Performance of Fredlund Thermal Conductivity Sensor

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ABSTRACT: Measurement of field suction is an important aspect in unsaturated soil mechanics. Suction measurements are useful in areas of mine reclamation and environmental protection. This paper presents a thermal conductivity suction sensor that measures matric suctions ranging from 1 to 1500 kPa. Sensor features include: digital design, smooth heating curve, high resolution in suction measurements, moisture barrier to protect electronics, and a durable ceramic tip. Suction measurements better than 5% of measured value are possible. Digital design minimizes the effect of ambient temperature, cable resistance, and eliminates signal noise enabling cable lengths of more than 100 m. An optimum quantity of heat is delivered to the sensor during testing, the peak temperature rise is measured, and the corresponding suction is obtained from a calibration curve. The heat transfer from the sensor to the surrounding soil during testing is negligible. Therefore, suction measurements are not influenced by the soil type or condition.

1 INTRODUCTION

Obtaining suction measurements in the field or in the laboratory is a challenging task for researchers and practicing engineers due to various limitations, laborious procedures, and the cost of currently available methods. Most common methods of suction measurements include psychrometers, filter papers, pressure plates, pressure membranes, tensiometers, and thermal conductivity sensors. The method of suction measurement, type of suction measured, range, and constraints associated with these methods are summarized in Table 1.

The information provided in Table 1 clearly shows the limitations associated with each method. For example, psychrometers show a poor sensitivity to low suction ranges, sensitivity deteriorates with time and require frequent maintenance. Filter papers are not possible to automate and calibration is sensitive to the elapsed time. Tensiometers are temperature dependent and require daily maintenance. On the other hand the thermal conductivity sensors are very promising in the field applications due to low maintenance, durability, accuracy of measurements, ability to automate the testing, for being unaffected by salinity and soil type, and low cost.

The objective of this paper is to introduce a newly developed thermal conductivity sensor and discuss the features, applications, and limitations of this sensor. This new sensor is herewith referred as the Fredlund Thermal Conductivity sensor or FTC sensor. The FTC sensor was developed by GCTS based on previous models developed by Fredlund and others. In the process, a considerable attention had been given to the accuracy and durability. The sensor indirectly measures the soil suction based on the thermal conductivity of a ceramic tip. A miniature-heating element embedded in the ceramic tip is heated by sending a constant electrical current for a specific time, and the temperature rise is monitored by a temperature sensor located near the heating element. The dissipation of heat, which controls the temperature rise, depends on the water content of the sensor. Therefore, the maximum temperature rise of the sensor is a function of the water content, and in turn a function of the suction.

The main features of this sensor include state-of-the-art digital design, high resolution in temperature measurements (0.004 °C), high accuracy in suction measurements, and ability to use cables more than 100 m long. The maximum suction that can be measured by the sensor is limited (1500 kPa) by the air-entry value of the plate used for calibration.

2 FREDLUND THERMAL CONDUCTIVITY SENSOR

A few years ago, Fredlund at the University of Saskatchewan (U of S) developed a thermal conductivity sensor for laboratory testing and field

Table 1. Methods for measuring total and matric suction (Ridley & Wray 1995, Fredlund & Rahardjo 1989).

