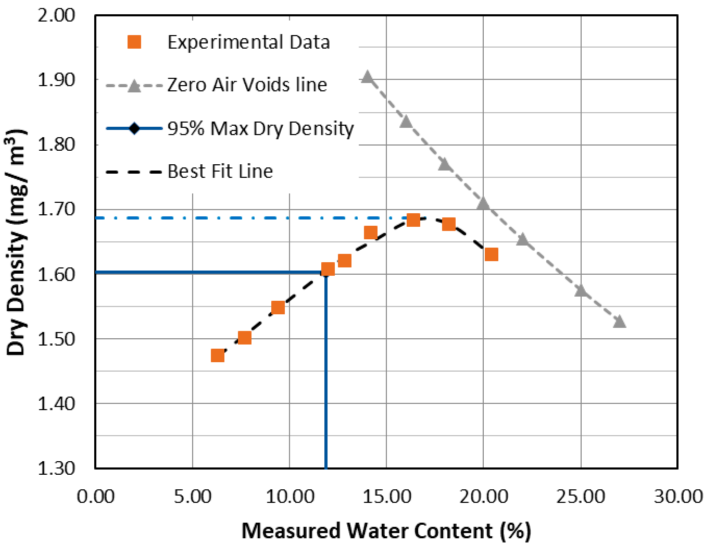


Figure 2. Compaction curve of vegetative soil.

Figure 3 shows the grain size distribution of the vegetative soil, analyzed in accordance with ASTM D6913-04 [26]. The soil mainly consisted of 90% sand and 10% fines. The soil was classified using the Unified Soil Classification System (USCS). The specific gravity (G_s) test was conducted according to ASTM D854-02 [27]. The specific gravity of the soil was about 2.61. The basic soil properties can be found in Table 1.

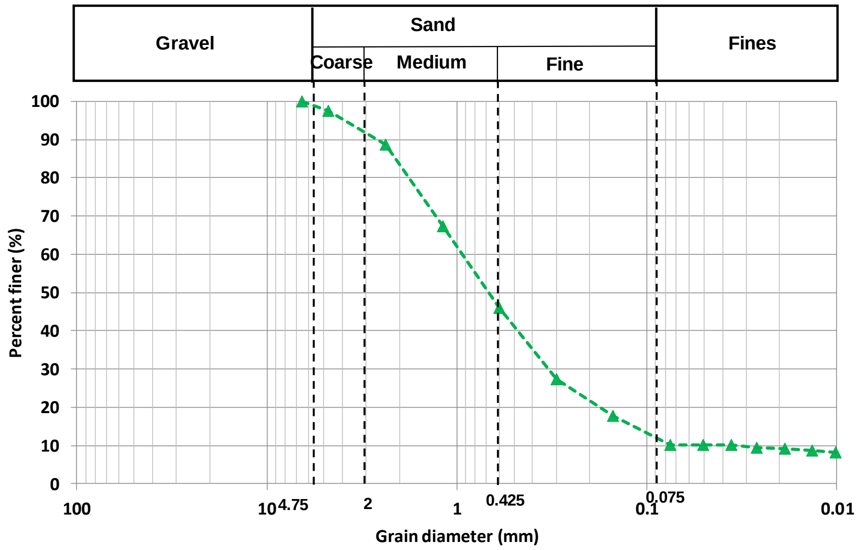


Figure 3. Grain size distribution of vegetative soil.

Table 1. Basic soil properties of vegetative soil.

Specific gravity, G_s	2.61
Dry density, ρ (mg/m^3)	1.60
Water content, w (%)	12
Grain Size—Gravel (%)	0
Grain Size—Sand (%)	90
Grain Size—Fines (%)	10
Soil Classification (USCS)	Silty Sand (SM)

2.2. SWCC Measurement Using Polymer-Based Tensiometer

The polymer-based tensiometer (PBT) used in this study is presented in Figure 4. The PBT followed the design described in Hamdany et al. (2022) [15], with modifications made to the tensiometer cap. The tensiometer cap was made by a ceramic disk with an air-entry value (AEV) of 1500 kPa. The pressure transducer had a capacity to measure pressure of up to 3000 kPa integrated with the temperature sensor. The synthesized polyacrylamide (PAM) polymer was used to prepare the PBT.

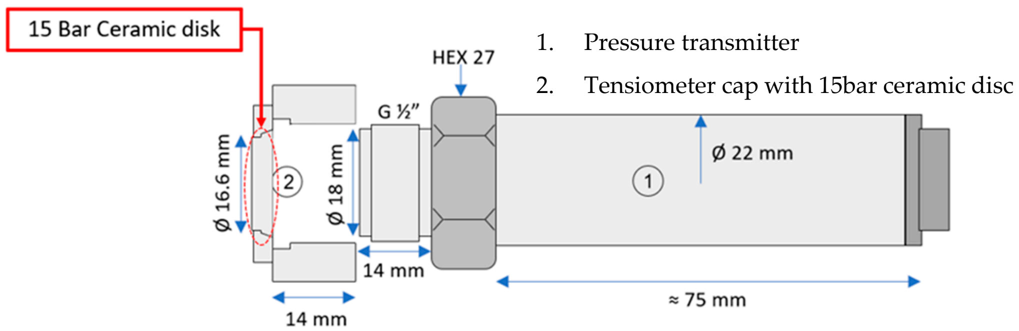


Figure 4. PBT design modified from Hamdany et al. (2022) [15].

