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Assessment of Various Methods to Measure the Soil Suction

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***Abstract**: The foundation of the lightweight structures is commonly in unsaturated state conditions because located above the ground-water table. The matric suction governs the hydro-mechanical behaviour of unsaturated soils. Soil suction estimation is challenging both in the field and lab. The indirect and direct techniques are utilized to measure the soil suction. Several types of equipment utilized to measure the soil suction have been developed with innovative technology. However, there are constraints on reliability, suction range estimation, application, etc. The primary objective of this study is to review, describe the working principle, report limits, and benefits of various techniques utilized to measure the soil suction and select the cost-effective. A comparative study on direct and indirect technique of soil suction estimation is conducted base on recent literature, with a focus on suction range, procedure, type of suction, processing time, and application (lab/field). The apparatus utilized to measure directly or indirectly the matric suction found in the literature displays the highest range in the order of 1500 kPa except for the filter paper. The thermocouple psychrometer and the transistor psychrometer can measure a maximal total suction of 8000 kPa. The chilled-mirror hygrometer can measure a maximal total suction of 30000 kPa in the laboratory. The filter paper technique and the chilled-mirror hygrometer are cost-effective techniques. However, the filter paper technique is likely the easiest and low-cost technique to measure the matric suction and total suction for the full range with extreme care in the test procedure both in the field and lab*.

***Keywords**: Chilled-mirror hygrometer, Filter paper, Matric suction, Osmotic suction, Suction range, Total suction.*

I. INTRODUCTION

In the past 50 years, unsaturated soil mechanics has developed as a thriving extension of mechanics of saturated soil in managing the mechanics of soil under partially saturated conditions [1]. Soil suction is a significant stress-state variable of unsaturated soils. The magnitude of soil suction influences the shear stress, the behaviour of the variation of volume, and the hydraulic conductivity of unsaturated soils. The estimation of suction is essential for the characterization of unsaturated soils. Soil suction is a free energy state of water inside the soil [2]. The matric suction is the difference between pore air stress and pore water stress [3,4]. In Equation 1, the total suction is denoted (Ψ_t), the matric suction is denoted (Ψ_m), and the osmotic suction is denoted (Ψ_o).

$$\Psi_t = \Psi_m + \Psi_o \quad (1)$$

Soil suction is a challenging parameter to measure [5,6]. The suction can be measured using the indirect or direct method. The direct estimation of soil suction depends on the direct observation of pore water pressure. In another study, [7] reported that indirect measurement of suction includes the determination of soil parameters directly connected to the soil potential through calibration with a known suction value. In engineering practice, several types of equipment have been developed to measure directly or indirectly the soil suction. Nonetheless, each apparatus has its limits and advantages in terms of suction range measurement, equilibrium time, reliability, type of suction to be measured (total suction, matric suction, osmotic suction), application (lab/field), availability, maintenance, calibration process, etc. Reference [8] conducted a comparative study on various techniques used to estimate the total suction: thermocouple psychrometer, non-contact filter paper, transistor psychrometer, and chilled-mirror hygrometer. The tests were performed using sand mixtures and bentonite. Results revealed that the chilled-mirror hygrometer technique gives the most precise results and can be used as a reference to check the accuracy of others. Nevertheless, the chilled-mirror hygrometer technique is used in the lab only and cannot measure the matric suction. In another study, [9] reported a comparative study on the total suction measurement using various techniques: thermocouple psychrometer, non-contact filter paper, and chilled-mirror hygrometer. The tests were performed using high plastic clay. The chilled-mirror hygrometer and the filter paper technique appear to give more precise results. However, the filter paper technique is time-consuming, and the chilled-mirror hygrometer technique cannot measure the matric suction. Reference [10] carried out a critical assessment of various measurement methods using the chilled-mirror hygrometer, filter paper, dew-point techniques, pressure plate, and null-type axis-translation. Compacted soil specimens were prepared to assess the influence of initial compaction conditions on suction estimations. It was found that at the high suction range, the test results of non-contact filter paper, chilled-mirror, and dew-point tests exhibit very similar values, and discrepancies observed at the low suction range on the results of null-type tests and pressure plate.

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Reference [11] studied the determination of soil suction using the filter paper technique. As a result, the soil suction determination using the contact filter paper is more precise than suction determination using the non-contact filter paper technique. That is due to the condensation induces in the non-contact filter papers to produce higher moisture content. Besides, the non-contact filter paper initially wet may follow the matric suction curve, and the non-contact filter paper initially dry follows the total suction curve. A few investigations have considered the matric suction evolution in compacted soils. Reference [12] reported that in compacted clay soil specimens, the matric suction values are within the range of 50 kPa and 8.000 kPa at the compaction degree of saturation values of 90 % and 35%. Another research work conducted by [13] revealed that the matric suction values in compacted heaving soils at the optimum moisture content are within the range of 671.89 kPa to 2021.8 kPa, which is greater than the matric suction range of the equipment limited to 1500 kPa. Furthermore, at the dry side, the specimen exhibits a matric suction value greater than 8000 kPa and a total suction greater than 10000 kPa. The matric has been the keystone for all design methodologies and theories for unsaturated soil. In engineering practice, the estimation of the matric suction is more significant compare to the osmotic suction. This research work reviews the working principle, identifies the advantages and limitations of various techniques used to measure directly or indirectly the soil suction, and select the cost-effective based on the engineering practice and the literature.

II. RESEARCH METHOD

Review different techniques used to measure directly and indirectly the soil suction according to the recent literature. Characterize the various suction measurement methods based on their background, working principle, apparatus description, utilization procedure, method benefits, and limitations with a focus on the suction range, nature of suction to be measured, processing time, and application (lab/field). Moreover, conduct a comparative study of direct and indirect methods used to measure the soil suction and choose the cost-effective.

III. DIRECT SUCTION MEASUREMENT

Matric suction is measured by direct determination of negative pore-water stress using a porous ceramic cup. The estimation of matric suction requires a separation among water and air phase using a ceramic disk. The matric suction maximal value is limited by the air entry value of the ceramic cup. The matric suction direct assessment apparatus includes the tensiometers, suction probe, suction plate, pressure plate, axis translation.

A. Conventional tensiometers

Tensiometer is used to measure the soil suction directly. The principle of operation is that water contained in a high air entry material in the tensiometer will have the identical negative pore-water pressure in the soil when the equilibrium is completed between the specimen and the gauge device. Since there is no authentic semi-permeable membrane for soluble salts in the tensiometer, the impact of the osmotic suction on total suction is not measured. Therefore, the pore-water pressure measured represents the matric suction component. Besides, due to the problem of water cavitation in the tensiometer, the ceramic cup with the higher air entry limits the matric suction range estimation to 90 kPa. A conventional tensiometer design with a high air section and porous ceramic cup is attached to a pressure gauge is shown in Fig. 1. The tensiometer is adjusted before utilization to obtain accurate results. The ceramic cup check for fissures. Air pockets drive out before the setup. The reaction time of a tensiometer check by allowing an increment of negative water pressure up to 90 kPa. The negative pressure is created by evaporation from the ceramic cup after the ceramic cup is submerged in water. The negative water pressure in the tensiometer must increment up to the atmospheric pressure in 5 min after immersion of the ceramic cup tip in water. The ceramic cup must be maintained submerged in water before its set up to prevent desaturation due to the evaporation from the ceramic cup. The prepared tensiometer is placed in a specimen in the lab or a pre-drilled hole in situ. Good contact must be established between the specimen and the ceramic cup to ensure continuity between water in the tensiometer tube and the pore-water in the soil. The matric suction denotes by (Ψ_m) is computed according to the relation in Equation 2. The reading at the location of vacuum gauge is (Ψ_{gauge}), and the indicating depth is (Z).

$$\Psi_m = \Psi_{gauge} + (Z_{gauge} - Z_{cup}) \quad (2)$$

The vertical length from the gauge surface to the cup is the negative value added to the suction estimated by the gauge (Ψ_{gauge}) to determine the matric suction at the cup depth. The positive head applies by the water column in the tensiometer at the ceramic cup depth is taken into account. The usage of the vertical elevation difference is suitable only when the soil potential.