Device	Method (Property Measured)	Suction measured	Range (kPa)	Principal constraints
Thermocouple psychrometers	Indirect (Relative Humidity)	Total	100 to 7500	Affected by temperature fluctuations. Sensitivity deteriorates with time.
Thermistor psychrometers	Indirect (Relative Humidity)	Total	100 to 10,000	Poor sensitivity in the low suction range. Frequent re-calibration is required.
Transistor psychrometers	Indirect (Relative Humidity)	Total	100 to 71,000	Frequent re-calibration is required. Specimens must be tested in order of increasing suction to avoid hysteresis.
Filter paper (non-contact)	Indirect (Water content)	Total	400 to 30,000	Calibration is sensitive to the elapsed time of the test.
Filter paper (in-contact)	Indirect (Water content)	Matric	Entire range	Automation of the procedure is impossible.
Suction plate	Direct	Matric	0 to 90	Low range of usefulness.
Pressure plate	Direct	Matric	0 to 1500	Range of suction limited by the air-entry value of the plate.
Pressure membrane	Direct	Matric	0 to 1500	Range in suction is limited by the air-entry value of the membrane.
Standard tensiometer	Direct	Matric	0 to 90	Requires daily maintenance. Temperature fluctuations affect readings. Slow to equilibrate in highly plastic soils.
Osmotic tensiometer	Direct	Matric	0 to 1500	Reference pressure can deteriorate with time. Temperature dependent.
Imperial College tensiometers	Direct	Matric	0 to 1800	Range in suction is limited by the air-entry value of the ceramic.
Porous block (Gypsum, nylon, fiberglass)	Indirect (Electrical resistance)	Matric	30 to 3000	Observations need to be corrected by temperature. Blocks are subject to hysteresis. Response to suction can be slow.
Heat dissipation sensors	Indirect (Thermal conductivity)	Matric	0 to 10,000±	High failure rate. Very fragile.
Osmotic cell	Indirect (Osmotic pressure of solutions)	Matric	Not available	Not available.

monitoring. The sensor was subjected to both laboratory and field testing by research groups in U of S and the results were published in several journal and conference papers (Fredlund et al. 2000, Shuai & Fredlund 2000, Marjerison et al. 2001, Feng et al. 2002, Shuai et al. 2002, Feng & Fredlund 2003, Shuai et al. 2003, Tan et al. 2003). Based on these studies, the sensor performed well in many ways, however, several drawbacks were identified. One of the main drawbacks was the failure of the sensor in moist environments due to ceramic cracking leading to moisture penetration into electronics. Another drawback was sensitivity of the readings to ambient temperature and length of the sensor cable, which were inherent to analog signals.

The new sensor presented in this paper is the next generation of the U of S sensor. It is geometrically similar to the U of S sensor and the ceramic tip is also made using similar materials and procedures. The improvements included using a moisture barrier around the electronics that solved the cracking and moisture penetration problem. Also, the adoption of state-of-the-art digital signals in the design eliminated the ambient temperature dependency and reduced the cable resistance effect enabling the use of cable lengths longer than 100 m (300 feet).

A cross-section of the FTC Sensor is shown in Figure 1 and a photograph of the sensor is shown in Figure 2. The ceramic block has a diameter of 28 mm and a height of 38 mm. The unconfined compressive strength of the sensor is approximately 7,000 kPa, dry density is 1.05 g/cm^3, and the porosity is approximately 60%. A small heating element and a digital temperature sensor are embedded in the center of the ceramic block, which are surrounded by a bonding material and a moisture barrier. The moisture barrier protects the electronics from moisture as well as prevents expansion of bonding material that used to cause cracking of the ceramic tip.

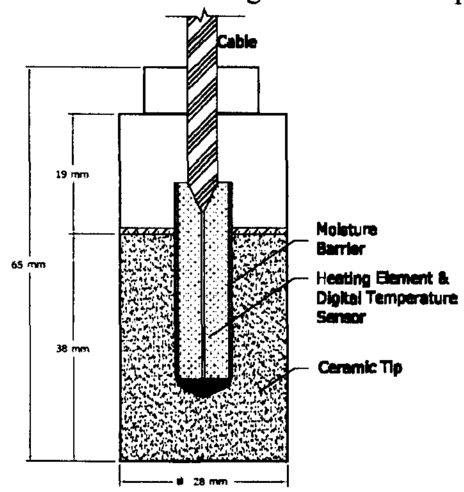

Figure 1. Cross-section of Fredlund thermal conductivity sensor.