2.2.1. Synthesized Polymer

PAM polymer was prepared following the work of Liu et al. (2022) [24]. The main composition of the PAM polymer consisted of acrylamide (AM) as a monomer and *N*,*N*′-methylenebisacrylamide (MBA) as a cross-linker. Benzoin was used as the photo-initiator during the polymerization process coupled with UV light irradiation. In this study, the polymer was synthesized to obtain a 10% degree of cross-linking. The mix proportion was as follows:

1. 7.11 g acrylamide (AM);
2. 0.77 g *N*,*N*′-methylenebisacrylamide (MBA).

A certain amount of AM and MBA was dissolved in distilled water and stirred continuously for 30 min at room temperature (23–25 °C) using a magnetic stirrer at 160 rpm. Following this, benzoin was dissolved in the solution and stirred for an additional 10 min. Subsequently, the combined solution was exposed to a UV light source for 3 h to complete the polymerization. The polymer hydrogel was then removed from the container and shaped as desired. The synthesis process of the polymer can be found in Figure 5.

Figure 5. Synthesis process of PAM polymer.

2.2.2. Preparation of Polymer-Based Tensiometer

After finishing the synthesis process of the polymer (PAM), the sensor was then prepared following the procedure described by Hamdany et al. (2022) [15] and Liu et al. (2022) [24]. Prior to contact with soil, the PBT was initially submerged into the water chamber to observe how the polymer hydrogel swelled when it absorbed the water. The swelling of PAM polymer hydrogel could generate positive pressure into the pressure transducer. The swelling pressure reached the maximum at a certain time after the polymer reached the maximum swell capacity. At this point, there was no suction in the soil.

Before conducting the suction measurement, the sensor needed to be calibrated. To calibrate the effect of temperature on PBT over time, PBT was saturated for 3 days, and the osmotic pressure in the water was measured to capture a sufficient temperature fluctuation. The measurement was conducted at a room temperature of 25 °C. The polymer pressure was calculated based on the difference between the reference pressure and the pressure measured by PBT, which can be written as follows:

$$p_{calibrated} = p_{PBT} - p_{corr} \quad (1)$$

where $p_{calibrated}$ is calibrated pressure of the PBT, p_{crorr} is the correction pressure (temperature-compensated), and p_{PBT} is the pressure measured by PBT. The pressure measured by PBT, p_{PBT}, changes with the temperature. As a result, the reference pressure needed to be determined during the calibration process at a specific temperature. The reference pressure could be determined from the regression of the uncorrected temperature–pressure relationship data.

Declines in swelling pressure indicated increases in the soil suction. The gap between the measured pressure and the maximum swelling pressure served as the soil suction. This value was regarded as negative pore-water pressure. Pressure and temperature were recorded, and these data were used for temperature calibration.

2.2.3. Evaluation of PBT Sensor Performance

The performance of the developed PBT sensor was evaluated through an evaporation test for 3 months. There were two types of evaporation tests conducted for this study. The first test is called EVP 1, in which the sensor was subjected to a wetting and drying cycle for 45 days, followed by continuous wetting for around 45 days. The second test is called EVP 2, in which the sensor was subjected to a continuous wetting and drying cycle for more than 90 days.

One PBT was used for each evaporation test. Hence, two evaporation tests were conducted simultaneously. In the continuous wetting and drying cycle evaporation test (EVP 1), PBT was subjected to wetting (up to maximum polymer pressure) and then dried up to the minimum polymer pressure. The cycle was repeated for three months. The purpose of the continuous wetting and drying cycle evaporation test was to verify whether the PBT would exhibit a decay problem when it was subjected to 3 months of wetting and drying cycles.

PBT underwent a wetting–drying cycle for 2 months, followed by being exposed to maximum swelling pressure through continuous wetting for 1 month during a continuous wetting evaporation test (EVP 2). The purpose of the second test was to verify whether PBT would exhibit a pressure decay problem due to continuous wetting.

2.2.4. Measurement of SWCC Test Using Polymer-Based Tensiometer

In order to obtain SWCC by using the PBT, a reconstituted specimen was put inside a beaker. PBT was placed at the base of the soil, and the change in the weight of the soil specimen was measured using a precision balance. The experimental setup of the measurement devices is shown in Figure 6. Both the PBT and weight scale were connected to a data logger in order to allow for automatic monitoring of soil suction and water content. Data were taken every 24 h on a real-time basis. The soil specimen is slowly dried through evaporation while both the soil suction and water content were recorded.

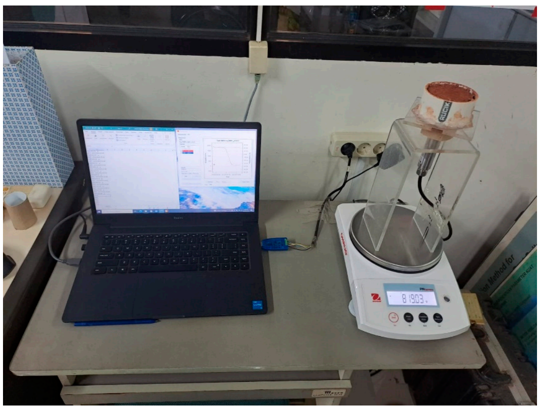


Figure 6. SWCC test by using PBT.