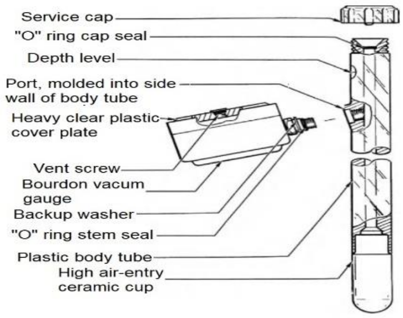

Fig. 1. Conventional Tensiometer

Advantages of conventional tensiometer

- Measure the matric suction quickly both in the field and lab.
- Easy to use with minimal soil disturbance.
- Simple physical working principle.
- Interchangeable porous ceramic cup.

Disadvantages of conventional tensiometer

- The direct measurement of suction also becomes problematic due to water cavitation [6].
- The suction capacity of the conventional tensiometer is of the order of 90 kPa due to air diffusion through ceramic material, and the driving out of the air as the water pressure decreases. The suction capacity is not enough to cover the compacted clayey soils suction range.

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The air in the sensor will result in inacurrate or less negative measurements of the pore water pressure when water vaporizes as the soil water stress approaches the vapour stress of water at the ambient temperature [14].

- Tensiometer operates correctly only when the soils are wet and may not be as quick to react in coarse sands.
- Required regular maintenance and cannot measure the total suction.
- May not be as responsive in coarse sands.

B. High suction tensiometer (HST)

In contrast with a conventional tensiometer, the High Suction Tensiometers (HST) is a sensor that can measure large pore-water tensions, well beyond the water cavitation threshold of -90 kPa, with a relatively quick response and good accuracy. The first HST prototype was developed by [15]. Improvements were made to the tensiometer measurement technique to estimate directly the matric suction as large as 1500 kPa [16,17,18,19,20,21]. These types of tensiometers avoid cavitation in which the water reservoir volume beneath the ceramic tip is reduced, and water in the water reservoir is pre-pressurized.

C. Imperial college tensiometer (Suction Probe)

Reference [15] developed a suction probe presented in Fig. 2 to measure the matric suction directly. They are small tensiometers firstly proposed by the Imperial College of London and able to estimate soil suction of the order of 1500 kPa. Comparative varieties of the suction probe have been proposed by [22,23]. Afterward, small probes have been proposed by Rahardjo and Leong (2006) for direct estimation of matric suction within the range of 100 to 500 kPa. However, [24] proposed a smaller suction probe for assessing matric suction along with the specimen's height during a triaxial test on an unsaturated soil. It is a specific one in its capacity to make direct estimations of soil suction of the order of 1500 kPa. Also, [25] designed the MIT tensiometer with a face width of 38 mm for use in triaxial soil testing. The principle for conducting suction estimations utilizing the Imperial college tensiometer depends on the equilibrium between the pore-water pressure in the water compartment and soil pore-water pressure. Before achieving the equilibrium, water flows from the water compartment in the soil or the other way around. Tensiometer is utilized to determine the pore-water pressure. The matric suction is calculated base on the known applied air pressure. The matric suction is the difference between pore-air pressure and pore-water pressure. The suction probe is made using a high air entry ceramic disk of 100 kPa fixed at the tip of a transducer. The sensor is attached to the end of the diaphragm. The de-aired water reservoir is placed in the small space between the permeable plate and diaphragm. Water in the container is pre-pressurized so that the high stress of water can be utilized. The diaphragm of the pressure transducer reacts to the pressure applied, and the water containers volume underneath the ceramic cup or ceramic disk is reduced. The fundamental issue in suction estimation using the suction probe is the cavitation and air dispersion through a ceramic head. The measurement is performed within 0 to 5m depth in a borehole, or on specimens collected from the site. The equilibrium time is about a few minutes. The suction probe test is performed in the field and lab.

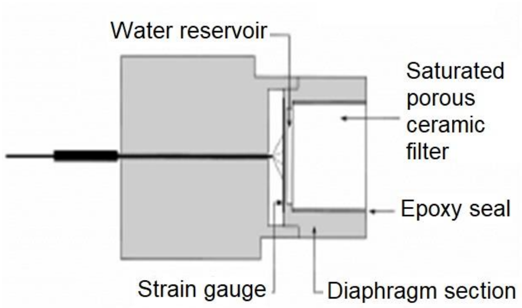

Fig. 2. **Imperial College Tensiometer or Suction Probe**

D. Suction plate

A suction plate is a direct method of measurement of the matric suction in the laboratory. The basic principle is that the soil specimen absorbs water from the container through a porous stone. At a particular point, the reduction in pressure in the pressure gauge is the matric suction of the soil. The suction plate equipment is designed with a saturated high air entry disk connected to a water container fixed to a U tube to which is joined a manometer or vacuum gauge as presented in Fig. 3.

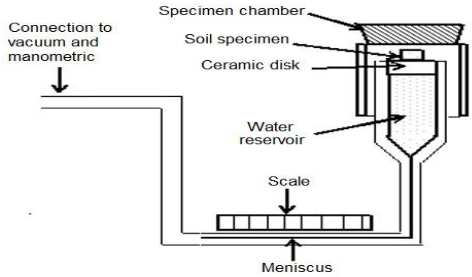

Fig. 3. **Suction Plate Method**

The suction plate can estimate the matric suction in the soil within the range of 20 to 85 kPa. When the matric suction values are greater than 85 kPa, air enters the system and induces the water cavitation phenomenon. The equilibrium time of the suction plate is in hours. The soil specimen is placed inside a saturated ceramic disk. Water flows from the water container in the soil specimen and induces a variation of the meniscus that is measured. The meniscus is then arranged based on its initial position by applying a vacuum and setting a few soil specimens at different moisture content on a saturated ceramic plate, and different suction values are estimated.

E. Pressure plate apparatus

A pressure plate is a direct method to measure the matric suction in the laboratory. The basic principle is the removal of specimen moisture under controlled conditions from specimens without disturbing the specimen structure. The soil water retention curves of each type of soils can be obtained using the pressure plate technique. Fig. 4 shows the pressure plate apparatus that consists of a pressure chamber, a supply air system, and a high air ceramic disk.

Two layers of plastic screens are attached to the underneath surface of the ceramic plate to provide space for water to flow between the neoprene membrane and the ceramic disk [26].