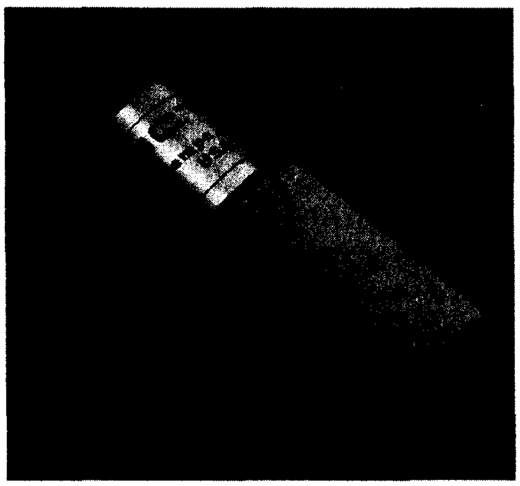
Figure 2. Photograph of Fredlund thermal conductivity sensor.

The digital temperature sensor has a resolution of 0.004°C. This temperature resolution contributes to highly accurate suction measurements even in the low ranges. The maximum possible accuracy of suction measurements is less than 0.2 kPa in the lowest suction range 1 to 10 kPa; less than 0.5 kPa in the mid range 10 to 100 kPa; and, less than 6 kPa in the high range 100 to 1,000 kPa. If the accuracy is expressed as a percentage of average measured suction in a given range, the maximum possible accuracy corresponding to low, mid, and high ranges are approximately 4.0%, 0.9%, and 1.0%, respectively. In general, it can be stated conservatively that the possible accuracy of suction measurements are better than 5% of the measured suction.

In earlier versions of the sensor, in which analog signals were used, the quantity of current transmitted through cables varied highly depending on the ambient temperature. Also, the intensity of signal output decreased with the cable length due to cable resistance, restricting cable lengths to a minimum. In addition, the readings showed a second temperature dependency due to the fact that the calibration curves were developed based on a standard temperature, 23°C, but the readings were taken in the field at different temperatures. Therefore, the data reduction required two temperature corrections. The first temperature correction posed a difficult task since the intended quantity of heat, which should truly be a constant, varied from one data point to another. The second correction, which depends on measured suction and ambient temperature, could be quantified adequately based on controlled laboratory testing. A method for applying the second temperature correction was presented by Nichol et al. (2003).

The adoption of digital design helped maintain a constant current during testing irrespective of the ambient temperature, which eliminated the first temperature correction. Also, the digital signals did not deteriorate with cable length enabling cable lengths of 100 m or more. However, the second temperature correction mentioned above is still required. The method presented by Nichol et al. (2003) was used in this study.

The use of special weather-resistant materials including direct burial cables contributed to the durability of the sensor. The sensor showed a compressive strength more than three times higher than the U of S sensor.

The sensors are manufactured in batches of 24. The manufacturing process is controlled such that each sensor in a batch has identical properties. The uniformity of sensors within a batch is verified by measuring the geometrical dimensions, dry density, and the calibration data at dry and wet extremes of each sensor. If these parameters are comparable then the sensors are considered identical. For an identical batch only one of the sensors is subjected to standard calibration process, which involves obtaining calibration data points at three additional suction values: 10, 100, and 500 kPa. The generated calibration curve is then used for all the sensors in the batch.