2.3. SWCC Test by Using Centrifuge

The procedure for the centrifuge test has been described by Rahardjo et al. (2019) [28]. An Eppendorf 5810R bench-top centrifuge (Eppendorf AG, Hamburg, Germany) was used in this study. Figure 7 shows the specimen prepared for the centrifuge test. The four specimens were then placed into the swing bucket rotor and subjected to different centrifugal forces. The buckets in the centrifuge could be rotated from 200 to 3900 rpm angular velocities. Different angular velocities of the centrifuge yielded different matric suction levels. Soil specimens were subjected to a specific angular velocity to observe the reduction in water from the specimens using a precision balance. The soil specimens underwent a series of angular velocities, with each velocity representing a specific matric suction to obtain the SWCC. Water loss from the soil specimens was measured at each velocity during this process.

Figure 7. Specimen for centrifuge test.

2.4. Best Fitting for SWCC

The unsaturated soil parameter was determined by fitting all the data using a curve-fitting equation from Fredlund and Xing (1994) [29], as follows:

$$\theta_w = C_{(\psi)}\left(\frac{\theta_s}{\ln\left[e+\left(\frac{\psi}{\alpha}\right)^n\right]^m}\right) \tag{2}$$

where θ_w is the volumetric water content; θ_s is the saturated volumetric water content; ψ is soil suction (kPa); and α, m, and n are the curve-fitting parameters.

The correction factor ($C_{(\psi)}$) is required for the equation to ensure that the water content is neglected at a soil suction of 1 GPa, as follows:

$$C_{(\psi)} = 1 - \frac{\ln\left(1+\frac{\psi}{\psi r}\right)}{\ln\left(1+\frac{10^6}{\psi r}\right)} \tag{3}$$

The equation by Fredlund and Xing (1994) [29] was selected as it can produce an accurate model for a wide range of soils.

2.5. Shrinkage Test

The water content measurement from the SWCC test with PBT and centrifuge was expressed as the gravimetric water content. It is highly important to determine the SWCC using the volumetric water content and degree of saturation. During the shrinkage test, the soil specimen was subjected to an evaporation process which allowed the specimen to slowly air-dry at a room temperature of 25 °C. The specimen's weight was measured regularly until it reached its equilibrium conditions. The 3D scanner was used to measure the volume of the soil specimen at regular intervals. This method accounts for the non-uniformity of the soil sample throughout the sample.

The shrinkage curve was then fitted to the measured data according to Fredlund et al. (2002) [30]. The following equation was used to generate the shrinkage curve:

$$e(w) = a_{sh}\left[\frac{w^{C_{sh}}}{{b_{sh}}^{C_{sh}}}+1\right]^{1/C_{sh}} \tag{4}$$

where a_{sh} is the minimum void ratio (e_{min}), b_{sh} represents the shrinkage limit (SL), c_{sh} is the parameter controlling the curvature of shrinkage curve, and e(w) represents the change in void ratio due to the change in w. A conversion between w and θ_w can be achieved through a correlation of basic soil properties as follows:

$$\theta(s) = \frac{w(s)G_s}{1 + e(w)} \tag{5}$$

where θ(s) is the volumetric water content, w(s) is the gravimetric water content that can be obtained from SWCC-w, G_s is the specific gravity, and e(w) is obtained from the shrinkage curve.

3. Results

3.1. Temperature Calibration

Before conducting suction measurement, the sensor needed to be calibrated. To calibrate the effect of temperature on the PBT over time, the PBT was saturated for 3 days, and the polymer swelling pressure in the water was measured to capture a sufficient temperature fluctuation. The measurement was conducted at a room temperature of 25 °C. The results of the change in uncorrected pressure and temperature over time can be seen in Figure 8. During the saturation process, the pressure started to increase significantly within the first six hours until reaching the maximum pressure. It is shown that the pressure fluctuated following the change in room temperature. Hence, the pressure measurement should be calibrated against the temperature change.

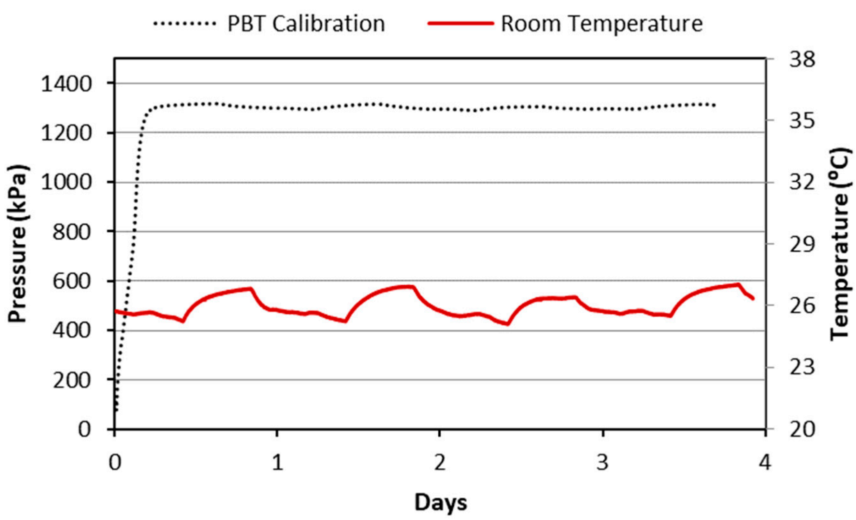


Figure 8. Change in polymer pressure and temperature over time.