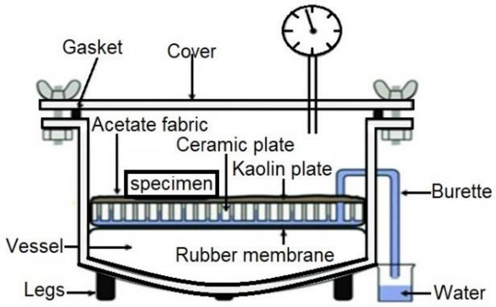

Fig. 4. **Pressure Plate Equipment**

The water container is attached to a pressure transducer placed outside the pressure chamber. A seepage pipe is attached to the water container that also vents outside the pressure chamber. The high air ceramic disk isolates the air phase from the water state to prevent air from flowing through the water. Soil specimens prepared at a similar density and water contents are placed in the ceramic disc. A slight suction is applied to the chamber, and the soil specimens absorb some water from the reservoir through the ceramic disc. The seepage is allowed, and the air pressure in the chamber expands to a given expected value. When the seepage is completed, the pressure chamber is opened, and the specimen water content is measured. This reading is the initial point on the water retention curve. Successive augmentation of air pressure is performed simultaneously with their water content assessment of the other specimens to develop other points on the water retention curve. The highest range of matric suction estimated on the pressure plate is of the order 1500 kPa. The equilibrium time takes a few hours to days. The test is conducted only in the laboratory for matric suction measurement.

F. Axis-translation technique

The axis-translation is utilized to estimate the matric suction of the soil in the lab directly. The suction estimation is within the range of 0 to 1500 kPa, and the equilibrium time ranges from 1 to 16 hours. The working principle of axis-translation consists of the translation of the origin of the reference for the pore-water pressure (u_w) from the current value to a higher value equivalent to the pressure of air applied to the soil sample (u_a). Thus, the matric suction (u_a-u_w) of the soil sample stays constant regardless of the translation of the pore-air and pore-water pressure. Reference [27] developed an axis-translation technique to resolve the issue of cavitation at low negative pore pressure. Axis-translation requires the monitoring of the pore-air pressure to measure the matric suction, and pore-water pressure maintained at atmospheric pressure. Axis-translation is performed by isolating air and water phases in the soil through a saturated high air-entry permeable material, typically a ceramic disk. The saturated high air-entry ceramic disk permits water flow. However, stop the flow of free air when applied, and the matric suction doesn't surpass the disk air-entry value. Good contact between the soil specimen and the saturated ceramic disk should be set up all through the test to guarantee the coherence between the water state in the soil sample tested and that in the pores of the ceramic disk used [28]. Since water pressure in the water container is maintained as close as achievable at zero, the method is designated null-type axis-translation technique [29].

Advantages of axis-translation

- The main benefit of axis translation is that no chemical is used in the process to control suction. Consequently, there is no risk of changing the chemistry of the pore liquid.
- The axis-translation technique is regularly utilized for testing unsaturated soils since it is moderately simple to modify existing apparatus for saturated soil testing by just including a high air entry channel and air pressure source.
- The technique is effectively applied to the volume change and shear stress testing of unsaturated soils, with apparatus including triaxial cell [30,31,32].

Disadvantages of axis-translation

- Axis translation technique does not yield instantaneous results when utilized to impose matric suction. Axis-translation requires the air and water states to be continuous between the pore-water in the soil and the water in the estimating device to describe the actual suction inside the soil specimen [33].
- Unsaturated soil testing utilizing the axis-translation requires an extended time frame. As the test advances, pore-air diffuses through the water in the high-air entry disk and shows up like air bubbles underneath the disk, which may introduce a mistake to the assessment of the pore-water pressure or volume of water [3]. A flushing system is required to overcome the problem [34,35,36].

IV. INDIRECT SUCTION MEASUREMENT

The methods utilized to measure directly the soil suction presented in this section are as follows: Electrical conductivity sensor, thermal conductivity sensor, filter paper technique, time-domain reflectometry, squeezing technique, thermocouple psychrometer, and chilled mirror hygrometer. The measurement is conducted by equilibrating the porous sensor with the negative pore pressure in the soil. In this section, the standards, characteristics, and procedures are described.

A. Electrical conductivity sensor

The soil resistivity and suction rely upon the degree of soil saturation. Water content variations can be measured using both methods. The electrical conductivity sensor estimates the electrical impedance of the porous block in contact with the soil in which suction is to be measured. A typical representation of the electrical conductivity sensor is presented in Fig. 6. The electrical impedance of the porous block reduces with the increment of moisture content.

This apparatus is designed with two concentric electrical electrodes installed in a permeable block typically made of gypsum. A calibration graph is developed between the moisture content indirectly correlated to suction and the block electrical impedance. The variation of electrical conductivity with matric suction depending on the soil type is presented in Fig. 5.

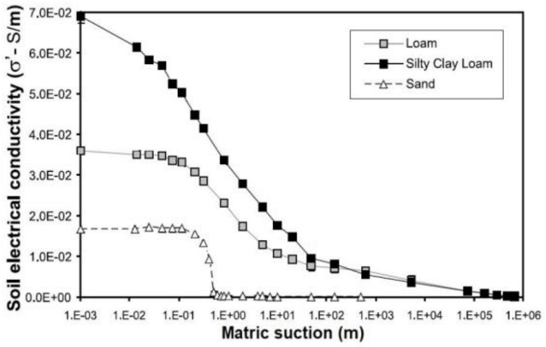

Fig. 5. **Variation of Electrical Conductivity with Matric Suction [37]**

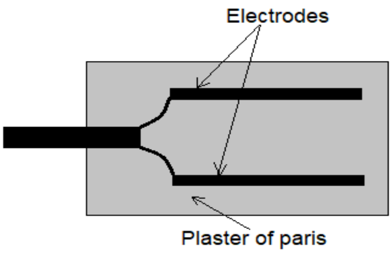

Fig. 6. **Typical Electrical Conductivity Sensor (Gypsum Block)**

Advantages of electrical conductivity sensor

- Efficient for suction determination in non-saline soils and can estimate the suction values between 30 to 1500 kPa.
- Simple to handle and use and can be utilized to perform soil suction estimation both in the laboratory and the field.

Disadvantages of electrical conductivity sensor

- The sensitivity drops when the matric suction is higher than 300kPa, and the block might be dissolvable in water and induce an augmentation in the salt substance in the soil. Furthermore, the block undergoes hysteresis during the wetting and drying cycle.
- The soil salt concentration influences the electrical resistance of the block, and the readings measured may not be a correct value of the moisture content inside the porous block.
- The porous block equilibrium time is estimated at 2 to 3 weeks. Also, the equilibrium time changes with matric suction values as follows: about 6 hours for the matric suction value of the order of 50 kPa. 2 days for the matric suction value of the order of 1500 kPa.

B. Thermal conductivity sensor

The negative pore pressure in the soil is estimated indirectly using a thermal conductivity sensor. The basic principle is that the matric suction gradient between the specimen and the porous block induces a water flux until the suction values are equal. The moisture content inside the porous block relies upon the matric suction applied on the block by the surrounding soil. The equilibrium time depends upon the temperature gradient, hydraulic conductivity of the porous medium, and surrounding soil. Reference [38] designed a device composed with a temperature sensor and heater that could be set up directly into the soil to estimate the thermal conductivity. Reference [39] proposed an electrothermal component to measure the moisture in a porous medium. The component is designed with a resistance thermometer wrapped with a smaller heat coil. Richards recommended the use of a sandy silt material as a porous block. Reference [40] investigated the materials used as a porous cup for a thermal conductivity sensor. It is found that castone is a suitable material. Reference [41] developed a thermal conductivity sensor utilizing a Germanium P-N diode as a temperature sensor. The sensor is wrapped with a 40-gauge Teflon-covered copper wire that served as a heating coil. The thermal conductivity sensor consists of a porous ceramic block containing a temperature detecting component and a small scale heater. The thermal conductivity of the ceramic block varies with moisture content inside the block. Fig. 7 shows a cross-section of a typical thermal conductivity sensor.