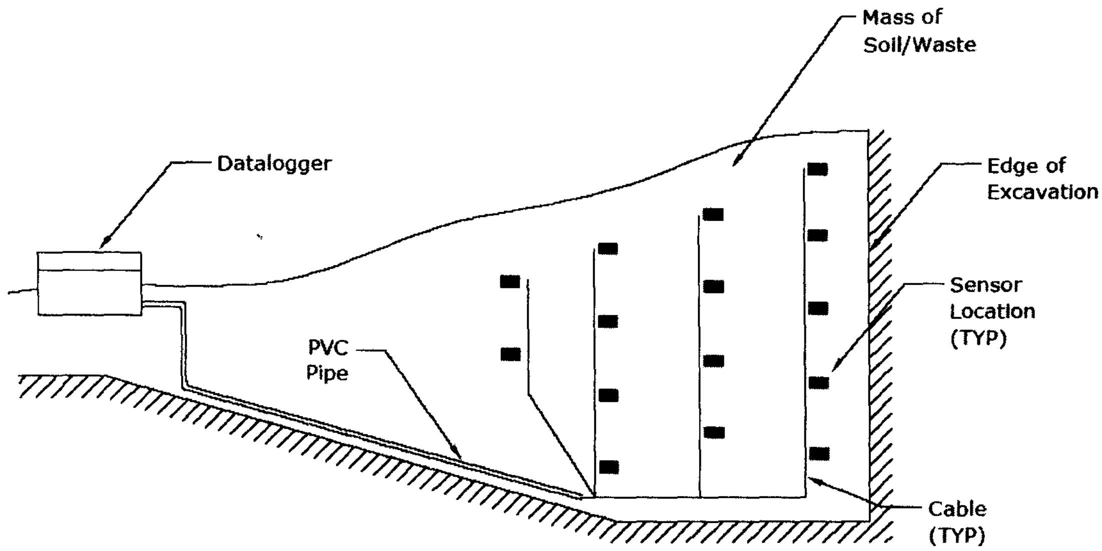

Figure 3. A sensor installation layout (Tan et al., 2003).

3 USING THE SENSORS

Typically multiple sensors are installed in unsaturated soil masses or waste piles at locations where the matric suction values are to be measured. Installation can be accomplished by excavating trenches, installing the sensors on trench walls, running cables to the datalogger, and backfilling the excavation simulating the preexisted condition. A typical sensor layout in the field is shown in Figure 3. Sensors can be installed in vertical, horizontal, or inclined boreholes provided the boreholes are properly backfilled preventing any preferential pathways of water movement. The installed sensors may experience saturation due to elevated groundwater levels during wet seasons or freezing conditions during winter months, but none of these extreme conditions harm the sensor.

The datalogger, which is housed in a weatherproof enclosure, contains the hardware and software required for monitoring the sensors. The datalogger is programmable to execute sensor-reading programs that could last up to a three-month period. The data stored in the datalogger can be retrieved for analysis by connecting a laptop, PDA or a PC via a USB port. The datalogger is powered by 12-volt rechargeable batteries along with a solar panel.

Taking a reading from a sensor involves: recording initial temperature (or ambient temperature); sending a constant current (200 mA) to the heating element of the sensor for a specific period (60 sec); tracking rise of temperature in the sensor; and recording peak temperature. The corresponding suction is then obtained by entering the calibration curve with the maximum temperature rise (ΔT). The calibration curve is predetermined in the laboratory as described in Section 4.

4 CALIBRATION CURVES

Generating reliable calibration data representing both drying and wetting curves is the most important factor in the sensor development process. A typical calibration curve is shown in Figure 4. A considerable amount of time, up to four weeks, is required to carry out a standard calibration procedure. For this reason only one of the sensors from a batch is subjected to calibration. It is also possible to undertake a more detailed calibration of the sensors.

In this study, a Fredlund SWCC (soil-water characteristic curve) device, which is a pressure plate device, was used for calibrating the sensors. High air-entry value (HAEV) disks rated 500 kPa and 1,500 kPa were used in the device. The two extreme points, dry and wet, on the calibration curve were obtained prior to installing the sensor in the pressure plate device. The sensor was tested in dry condition to obtain the value of ΔT corresponding to 1M (1,000,000) kPa, under the assumption that dry condition represents a very high suction approximately equals to 1M kPa. Then, the sensor was saturated by partially submerging it in water for one day, and then fully submerging it for another day. The saturated sensor was tested to obtain the ΔT value corresponding to 0 kPa. In semi-log plots, 0 kPa suction was approximated to 0.1 kPa.