Figure 9 shows the change in uncorrected pressure due to the temperature variation over a period of 3 days. The relationship between temperature and polymer pressure is closely linear, indicating that the pressure increased with increasing temperature. The linear regression from the data represents the correction pressure, p_{corr}. The slope and intercept obtained from linear regression are 13.4 and 967.2, respectively. Hence, the calibrated pressures from Equation (1) can be rewritten as follows:

$$p_{calibrated} = p_{PBT} - p_{corr} = p_{PBT} - (13.4T + 967.2) \tag{6}$$

where T is the current measured temperature. It is shown that a simple regression function can be used to calibrate the effect of temperature on the uncorrected polymer pressure. The pressure was calibrated with a room temperature of 25 °C.

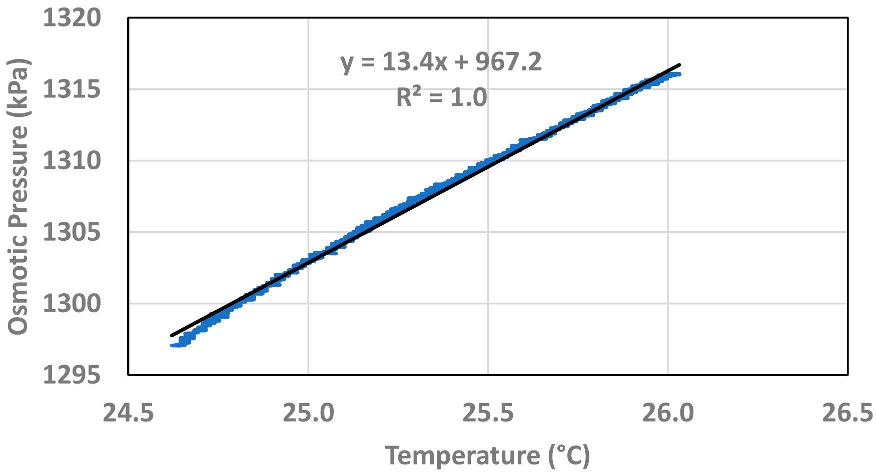


Figure 9. Temperature correction.

3.2. Evaporation Test Result

Figure 10 shows the results for the evaporation test. The evaporation test was conducted with two scenarios called EVP 1 and EVP 2. In EVP 1, drying and wetting cycles were conducted six times over 45 days. In EVP 2, drying and wetting cycles were conducted continuously for more than 90 days. It is noteworthy that the measurements of polymer pressure for both evaporation test scenarios were identical and showed consistent behavior regardless of whether the test was EVP 1 or EVP 2.

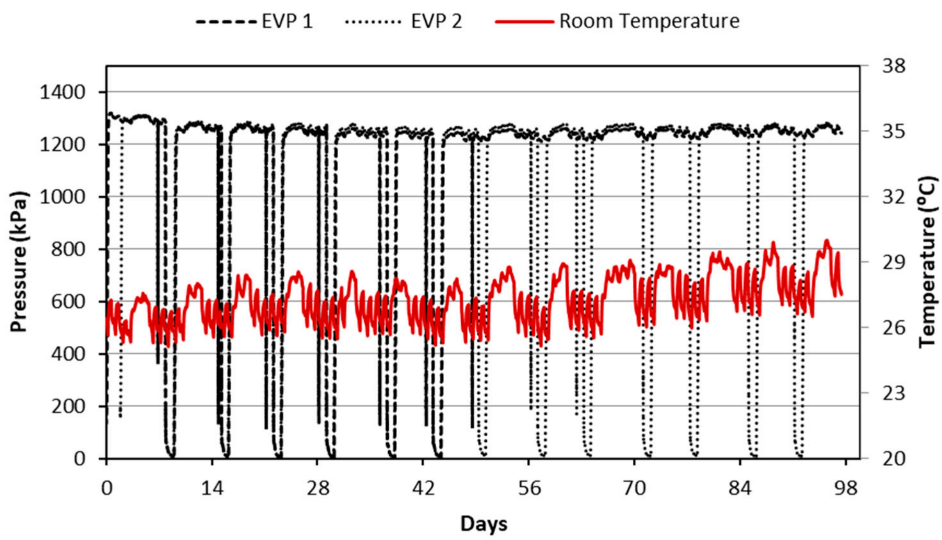
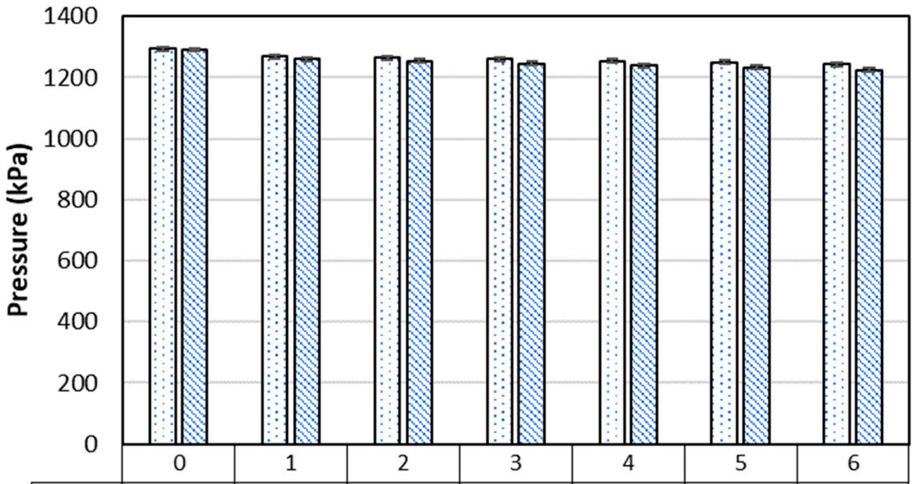


Figure 10. Evaporation test results.