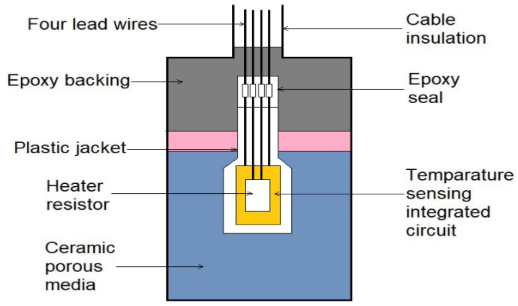

Fig. 7. Cross Section of Thermal Conductivity Sensor [41]

The matric suction is estimated using a calibrated sensor by setting the sensor in the soil and permitting it to come to equilibrium with the state of stress in the pore-water. The sensing part is installed in a porous block. The block should be huge to contain the heat pulse without impedance from the surrounding soil. The thermal conductivity estimation at equilibrium depends on the matric suction in the soil determined through the utilization of the calibration curve. The heat dispersion inside the permeable block is measured using the thermal conductivity. The moisture content inside the block is estimated by heating the porous block with a heater embedded in the center of the porous block and by measuring the temperature increment during heating. Reference [42] reported that, in engineering practice, an adequate calibration method should be utilized. The properties of the porous block are different. Calibration is required to achieve reliable and accurate measurements. A calibration reading is performed by putting sensors inside the water. When sensors are dried, additional calibration readings are performed at a specifically applied suction.

Advantages of thermal conductivity sensor

- Capacity to perform a reliable estimation of negative pore pressure within a wide range of suctions, and the measures are not impacted by the soil salt content [43,42].
- Ability to be attached to a data logger system for continuous and remote monitoring of suction.
- Suction measurement can be conducted both in the field and lab.

Disadvantages of thermal conductivity sensor

- The primary issue with the thermal conductivity sensor is the variable uniformity of the porous block from one sensor to another.
- A different calibration curve is required for every thermal conductivity sensor before their utilization for suction estimation.
- The thermal conductivity sensor exhibits hysteretic behaviour upon the wetting and drying cycle.
- The maximal matric suction value that can be measured is of the order of 1500 kPa. Inaccuracy generally occurs at a higher range of suctions.

C. Filter paper technique (FPT)

The FPT is an indirect method to estimate the negative pore pressure in the soil. FPT is the easiest method for estimating soil matric suction. It was first utilized by [44] in Denmark. Nevertheless, [45,46,47,48] might be credited by having made it well known. Endeavors to utilize the FPT in engineering practice were made [49,50,51]. The FPT can be used To measure the swell potential profile of pavement subgrades in heaving soils [50]. The FPT has been commonly used to estimate soil suction in recent years and now a U.S. standard. The method has been accessible and has currently undergone a revival with the arrival of low-cost and precise digital scales [52]. The FPT is based on the water absorptive properties of the filter paper (FP). When the FP is exposed to a soil environment, it will either desorb or absorb moisture until the suction within the FP and the soil are identical. Essentially, the FP achieves the equilibrium with the specimen over a fluid flow (matric suction estimation) or vapour (total suction estimation). The FP works as a moisture detector. FPT is a versatile test technique for soil suction estimation because of its benefits over other suction estimation techniques. Fig. 8. shows a typical draft of non-contact and in-contact FPT for total and matric suction estimation. FPT is utilized for a few kilopascals to several hundred thousand kilopascals [46,47]. Nonetheless, the measurements must be conducted with extreme care to obtain reliable results. The total suction in the soil is estimated utilizing the non-contact FP, and the matric suction is measure utilizing the contact FPT approach.

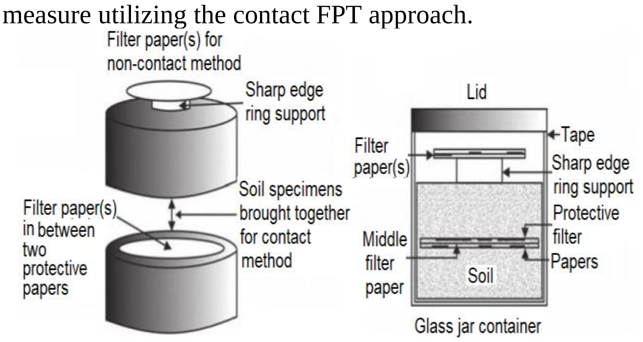

Fig. 8. Non-Contact and in-Contact Filter Paper Technique for Total and Matric Suction Measurements

In-contact filter paper technique

The in-contact FP achieves the equilibrium with the soil over a fluid flow (matric suction estimation). The soil suction is measure from the moisture content inside the FP. Two kinds of FP are utilized commonly for suction assessment: Schleicher and Schuel No. 589 WH and Whatman No. 42. Between the two types of FP used FP, the Whatman No. 42 FP appears to be more reliable than the Schleicher and Schuell No. 589 [6,53]. Fig. 9 shows a Whatman No 42 type FP (Ashless circles 70 mm diameter, Cat No 1442-070). Fig. 10 shows the scanning electron micrograph of the FP formed of a porous matrix of cellulose fibers.

Fig. 9. Whatman Grade 42 Filter Paper

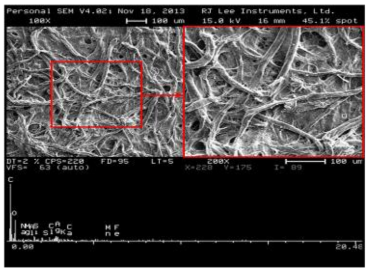

Fig. 10. SEM Whatman No 42 Filter Paper [56]

The pore within the specimen governs the amount of moisture absorbed by the FP. at high moisture contents or its cellulose fibers at low moisture contents. Reference [53] found no reports in the literature of significant issues with bacterial or algal growth on FP when they are utilized to estimate the suction because the equilibrium time doesn't offer enough time for bacterial growth. Later on, [6] reported that no concerns is raised in the literature of bacterial or algal growth on FP used to measure the matric suction. To measurement of the matric suction is as follows: a small contact force should be applied to the FP for good contact between the soil and FP during the equilibration time. The FP of known mass is placed to direct contact with the soil specimen and place in a glass jar, sealed with a lid an electric tape, and place in a temperature regulator apparatus.

The specimen in the wet state takes longer to attain an equilibrium. The equilibrium is achieved usually in 4 days to a 1% error [54]. Nonetheless, seven days are required, but at list five days [51]. Reference [55] suggested an equilibrium period of one week. Besides, the matric suction estimated by the FPT is affected by a few variables: Equilibration time, hysteresis on wetting and drying, and the type and quality of FP [56]. The process accuracy relies upon the nature of the FP utilized, the precision of the established calibration curve, and the sensitivity of the weighing scale. The calibration curve for the FP is developed by equilibrating the FP in a suction plate (or pressure plate) at different applied suction pressure, and the moisture content within the paper is estimated alone.

The FP calibration is also conducted through a salt solution as an osmotic potential for negative pore pressure. Researchers like [57,51,58,59,13] have performed the calibrations of Whatman No. 42 FP for both the contact and non-contact FP. Researchers such as [47,48,60,58] have performed the calibration of Schleicher and Shuell No.589 FP for both the contact and non-contact FP. The calibration curves for Whatman No.42 FP, Schleicher, and Shuell No.589 FP are summarized in Table 1.

