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POLYMER SENSOR FOR MEASUREMENT OF SOIL-WATER CHARACTERISTIC CURVES (SWCC)

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Açıklamalı [AS1]: Please add position of each author, affiliation. For corresponding author, please add email

ABSTRACT

Soil-water characteristic curves (SWCC) are an important properties of unsaturated soil, but the technology used to obtain them has severe constraints, including time, effort, and cost. In this study, a newsensor based polyacrylamide (PAM) polymer sensing technology is developed for measuring soil suction using osmotic pressure rather than capillary pressure. The soil sample from Astana, classified as clayey sand was used for validation of the developed polymer sensor. Tempe Cell was used to assess the performance of the measured data from this new polymer sensor. Since the current developed sensor is only applicable from low to middle suction region, the entire SWCC was created with the help of conventional unsaturated devices such as Tempe Cell for low suction area and WP4C for high suction area. However, it has been demonstrated that the sensor can be used as an alternative device for rapid measurement of SWCC.
Keywords: *Polymer sensor, polyacrylamide, unsaturated soil, soil-water characteristic curves*

1. INTRODUCTION

Design of geotechnical structures are affected by the location of groundwater table (GWT) in the soil. The presence of GWT generates the soil suction in the unsaturated zone above GWT, which is a component of soil-water characteristic curves (SWCC). It is defined as the difference between pore-air and pore-water pressures in soil, and it is regulated by capillary movement between macro and micro pores. (Fredlund & Rahardjo, 1993; Zhai et al., 2020).

Numerous indirect and direct measurement techniques for SWCC have been developed. Gardner (1937) proposed indirect measurement, for example, using filter paper, where the methods and data processing are easier than in other methodologies. However, this method is time-consuming, has low measurement precision, and necessitates the use of a calibration curve between soil suction and observed parameters (Ren et al., 2020; Liu et al., 2022). In contrast, examples of direct measurements are Tempe Cell and pressure plates (Abeykoon et al., 2017). Although direct techniques are more accurate, they are also more costly, laborious, and sophisticated. For example, they have the ability to measure suction until 1500 kPa, yet it takes between 6 and 8 weeks to gather 10 results in clayey soil (Rahardjo et al., 2018).

Several tools have been developed with the help of technology to ease the process of measuring SWCC. A conventional tensiometer and a METER group HYPROP can be used to measure suction in the field and laboratory, respectively; however, their suction range is restricted to 100 kPa due to cavitation. A centrifuge in conjunction with a cooled mirror psychrometer may be used, but it requires a high-speed machine to create a greater suction range (Rahardjo et al. 2018). The WP4C potentiometer is not applicable at suction values less than 1500 kPa (Liu et al. 2022). High capacity tensiometers can measure suction up to 1500 kPa (Mendes et al., 2020); nevertheless, the suction of the soil specimen was modified continuously or discretely (Liu et

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al., 2022). Thus, polymer has been used as an alternative since it is based on the gradient of hydraulic or osmosis pressure rather than pure water pressure.

In this study, the polymer sensor, were used to measure the SWCC of Astana's soil. The sensor consisted of polyacrylamide (PAM) polymer with 5% concentration of cross-linking, since according to Liu et al., (2022), it provides the highest and most stable pressure of all. The scope of work in this study includes review of polymer characteristic, index properties, preparation of sensor, Tempe Cell validation, and SWCC measurement.

2. TOOLS

2.1. PAM Polymer

The polymer was made with crosslinking method with the procedure was according to Liu et al. (2021). The crosslinking is chosen since it helps maintain the polymer structure and improves its properties (Kuckling et al. 2012). According to Heidari et al., (2018), the materials are acrylic acid and acrylamide as monomer, N,N'-methylenebisacrylamide as the crosslinker, and potassium peroxodisulphate, potassium persulfate, and sodium hydrogen sulfate as the initiators. The utilized PAM weighs 0.1 gram and has a diameter of 1.51 cm since it is accordance with the previous study conducted by Liu et al., (2021).

2.2. Polymer Sensor

The sensor was originally manufactured by KELLER where under the chamber, the sensor is equipped with an insulated piezoresistive sensor (KELLER, 2022). The sensor was later improved by incorporating a ceramic disc with a 15 bar capacity at the cap, which works as a semipermeable barrier for the polymer and water (Figure 1). When the ceramic disc achieves a reading less than the air-entry-value (AEV), it can prevent possible water loss from the saturated ceramic disc during soil suction testing (Liu et al., 2022). Water may flow into the chamber due to the different hydraulic gradient, but the polymer is unable to convey its particle beyond the chamber. The pressure transducer's present capacity is 3 MPa, however this will be enhanced for future study.