The maximum polymer pressure for each wetting cycle is presented in Figure 11. It is shown that the maximum pressure was around 1300 kPa. After 3 months of monitoring, it was observed that the pressure decay was negligible. Hence, the performance of the PBT is satisfactory.



	0	1	2	3	4	5	6
EVP 2	1293	1267	1264	1259	1254	1249	1244
EVP 1	1290	1259	1254	1246	1238	1232	1223

Figure 11. Maximum polymer pressure.

3.3. Shrinkage Test Result

The vegetative soil consisted mostly of sand with some organic matters, and, hence, was subjected to shrinkage [31]. The volume change of the soil specimen during the drying process was determined by conducting a shrinkage test. Figure 12 shows the results of the shrinkage test conducted on vegetative soil. Figure 12 illustrates the relationship between the void ratio and water content. The void ratio varied from 1.2 to 0.54, indicating the volume change of the soil. This soil had a void ratio of 1.2 at 42% water content, and the void ratio continued decreasing as the water content decreased until it reached the minimum void ratio.

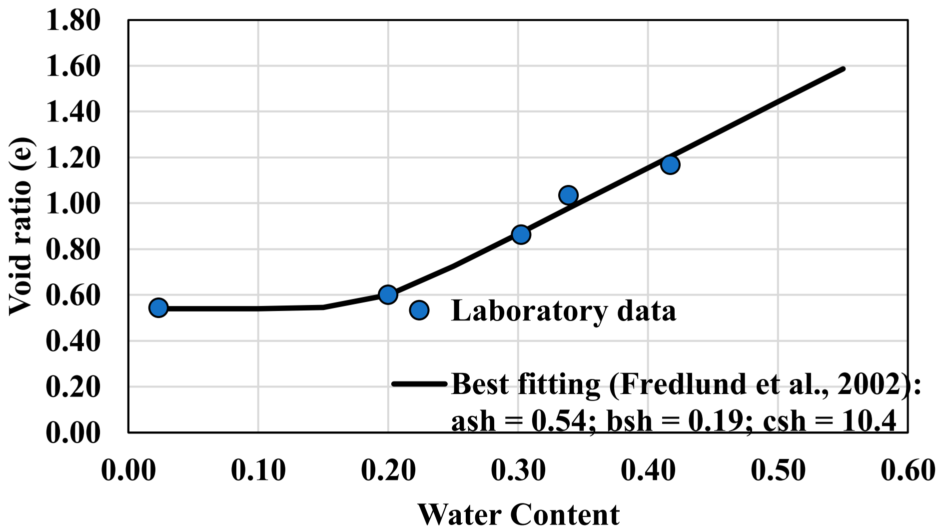


Figure 12. Shrinkage curve of vegetative soil [30].

3.4. SWCC of Vegetative Soil

Figure 13 shows the change in soil suction measured by the PBT and the water content measured by an automatic weighing balance. It can be seen that the maximum gravimetric water content started at around 35% and linearly decreased over a period of time due to the evaporation process. The soil reached the minimum gravimetric water content at around

20% after 20 days of monitoring. The shrinkage test results were then used to convert the gravimetric water content into the volumetric water content.

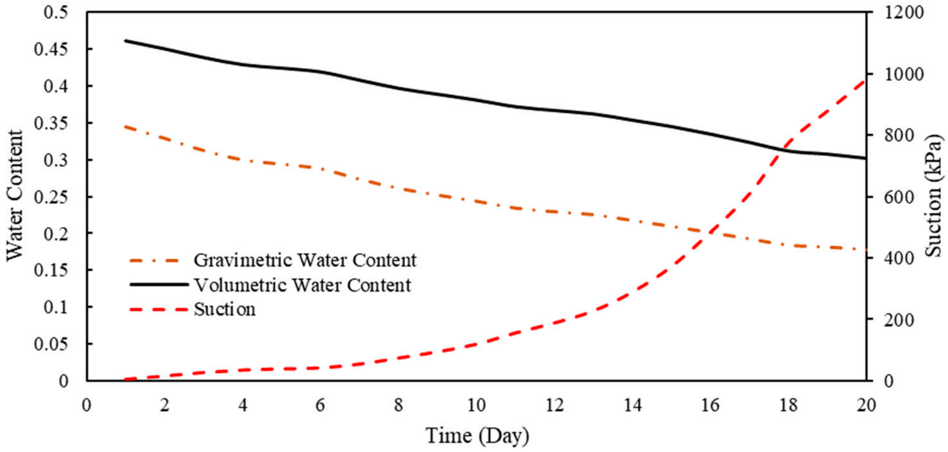


Figure 13. Monitoring of soil suction and volumetric water content for 20 days.