Table-I: Calibration Curves for Whatman No.42 ; Schleicher and Shuell No.589 filter papers

Whatman No.42 Filter Paper		
References	**Calibration curves Ψ = suction (kPa)**	**Filter paper water content W_f (%)**
[57]	$Log(\Psi)= 8.022 - 3.683log(W_f)$	-
[51]	$Log(\Psi)= 4.84 – 0.0622 log(W_f)$	$W_f < 47$
[59]	$Log(\Psi)= 6.05 – 2.48 log(W_f)$	$W_f \geq 47$
[58]	$Log(\Psi)= 5.327 – 0.0779log(W_f)$	$W_f < 45.3$
[61]	$Log(\Psi)= 2.413 – 0.0135log(W_f)$	$W_f \geq 45.3$
[13]	$Log(\Psi)=5.313 – 0.0791log(W_f)$	$W_f \leq 50$
Schleicher and Schuell No.589 Filter Paper		
[47]	$Log(\Psi)=5.238 – 0.0723log(W_f)$	$W_f < 54$
	$Log(\Psi)=1.8966 – 0.01025 log(W_f)$	$W_f \geq 54$
[48]	$Log(\Psi)=4.136 – 0.0337 log(W_f)$	$W_f < 85$
	$Log(\Psi)=2.0021 – 0.009 log(W_f)$	$W_f \geq 85$
[60]	$Log(\Psi)= 4.9 – 0.0624 log(W_f)$	$W_f < 66$
	$Log(\Psi)=1.25 – 0.0069 log(W_f)$	$W_f \geq 66$
[58,61]	$Log(\Psi)=5.056 – 0.0688 log(W_f)$	$W_f < 54$
	$Log(\Psi)=1.882 – 0.0102 log(W_f)$	$W_f \geq 54$

Non-contact filter paper technique

The non-contact FP is utilized to estimate the total negative pore pressure. In this technique, the vapour phase isolates the FP and the soil that acts as a barrier, and the transfer of solutes is not possible. A dry FP is suspended over a soil specimen in an airtight glass jar for water vapour equilibrium between the soil specimen and the FP at a constant temperature. The vapour space over the soil specimen acts as a genuine semi-porous film to water vapour, not to ions from the pore-water. Thus, only the total suction is measured. After equilibrium is terminated, FP is removed, and the moisture content in the FP is estimated as quickly as possible. Before the total suction measurement, the FP is calibrated to describe the correlation between the relative humidity and water equilibrium, or the soil suction is measured using existing calibration curves equations. Reference [29] reported that the non-contact FPT is utilized both in the field and laboratory to estimate the total suction. Reference [51,57] reported that the FP is a non-expensive, simple, and reliable. Reference [53] studied the factors that influence the matric suction estimation by the FP. As a result, the nature of the FP, hysteresis, suction source, and equilibrium time have a significant impact on soil suction estimation.

Advantages of filter paper technique

- Simplicity, low cost, reasonable accuracy, and does not require any special equipment.
- Wide range of suction values that it can measure.
- Total and matric suction are estimated both in the field and the laboratory.

Disadvantages of filter paper technique

- Extreme care is required during the test procedure, and suitable calibration curves must be utilized [62].
- The accuracy of the suction measurement values depends on the accuracy of calibration curves [63].
- The method is time-consuming. Days, weeks are required for the FP to attain the equilibrium.

D. Time Domain Reflectometry (TDR)

The time-domain reflectometry is utilized to measure the matric suction indirectly in the field and lab. Reference [64] proposed TDR estimate the soil water content by for the first time. After, numerous others have utilized it, for instance, [65,66,67,68]. The TDR working principle method is based on the estimation of the soil apparent dielectric constant, which is related to the water content of the soil [64]. The pore-water held in the voids between the clay clusters is the bulk pore-water, which gives rise to the capillary phenomenon (i.e., matric suction) in the absence of a genuine semi-porous membrane. Hence, the TDR technique essentially quantifies the matric suction rather than the total suction. Fig. 11 shows the main component of a typical TDR: An oscilloscope, coaxial cable, waveguide, and step pulse generator.

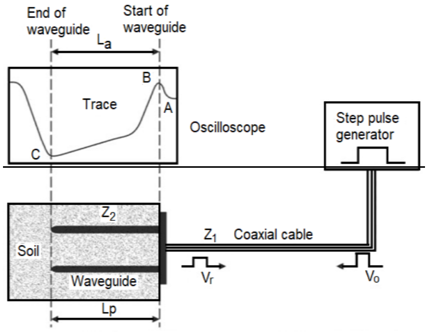

Fig. 11. Four Main Components of a Typical TDR System

TDR technique requires the utilization of at least two metal rods into the ground that acts as a waveguide or parallel transmission line. The measurement is performed by transmitting an electromagnetic signal through the soil along the conductor. The signal arrives at the waveguide end. It is back-reflected to the transmitter, the oscilloscope record the return time and the wavelength. The electromagnetic wave velocity in the soil is designated by (C) and given in Equation 3. C_o=3x108m.s-1 is the light velocity in a vacuum, the dielectric number relative to a vacuum is denoted by (ε), and the magnetic permeability of the vacuum is designated by (μ).

$$C = \frac{C_O}{\sqrt{\varepsilon\mu}} \qquad (3)$$

The relative magnetic permeability of soils is generally unity since they rarely contain the amounts of ferromagnetic minerals significantly. The dielectric number of the soil is designated by (ε_s), the length of the conductors or waveguides is represented by (l), the time return is denoted by (t), and the wave velocity is represented by (C=2l/t). In Equation 4, $\varepsilon = \varepsilon_s$.

$$\varepsilon_s = \left[\frac{C_O{}^2}{C^2\mu}\right] = \left[\frac{t^2}{\mu}\right] \times \frac{C_O{}^2}{4l^2} \qquad (4)$$

The estimation is duplicated in the water at a similar temperature as the soil if L is the travel time inside the soil specimen, and lw is the time of travel inside the water which follows that ε_w.

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Equation 5 describes the value of the water dielectric number.

$$\varepsilon_w = \varepsilon_s \left[\frac{l_w^{\,2}}{L^2}\right] \qquad (5)$$

The ratio lw^2/L^2 can be calibrated against the volumetric or gravimetric water content (θ or ω). The volumetric water content θ is related to gravimetric water content ω given in Equation 6. The specific gravity is (G), the void ratio is (e), and the degree of saturation is (S).

$$\theta = \frac{\omega\, G}{1+\omega G} = \frac{eS}{1+eS} \qquad (6)$$

Fig. 12 shows a calibration between volumetric water content θ and l_w^2/L^2 is obtained from in situ measurement on several soils [69] varying in particle size composition from 54% clay, clay 41% silt & 5% sand to 9% clay, 10% silt and 81% sand, 2% clay and 98% organic matter.

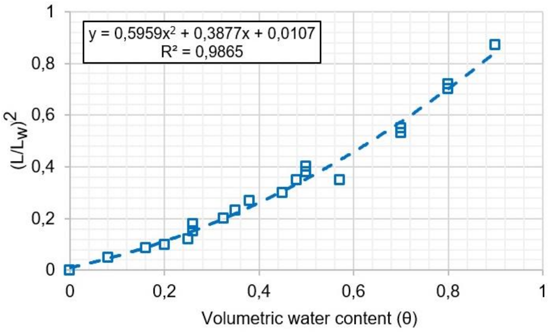

Fig. 12. Time Domain Reflectometry [69] Calibration for Several Soils with Particle Size Distributions

Fig. 13 shows the calibration of the apparent dielectric constant ($K_a = \varepsilon_s/\varepsilon_w$) against the matric suction. Also, the length of the insertion of the waveguide, between 0.4L and L, has a negligible effect on the calibration [53].