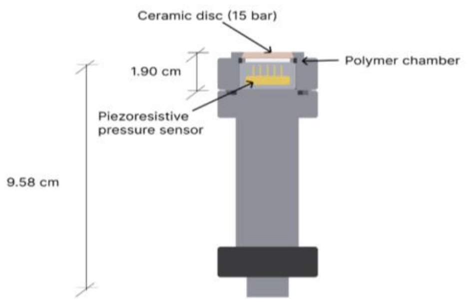

Figure 1.Cross section of polymer sensor

3. LABORATORY TESTİNG

3.1. Index Properties

The soil that are used in this study is soil from the construction site inside Nazarbayev University, located in Turan Avenue, Astana, Kazakhstan. The index properties were tested using the American Soil Testing Machine (ASTM) standard, and the soil classification was provided using the Unified Soil Classification System (USCS) technique, as shown in Table 1. The compaction test was also carried out in accordance with ASTM D698-12.

Table 1. Index properties

Index Property Experiment	ASTM Code	Value
Natural water content, w (%)	D2216-10	2.19
Specific gravity, Gs	D854-02	2.50
Plastic limit, PL (%)	D4318-00	19.33
Liquid limit, LL (%)		39.58
Plasticity index, PI		20.25
Sand (%)	D422-63	84.42
Fines (%)		12.64
Soil classification (USCS)	D2487-00	Clayey sand (SC)
Maximum dry density, MDD (g/ cm^3)	D698-12	1.91
Optimum moisture content, OMC (%)		13.5

3.2. Soil-Water Characteristic Curves

The sample was compacted until it reached the maximum dry density (MDD) condition before the sensor was placed on top of the soil (Figure 2). Water flowed out of the polymer as a result of the difference in osmotic pressure between the polymer and the soil, causing the pressure inside the instrument to fall, acting as a true measurement of soil suction (van der Ploeg, 2008). When the hydraulic gradient between the polymer and the soil became small, the pressure reached equilibrium, indicating that the flow of water stopped and the polymer shrank to its original size. While for the procedure for both Tempe Cell and WP4C is referred to Satyanaga et al. (2019).

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Figure 2. Interaction between sensor cap and soil

The results from all of the data then were best fitted using both Fredlund & Xing (1994) (eq.1) and Satyanaga et al. (2022) (eq.3) equations in order to obtain the SWCC parameter. Both equations need the correction factor (C(ψ)) in eq.2 to guarantee that the water content is negligible at 1 GPa of soil suction (Guan et al. 2009). The Fredlund & Xing (1994) equation was used since it is an effective formula for a variety of soils, whereas Satyanaga et al. (2022) was used to determine whether or not the soil has a bimodal tendency.

$$\theta_w = C_{(\psi)} \left(\frac{\theta_s}{\ln\left[e + \left(\frac{\psi}{\alpha}\right)^n\right]^m} \right) \quad (1)$$

$$C_{(\psi)} = 1 - \frac{\ln\left(1 + \frac{\psi}{\psi r}\right)}{\ln\left(1 + \frac{10^6}{\psi r}\right)} \quad (2)$$

$$\theta_w = C_{(\psi)} \left[\theta_r + (\theta_{s1} - \theta_{s2}) \left(1 - \operatorname{erfc} \frac{\ln\left(\frac{\psi_{a1} - \psi}{\psi_{a1} - \psi_{m1}}\right)}{s_1} \right) + (\theta_{s2} - \theta_r) \left(1 - \operatorname{erfc} \frac{\ln\left(\frac{\psi_{a2} - \psi}{\psi_{a2} - \psi_{m2}}\right)}{s_2} \right) \right] \quad (3)$$

where θ_w is volumetric water content at any suction; θ_s is saturated volumetric water content; ψ is soil suction of the soil (kPa); α is soil parameter that is primarily determined by the soil's air entry value (AEV) (kPa); n is a function of the rate of soil water extraction when the AEV has been reached; m is a function of the residual water content; ψ_m is soil suction at the inflection point (kPa); ψ_a is the air-entry value of soil (kPa); and s is the geometric standard deviation.

4. RESULTS AND DİSCUSSİON

The sensor was initially tested with Tempe Cell after being soaked in water until it reached its maximum swelling potential. Figure 3 depicts the results. These data indicate that the soil suction from HSPS is confirmed, as it has a similar value to Tempe Cell's soil suction. Further, the regression value is near to 1, implying that it is already verified.