SWCC-w can be obtained by combining the gravimetric water content, volumetric water content, suction reading (Figure 14), and SWCC-θ_w (Figure 15). The SWCC data were then curve-fitted using the equation of Fredlund and Xing (1994) [29]. Fredlund and Xing's curve-fitting parameters for all SWCCs can be seen in Table 2. SWCCs obtained from PBT were compared with SWCCs obtained from the centrifuge test, showing that both tests gave comparable results. This result shows that the soil suction of vegetative soil can be accurately measured using PBT.

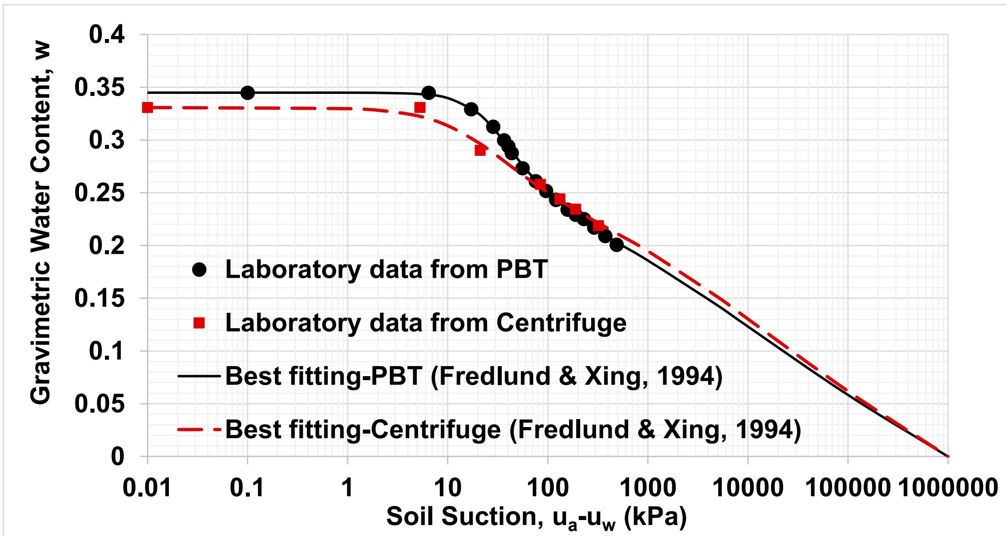


Figure 14. SWCC-w of vegetative soil [29].

Table 2. Fredlund and Xing [29] curve-fitting parameter.

Curve-Fitting Parameters	VWC Centrifuge	VWC PBT	GWC Centrifuge	GWC PBT
a	15.04	20.99	13.11	22.20
n	1.24	1.31	1.34	2.27
m	0.15	0.21	0.25	0.25
ψ_r	1500	1500	1500	1500

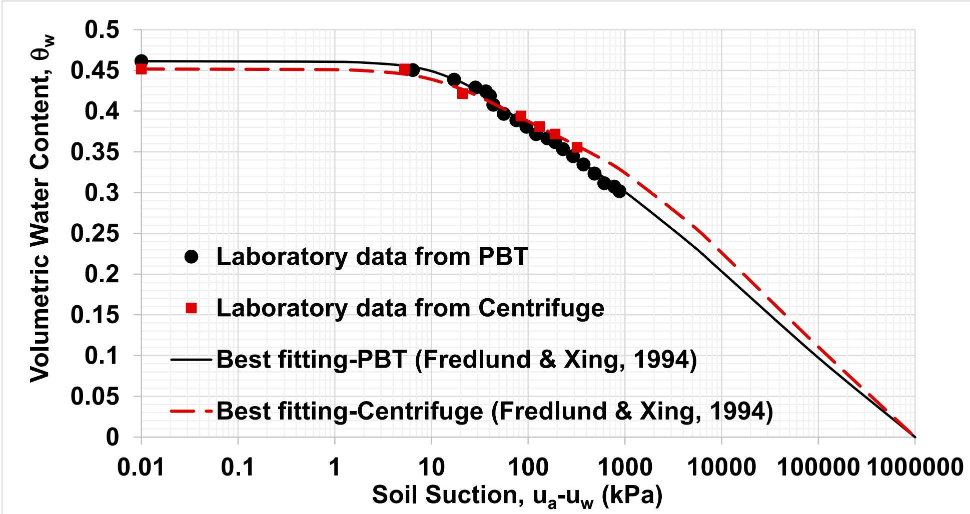


Figure 15. SWCC-θ_w of vegetative soil [29].

4. Discussion

In this study, commercially available vegetative soil was investigated. The soil sample was compacted to achieve a dry density at 95% of the maximum dry density, approximately 1.6 mg/m^3, with a water content of 12%. According to the Unified Soil Classification System (USCS), the vegetative soil was categorized as SW. The soil water characteristic curve (SWCC) testing was carried out on the investigated soil using a polymer-based tensiometer (PBT). This tensiometer was supported with a tensiometer cap made from a ceramic disc with an air-entry value (AEV) of 1500 kPa. The pressure transducer had the capability to measure pressures up to 3000 kPa and was integrated with a temperature sensor. The PBT was prepared using the synthesized polyacrylamide (PAM) polymer. The performance of the PBT was verified through a 3-month evaporation test.