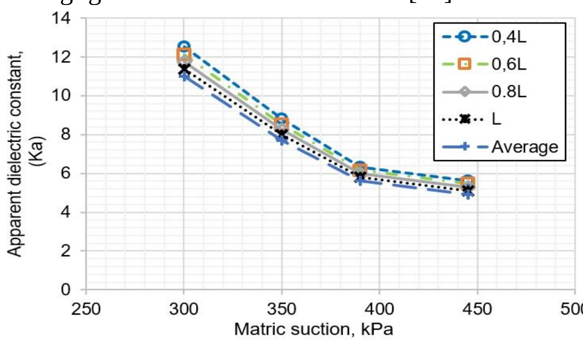

Fig. 13. TDR: Relationship of Apparent Dielectric Constant Versus Matric by Different Insertion Length

Advantages of TDR technique

- The main benefit of the method is that a reliable estimation of volumetric water content is performed over a short time [66].
- Since the TDR technique exhibits a small response zone perpendicular to the waveguides, the volumetric water content can is obtained at higher degrees of vertical resolution, and continuous investigation of soil moisture estimations is conceivable through computerization and multiplexing.
- They are suitable for the estimation of volumetric water content with a precision of 1-2 %.

Disadvantages of TDR technique

- The limitation is that the method requires a very sophisticated electronic device, and the accuracy of TDR for estimating matric suction relies upon the precise estimation of the SWRC of the tested soil.
- The wave formed of the input signal can produce errors between the actual and measured water content of as much as 65% at low water contents (θ = 0.1 and less), falling to 15% at high water contents (θ = 0.4 and above).
- There is a high possibility of signal attenuation in saline soils, and it is not recommended for waterlogged soils or soils having high organic contents.

E. Squeezing technique

Many researchers are focused on the correlation between matric suction and water content. Nevertheless, the osmotic suction may also play a significant role in the hydro-mechanical behaviour of clayey soils [14]. Osmotic suction relies upon the concentration of dissolved ions in the pore water. The squeezing technique is utilized commonly to measure the osmotic suction in the soil indirectly. The osmotic suction range is within the range of 0 to 1500 kPa, and the equilibrium period takes days. A typical representation of pore fluid squeezer is shown in Fig. 14.

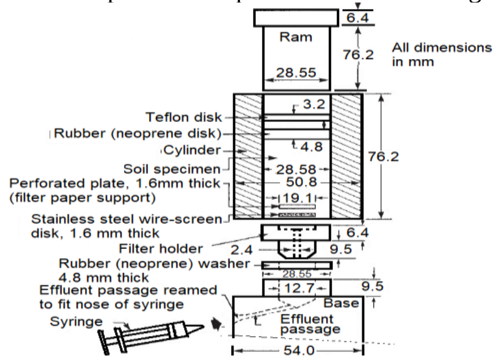

Fig. 14. Design of Pore Fluid Squeezer [73]

Soil pore-water can be removed using a pore-liquid squeezer, precisely the squeezing technique. This method consists of squeezing a soil specimen to remove the large macropore of water and then after estimating its electrical conductivity, that is related to the total concentration of dissolved salts and can be related to the osmotic suction in soil. The pore liquid squeezer method allows the whole range of osmotic suction to be estimated and give an accurate estimation of suction [70,71]. This technique consists of separating the pore liquid from soil specimens sandwiched between a squeezing cylinder and a set of disks at one side and the opposite end of another disk, filter paper, and a cylindrical base where a syringe is used to drive out the pore fluid. The electrical signal is transformed into osmotic suction when using the osmotic suction versus the conductivity curve [71]. The results obtained utilizing the squeezing method by [72] are described to be impacted by the intensity of the extraction force. The osmotic suction appeared to concur nearly with the total suction utilizing a psychrometer minus matric suction estimations from the pressure plate. The pore fluid squeezer technique gives an acceptable measurement of osmotic suction [72].

F. Thermocouple psychrometer technique

The thermocouple psychrometer is a method that infers the suction of the fluid phase of a specimen from estimations inside the vapour phase that is in equilibrium with the specimen.

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The total negative pore pressure in the soil is estimated using the relative humidity or air phase of voids. In theory, the correlation relative humidity of the vapour phase and water potential of the liquid phase is described by Kelvin relation [3] given in Equation 7. Where Ψ is the total suction, R is the gas universal constant (8.314x10-6 MJmol-1K^{-1}), T is the thermal reading (K), Vw is the molar volume of water (1.8x10-5m3mol-1), and P/P_o is relative humidity expressed as a fraction where P is the actual vapour pressure of air in equilibrium with the liquid phase, and P_o is saturation vapour pressure at T.

$$\Psi = \frac{RT}{V_w} \times \ln\left(\frac{P}{P_o}\right) \quad (7)$$

Peltier psychrometer is utilized to measure the total suction ranging from 100 to 8000 kPa both in the field and the laboratory. Peltier type [74] and the wet loop-type [75] are the two essential types of thermocouple psychrometers. Peltier-type psychrometers and wet-loop are different in the way that the evaporating junction is wetted to initiate dissipation. Fig. 15 shows a Peltier-type psychrometer commonly used in civil engineering in Fig. 15. A thermocouple consists of 0.025-mm diameter wires of constantan and chrome. The wires are welded together to shape a dissipative or a measurement junction. Wires at the other end are attached to 26 American Wire Gauge (AWG) copper lead wires to form a reference junction. The conductive copper wires have a large width and are used as heat sinks that keep up a constant temperature at the reference junction. The heat sink absorbs the heat created close to the reference junction when the estimating junction is cooled. The higher level of cooling produced by the chrome constantan thermocouple is about 0.6 °C under the surrounding temperature [76]. This higher cooling shows the minimum relative humidity or the highest limit of the total suction that can be estimated utilizing the thermocouple psychrometer. The assessment of the total suction is achieved by putting a psychrometer near the specimen in a closed domain. At the point where the equilibrium is complete, the relative moistness is measured. The isothermal equilibrium is performed between the air and soil before recording the psychrometer's reading. A precision of ±0.001°C in the temperature controller is needed to gauge the total suction with an accuracy of ±10 kPa [72]. The thermal equilibrium in the psychrometer is achieved by setting the microvoltmeter reading at zero.

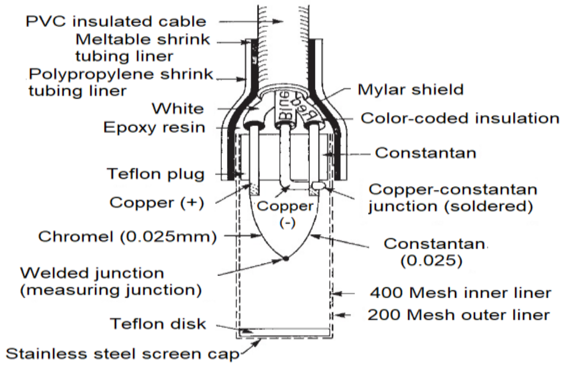

Fig. 15. Schematic Diagram Peltier Type Thermocouple Psychrometer [77]

The calibration of the psychrometer is achieved by a correlation between microvolt outputs of the thermocouple for a salt solution with an acceptable total suction value. The psychrometer is mounted in a chamber. The filter paper is saturated with NaCl or KCl and set at the base of a chamber. The osmotic suction for NaCl and KCl solutions at various molalities and temperatures are measured utilizing the graphs shown in Fig. 16 and Fig. 17.