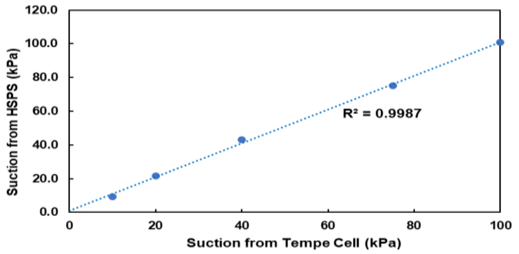

Figure 3. The calibration of HSPS soil suction with respect to Tempe Cell

Figure 4 depicts the SWCC developed by Fredlund & Xing (1994) equation for three conditions: gravimetric water content (w), volumetric water content (θ), and degree of saturation (S). The w result was taken directly from the experimental data, while the θ was calculated by multiplying the w by the MDD from the compaction curve, and the S value was calculated by considering that the starting state was fully saturated. The best fitting SWCC with the parameters indicated in Table 2. The sensor calculates suction in the lower to middle range and links Tempe Cell and WP4C. The suction difference between sensor and WP4C is still large, allowing the development of a polymer that is more efficient than PAM.

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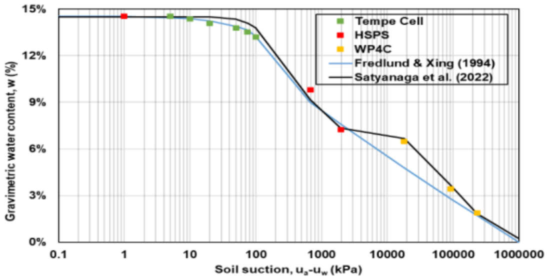
Table 2. Fredlund & Xing (1994) SWCC parameters

Parameters	w – SWCC	θ – SWCC	S – SWCC
a	100	50.79	64.09
n	50	1.89	2.94
m	0.05	0.22	0.17
ψ_r	1500	1500	1500
R^2	0.999	0.998	0.988

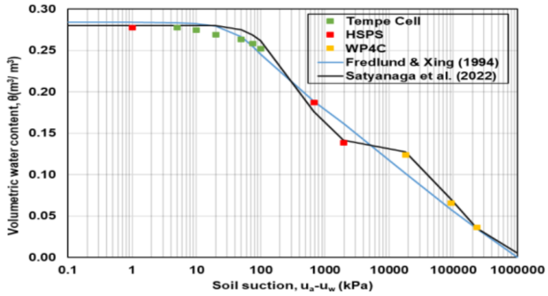
The result is then further verified using Satyanaga et al., (2022) equation as can be seen in Figure 4 with the parameter shown in Table 3. The soil has a bimodal SWCC tendency, as demonstrated by two AEV in the SWCCs. The experimental data, particularly those from the middle to high suction zones measured with sensor and WP4C, correspond more closely using Satyanaga et al. (2022) model, implying that the soil has bimodal pores. The bimodal SWCC resulted from the soil's duality in particle size due to the soil is SC and comprises both granular with big pore-size and fines particle with smaller pore-size.

Table 3. Satyanaga et al. (2022) SWCC bimodal parameters

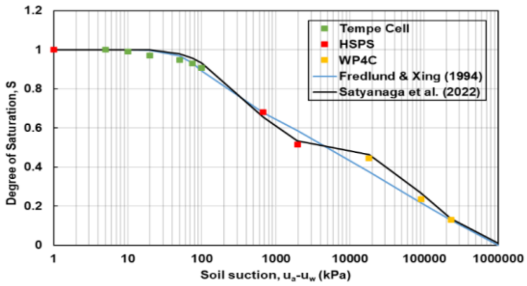
w – SWCC		θ_w – SWCC		S – SWCC	
w_{s1}	0.145	θ_{s1}	0.28	S_{s1}	1.00
ψ_{a1}	10 kPa	ψ_{a1}	10 kPa	ψ_{a1}	10 kPa
ψ_{m1}	400 kPa	ψ_{m1}	380 kPa	ψ_{m1}	400 kPa
s_1	1.1	s_1	1.2	s_1	1.3
w_{s2}	0.068	θ_{s2}	0.13	S_{s2}	0.48
ψ_{a2}			25000 kPa		
ψ_{m2}			100000 kPa		
s_2			1.5		
ψ_r			30000 kPa		
w_r	0.01	θ_r	0.02	S_r	0.15
R^2	0.997	R^2	0.995	R^2	0.995



(a)



(b)



(c)

Figure 4. Comparison of SWCC results – (a) gravimetric; (b) volumetric; and (c) degree of saturation

5. CONCLUSIONS

SWCC was quantified in this study using a polymer sensor and both the Tempe Cell and the WP4C, acting as a link between the two measuring equipment. The sensor can measure soil suction from low to middle suction; however, polymer research should be expanded since it cannot monitor soil suction at high suction. More engineering methodologies should be employed to test the effectiveness and capability of the sensor.

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