The results for EVP 1 and EVP 2 indicated that the maximum polymer pressure for both PBTs were equal and showed consistent behavior regardless of whether they were subjected to EVP 1 or EVP 2. It was shown that, for 3 months of reading, there appeared to be no pressure decay observed. Hence, the performance of PBT was satisfactory. Changes in soil suction measured by PBT and water content were monitored over 20 days. The variables of SWCC from the measurement using the PBT were in agreement with those from the measurement using a centrifuge. The typical variables of SWCC for the investigated vegetative soils are as follows: The air-entry value is approximately 20 kPa, the saturated volumetric water content is 46%, the inflection point is at 1000 kPa, and the residual water content is zero.

SWCCs obtained from the PBT were compared with SWCCs obtained from a centrifuge, and it is shown that both tests gave comparable results. This result shows that the PBT is capable of precisely measuring soil suction in vegetative soil. This study offers valuable insights into monitoring plant health for urban sustainability.

5. Conclusions

In this study, a polymer-based tensiometer (PBT) was developed by using a 15 bar ceramic disk and 10.8% PAM. The study investigated commercially available vegetative soil using a polymer-based tensiometer (PBT). Before suction measurement, the sensor was calibrated by saturating the PBT for 3 days and measuring the osmotic pressure in water to account for temperature fluctuations over time. Temperature calibration of the PBT was performed using a simple regression function. The performance of the PBT with a 15 bar disk was evaluated using evaporation tests. Two types of evaporation tests, which were referred as a continuous wetting–drying cycle test (EVP 1) and a wetting–drying cycle test followed with continuous wetting (EVP 2), were conducted on two different PBTs. The evaporation tests show that the PBT was not subjected to pressure decay over a 3-month period. Hence, the performance of the developed PBT was satisfactory. Based on the SWCC test conducted using the PBT and centrifuge on vegetative soil, it was shown that the SWCCs from both PBT and centrifuge tests were comparable. This indicates that soil suction in vegetative soil can be accurately measured using the PBT. Hence, suction measurement using the PBT is deemed reliable.

Author Contributions: Conceptualization, W.A.P.; methodology, W.A.P. and A.H.H.; software, M.W.; validation, A.W.A.; formal analysis, W.A.P., A.H.H. and G.A.A.; investigation, A.H.H. and G.A.A.; resources, R.I.R.; data curation, M.W., R.I.R., A.W.A. and G.A.A.; writing—original draft, W.A.P., A.H.H., M.W., R.I.R. and A.W.A.; writing—review and editing, A.S. and J.K.; visualization, J.K.; supervision, A.S. and J.K.; project administration, A.S.; funding acquisition, W.A.P. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Directorate of Research and Development, Universitas Indonesia, under Hibah PUTI 2023 (Grant No. NKB-544/UN2.RST/HKP.05.00/2023). This research was also funded by Nazarbayev University under Faculty-development competitive research grants program for 2023–2025 Grant № 20122022FD4133.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Acknowledgments: The Authors would like to acknowledge the research funding from Nazarbayev University. This research was funded by Nazarbayev University under Faculty-development competitive research grants program for 2023–2025 Grant № 20122022FD4133.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Stocker, T.F.; Qin, D.; Plattner, G.K.; Tignor, M.M.B.; Allen, S.K.; Boschung, J.; Nauels, A.; XIa, Y.; Bex, V.; Midgley, P.M. Summary for Policymakers. In *Climate Change 2013: The Physical Science Basis; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2015.
2. Sapes, G.; Roskilly, B.; Dobrowski, S.; Maneta, M.; Anderegg, W.R.L.; Martinez-Vilalta, J.; Sala, A. Plant water content integrates hydraulics and carbon depletion to predict drought-induced seedling mortality. *Tree Physiol.* **2019**, *39*, 1300–1312. [CrossRef] [PubMed]
3. Lewis, S.; Brando, P.; Phillips, O.; van der Heijden, G.; Nepstad, D. The 2010 Amazon Drought. *Science* **2011**, *331*, 554. [CrossRef] [PubMed]
4. Williams, A.P.; Allen, C.D.; Macalady, A.K.; Griffin, D.; Woodhouse, C.A.; Meko, D.M.; Swetnam, T.W.; Rauscher, S.A.; Seager, R.; Grissino-Mayer, H.D.; et al. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nat. Clim. Chang.* **2013**, *3*, 292–297. [CrossRef]
5. Adams, H.D.; Zeppel, M.J.B.; Anderegg, W.R.L.; Hartmann, H.; Landhäusser, S.M.; Tissue, D.T.; Huxman, T.E.; Hudson, P.J.; Franz, T.E.; Allen, C.D.; et al. A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nat. Ecol. Evol.* **2017**, *1*, 1285–1291. [CrossRef]
6. Zhai, Q.; Rahardjo, H.; Satyanaga, A.; Dai, G.; Zhuang, Y. Framework to estimate the soil-water characteristic curve for soils with different void ratios. *Bull. Eng. Geol. Environ.* **2020**, *79*, 4399–4409. [CrossRef]
7. Zhai, Q.; Rahardjo, H.; Satyanaga, A.; Dai, G.; Du, Y. Estimation of the wetting scanning curves for sandy soils. *Eng. Geol.* **2020**, *272*, 105635. [CrossRef]
8. Sun, D.A.; Sun, W.; Xiang, L. Effect of degree of saturation on mechanical behaviour of unsaturated soils and its elastoplastic simulation. *Comput. Geotech.* **2010**, *37*, 678–688. [CrossRef]
9. Khalili, N.; Habte, M.A.; Zargarbashi, S. A fully coupled flow deformation model for cyclic analysis of unsaturated soils including hydraulic and mechanical hystereses. *Comput. Geotech.* **2008**, *35*, 872–889. [CrossRef]