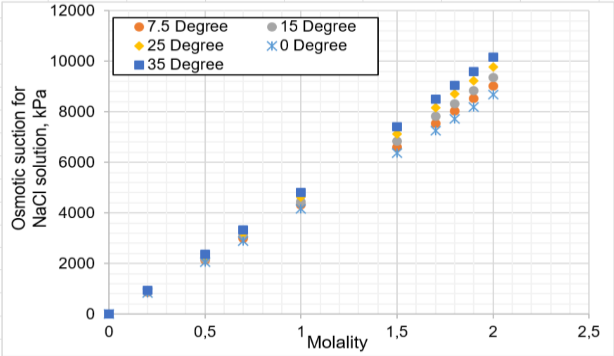

Fig. 16. **Calibration of Peltier-Type Psychrometers with Nacl Solution [78]**

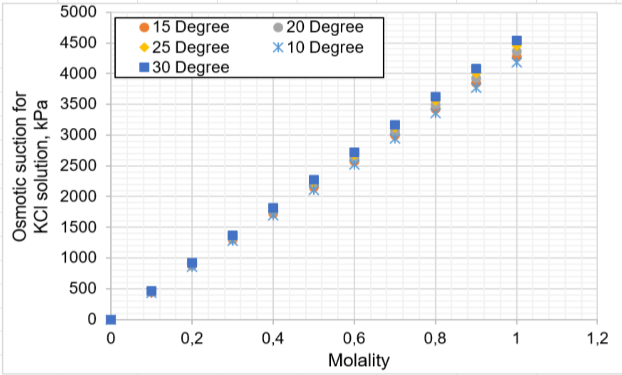

Fig. 17. Calibration of Peltier-Type Psychrometers With Kcl Solution [79]

When using in the field, the soil temperature adjacent to every psychrometer should be estimated by another calibrated thermocouple. That is to guarantee that the calibration of the psychrometer is valid at the soil temperature. Fig. 18 shows the calibration line of thermocouple psychrometers derived from measurements by several psychrometers. These measurements are compared to suction obtained from NaCl solutions of various concentrations [80].

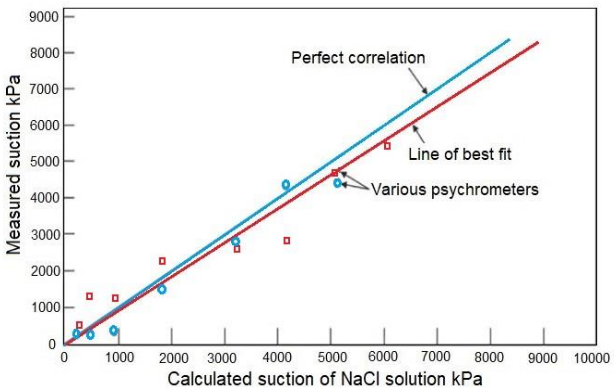

Fig. 18. Calibration of Psychrometers Against Sodium Chloride Solutions [80]

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Advantages of thermocouple psychrometer

- Thermocouple psychrometer is a precise and reliable technique to estimate the total suction if appropriate procedure and precaution are taken.
- The technique covers a wide range of suction estimation of interest in engineering practice and most appropriate for drier soils.
- Since the method estimates the conditions in the vapour phase, it doesn't require a constant fluid phase, and just a microscopic amount of water is associated with the estimation.
- The technique is flexible, and the device is commercially accessible for use in field and lab tests.
- The estimations can be made decently fast, often with the utilization of the automated data-acquisition device.
- Lab estimations made with a sample chamber require just a small specimen, which is beneficial for continuous testing.

Disadvantages of thermocouple psychrometer

- Adequate time must be allowed to guarantee total vapour-pressure equilibration, and steps must be taken to detect and prevent temperature-gradient errors.
- When working with small specimens, precautionary measures are necessary to prevent huge mistakes that can be induced by evaporative loss during specimen handling.
- The operational service life of these instruments is generally short.
- Calibration dependence, vulnerability to an error in environments with quickly changing temperature, susceptibility to corrosion in acidic environments, a requirement for sensitive measuring equipment, and a level of complexity makes the technique difficult to comprehend and apply.

G. Chilled-mirror hygrometer technique

The chilled-mirror hygrometer is an indirect method utilized to measure the total suction of soil. Fig. 19 shows a schematic drawing of a chilled-mirror hygrometer.

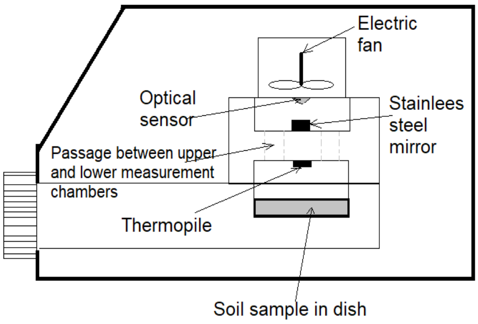

Fig. 19. Chilled-Mirror Hygrometer

In geotechnical engineering applications, the technique is utilized for measuring the negative pore pressure of soil [26,81,82]. A chilled-mirror hygrometer uses the chilled-mirror dew point process to infer total suction. The process is conducted under isothermal conditions in a closed chamber. The estimation of the total negative pore pressure depends on the fluid equilibrium phase of the water in a soil specimen, with the water vapour phase in the air space over the soil specimen in an airtight chamber [83]. The apparatus gear is like the thermocouple psychrometer. The total suction range estimation is within the range of 150 kPa to 30000 kPa with an equilibration time estimated to 10 minutes. The airtight container includes a fan, an optical sensor, an infrared sensor, a thermocouple, a mirror, and a soil specimen. The chilled- mirror hygrometer quantifies the dew point and temperature of the headspace over the specimen. The specimen is placed in an appropriate closed chamber to limit the drying of the soil specimen. Water vapour from the soil specimen is permitted to condense on the mirror, and a photoelectric cell is utilized to detect the specific point whereby condensation shows up firstly in the mirror. The thermal reading of the specimen that is the same as the thermal reading of the vapour space is estimated through an infrared thermocouple. The relative humidity or the water movement of the soil specimen is computed from the estimated dew point and temperature. A small fan is utilized to circulate the air in the sensing chamber and accelerate vapour equilibrium. The soil specimens and devices were kept at a similar area for at least several hours for temperature equilibrium before the test. The chilled-mirror gives an essential characterization of moisture in terms of the temperature at which vapour condenses. Temperature control is significant, and the measured difference between the dew point and specimen temperatures must be maintained low. A curve is calibrated utilizing standard salt solutions with known concentrations against their osmotic suctions. Fig. 20 shows the calibration curve developed by [84].

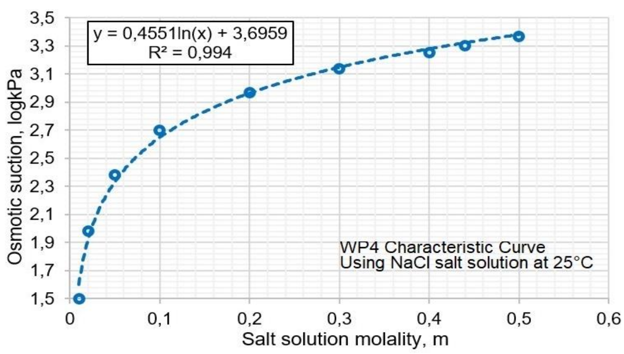

Fig. 20. Calibration of WP4 Chilled-Mirror Hygrometer [84]

Reference [26] investigated the exactness of a chilled-mirror dew point for compacted soil specimens. Careful calibration of the instrument utilizing a few standard salt solutions is conducted. The equilibration time during total suction estimation and calibration are short, under 15 min. The total suction of compacted specimens is compared with the sum of matric and osmotic suction of the similar soils that are estimated independently. The matric suction is estimated utilizing the axis-translation device, and the osmotic suction of the samples is evaluated from electrical conductivity estimations of the soil water solution derived from a pore water squeezer device.

The test outcomes indicated that total suction measured utilizing the chilled mirror dew point device is usually higher than the sum of matric and osmotic suction obtained. Nevertheless, by considering the discrepancies of total suction estimation, the procedure of equilibrium between the specimen and the vapour space is maintained. The chilled-mirror hygrometer technique is considered as the most precise approach for estimating total suction. Another promising hygrometer for total suction estimating is the polymer capacitance sensor that comprises two electrodes isolated by a film of thermoset polymer that releases or absorbs moisture when the relative density of the surrounding air changes [81].

H. Relative Humidity Sensor (Transistor Psychromter)

The relative humidity sensor is utilized to measure the total negative pore pressure in the soil indirectly. The instrument performance was enhanced to allow the measurement of a wide range of negative pore pressure ranging from 100 kPa to 10,000 kPa. The enhancement is achieved through the calibration process, and innovation in micro-chip applied science [85]. The range and precision in estimations depend on the sensitivity of the transistors to changes in temperature. Soil Mechanics Instrumentation [85] produces two sorts of thermally protected containers for the transistor probes: 12-probe unit and 8-probes unit. The 8-probes psychrometer is equipped with an insulated cover for better temperature control. Each sensor can gauge a total suction in 1 hour. Twelve and eight specimens total negative pore pressure estimations can be achieved respectively in 1 hour with the 12-and 8-probe units. Reference [86] reported that the transistor psychrometer has a superior ability to estimate total suction at lower moisture content. The relative humidity and temperature of the vapour space of the soil are measured, and the total suction is computed using Kelvin's law [3] described in Equation 7. The transistor psychrometer comprises a thermally insulated reservoir that holds the probes and a data logger. They are used to estimate and record the output. The instrument is like the same as in operation to the thermistor psychrometer [85]. The transistor psychrometer is a wet and dry bulb thermometer in which a dry and wet transistor probe is utilized. The transistor probe gauges the relative humidity of the air space in equilibrium with a soil specimen. The wet transistor temperature depression is estimated using a transistor psychrometer as presented by Fig. 21.

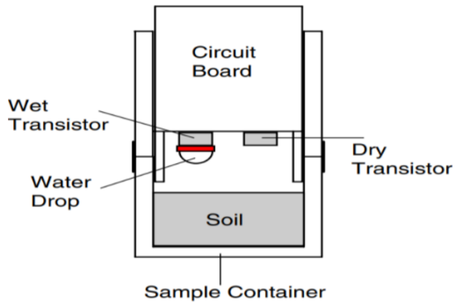

Fig. 21. Schematic Drawing of a Transistor Psychrometer Probe

Fig. 22 shows a typical calibration curve of a transistor psychrometer probe. The wet and dry transistors are used as heat sensors, and the potential difference output of the sensor probe is used to deduce the total negative pore pressure. The calibration curve is influenced by temperature variation, hysteresis, and water drop size. The transistor probes the equilibrium process takes a minimum of 4 hours at zero total soil potential over distilled water, and the output is changed under initial zero reading before the calibration process for negative pore pressure estimation. After, the voltage outputs are recorded by datalogger 1 hour after equilibration. The thermally insulated reservoir provided for the probes keeps up a steady temperature during the time of the test. More accuracy and reproducibility of outcomes are obtained in a room where the temperature is controlled to about ± 0.5 C [85]. A transistor psychrometer can only perform point estimations.

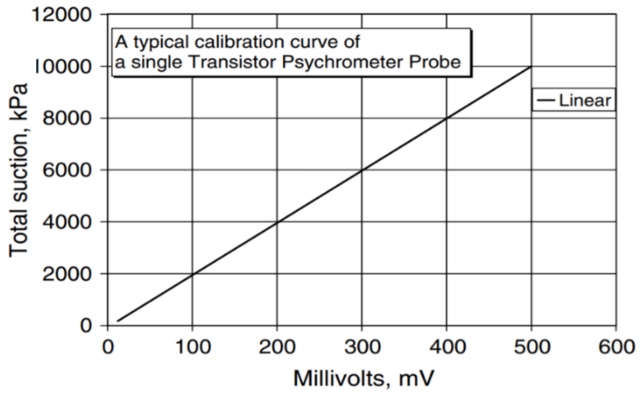

Fig. 22. A Typical Calibration Curve

V. SUMMARY OF SUCTION MEASUREMENT METHODS

The methods commonly used to measure the soil suction directly or indirectly are summarized in Table 2, depending on the method type, suction range, equilibrium time, and application (Lab/Field).

Table-II. Summary of Suction Measurement Methods

		Method / Technique	Suction Range (kPa)	Equilibrium time	Laboratory (L) or field application (F)
Direct method	Matric suction	Conventional tensiometer	0 - 90	Minutes	L & F
		Suction plate	20 to ~ 85	Hours	L
		High suction tensiometer : Imperial college tensiometer or Suction probe	0 – 1.500	Minutes	L & F

		Pressure plate	0 – 1.500	Hours-day	L
		Null-type Axis-translation	0 – 1.500	1 to ~ 16 hours	L
Indirect Method	Matric suction	Electrical conductivity sensor	50 to ~ 1.500	6 to ~ 50 hours	L & F
		Thermal conductivity sensor	10 to ~ 1.500	Hours-day	L & F
		In - contact filter paper	Entire range	7 to ~ 14 days	L & F
		Time Domain Reflectometry (TDR)	0 – 1.500	Hours	L & F
	Osmotic suction	Squeezing technique	0 – 1.500	days	L
	Total suction	Thermocouple psychrometer	100 to ~ 8.000	1 Hours	L & F
		Relative Humidity Sensor (Transitor Psychrometer)	100 to ~ 10.000	Hours-day	L
		Chilled-mirror hygrometer	150 to ~ 30.000	10 minutes	L
		Non - contact filter paper	Entire range	7 to ~ 14 days	L & F

VI. CONCLUSION

In summary, conventional tensiometer, high suction tensiometer, suction plate, imperial college tensiometer (suction probe), pressure plate, null axis translation are utilized for the direct suction measurement. The indirect method comprises three groups, namely, the measurement method of total suction, osmotic suction, and matric suction. The total suction measurement apparatus includes the thermocouple psychrometer, transistor psychrometer, chilled-mirror hygrometer, non-contact filter paper. The osmotic suction estimation includes squeezing technique. The matric suction measurement apparatus consists of an electrical conductivity sensor, thermal conductivity sensor, in-contact filter paper, time-domain reflectometry, and their highest range is in the order of 1500 kPa. The thermocouple psychrometer and the transistor psychrometer can measure the highest total suction of the order of 8000 kPa. The chilled-mirror hygrometer can measure the maximal total suction of the order of 30000 kPa in the lab. The filter paper method and the chilled-mirror hygrometer are cost-effective in suction estimation. The filter paper technique is likely the easiest and low-cost method to measure the matric suction and total suction for a wide range by a correct lab or field practice. No serious issues have been found in recent literature over algal or bacterial growth on filter paper when they are used to measure soil suction. It should be useful to develop a mathematical predictive model for soil suction estimation utilizing the soil properties.

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