10. Briggs, L.J.; Shantz, H.L. The wilting coefficient and its indirect determination. *Bot. Gaz.* **1912**, *53*, 20–37. [CrossRef]
11. Fredlund, D.G. Unsaturated Soil Mechanics in Engineering Practice. *J. Geotech. Geoenviron. Eng.* **2006**, *132*, 286–321. [CrossRef]
12. Zhai, Q.; Rahardjo, H.; Satyanaga, A. Uncertainty in the estimation of hysteresis of soil–water characteristic curve. *Environ. Geotech.* **2019**, *6*, 204–213. [CrossRef]
13. Rai, R.K.; Singh, V.P.; Upadhyay, A. Chapter 17—Soil Analysis. In *Planning and Evaluation of Irrigation Projects*; Rai, R.K., Singh, V.P., Upadhyay, A., Eds.; Academic Press: Cambridge, MA, USA, 2017; pp. 505–523.
14. Leong, E.C.; Wijaya, M. *Laboratory Tests for Unsaturated Soils*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2023; p. 436.
15. Hamdany, A.H.; Shen, Y.; Satyanaga, A.; Rahardjo, H.; Lee, T.-T.D.; Nong, X. Field instrumentation for real-time measurement of soil-water characteristic curve. *Int. Soil Water Conserv. Res.* **2022**, *10*, 586–596. [CrossRef]
16. Degré, A.; van der Ploeg, M.J.; Caldwell, T.; Gooren, H.P.A. Comparison of Soil Water Potential Sensors: A Drying Experiment. *Vadose Zone J.* **2017**, *16*, vzj2016.08.0067. [CrossRef]
17. Durigon, A.; Gooren, H.P.A.; van Lier, Q.d.J.; Metselaar, K. Measuring Hydraulic Conductivity to Wilting Point Using Polymer Tensiometers in an Evaporation Experiment. *Vadose Zone J.* **2011**, *10*, 741–746. [CrossRef]
18. van der Ploeg, M.J. Polymer Tensiometers to Characterize Unsaturated Zone Processes in Dry Soils. Ph.D. Thesis, Wageningen Universiteit, Wageningen, The Netherlands, 2008.
19. Peck, A.J.; Rabbidge, R.M. Soil-Water Potential: Direct Measurement by a New Technique. *Science* **1966**, *151*, 1385–1386. [CrossRef]
20. Peck, A.J.; Rabbidge, R.M. Design and Performance of an Osmotic Tensiometer for Measuring Capillary Potential. *Soil Sci. Soc. Am. J.* **1969**, *33*, 196–202. [CrossRef]
21. van der Ploeg, M.J.; Gooren, H.P.A.; Bakker, G.; Hoogendam, C.W.; Huiskes, C.; Koopal, L.K.; Kruidhof, H.; de Rooij, G.H. Polymer tensiometers with ceramic cones: Direct observations of matric pressures in drying soils. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 1787–1799. [CrossRef]
22. Liu, H.; Hamdany, A.H.; Rahardjo, H. Laboratory investigation of osmotic tensiometers filled with cross-linked polyacrylamide. *Transp. Geotech.* **2024**, *44*, 101173. [CrossRef]
23. 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. New Polymer Tensiometers: Measuring Matric Pressures Down to the Wilting Point. *Vadose Zone J.* **2007**, *6*, 196–202. [CrossRef]
24. Liu, H.; Rahardjo, H.; Satyanaga, A.; Du, H. Use of synthesised polymers for the development of new osmotic tensiometers. *Géotechnique* **2022**, *73*, 544–552. [CrossRef]
25. *ASTM D698-12*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM International: West Conshohocken, PA, USA, 2012.
26. *ASTM D6913-04*; Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International: West Conshohocken, PA, USA, 2004.
27. *ASTM D854-02*; Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International: West Conshohocken, PA, USA, 2004.
28. Rahardjo, H.; Satyanaga, A.; Mohamed, H.; Yee Ip, S.C.; Shah, R.S. Comparison of Soil–Water Characteristic Curves from Conventional Testing and Combination of Small-Scale Centrifuge and Dew Point Methods. *Geotech. Geol. Eng.* **2019**, *37*, 659–672. [CrossRef]
29. Fredlund, D.G.; Xing, A. Equations for the soil-water characteristic curve. *Can. Geotech. J.* **1994**, *31*, 521–532. [CrossRef]
30. Fredlund, M.D.; Wilson, G.W.; Fredlund, D.G. Representation and estimation of the shrinkage curve. In Proceedings of the 3rd International Conference on Unsaturated Soils (UNSAT 2002), Recife, Brazil, 10–12 March 2002; Jucá, J.F.T., de Campos, T.M.P., Marinho, F.A.M., Eds.; Swets & Zeitlinger: Lisse, The Netherlands, 2022; pp. 145–149.
31. Xuefeng, N.; Rahardjo, H.; Tsen-Tieng, D.; Leong, E.; King, F. Effects of Organic Content on Soil-Water Characteristic Curve and Soil Shrinkage. *Environ. Geotech.* **2019**, *8*, 442–451.