The wet sensor was installed in the SWCC device as shown in Figure 5. A thin paste of kaolin was applied in between the sensor and the ceramic plate to facilitate moisture migration. Once the setup was complete, an air pressure of 10 kPa was applied to

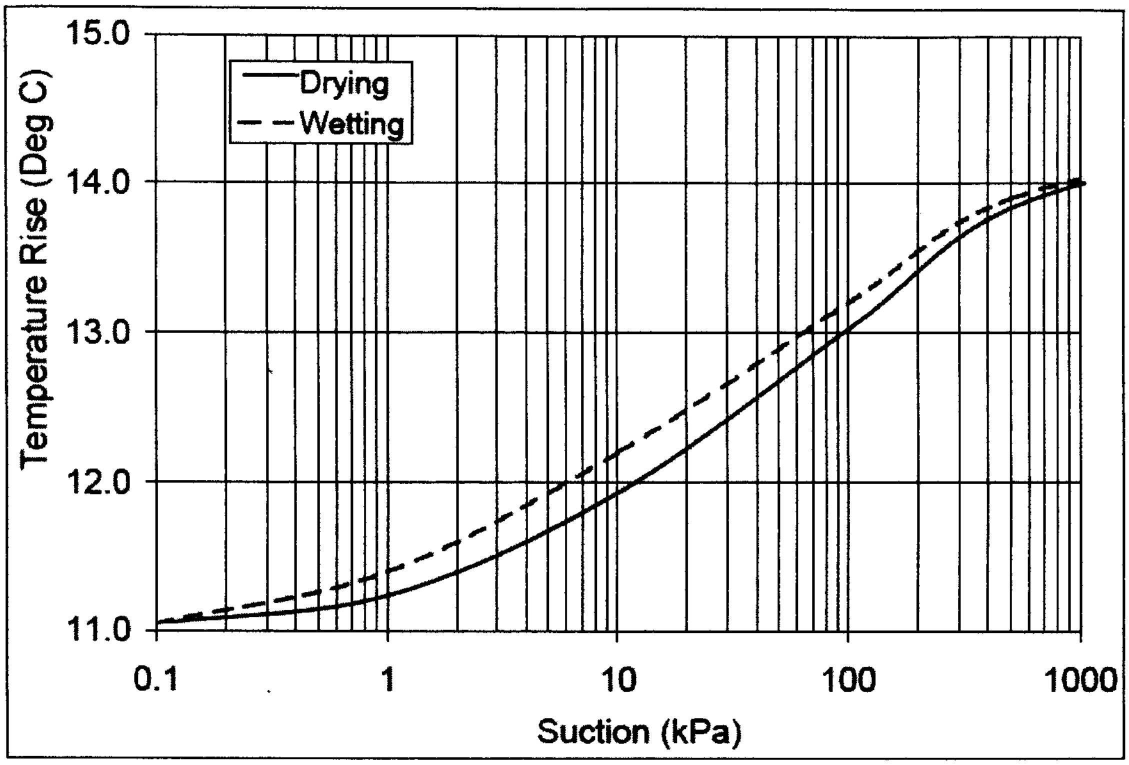

Figure 4. Typical calibration curve.

the cell chamber, and the sensor was allowed to equilibrate over time. The sensor response to applied pressure was monitored by testing the sensor a few times a day. The final ΔT corresponding to10 kPa suction was recorded once the equilibrium had been reached. The procedure was repeated for 100 kPa and 500 kPa chamber pressures. The data was plotted on a semi-log plot to obtain the "Drying" calibration curve similar to the solid curve shown in Figure 4.

Similarly, the "Wetting" curve was obtained with a dry sensor subjecting to a decreasing pressure sequence of 500, 100, and 10 kPa, respectively. The dotted curve in Figure 4 represents a wetting curve. The wetting curve lies above the drying curve illustrating the hysteresis behavior of ceramic tip (Feng Man et al., 2002). Both curves should be available for the user to make realistic suction measurements. Once the sensor is installed, the correct curve, drying or wetting, can be selected automatically by tracking the suction history.

4.1 *Determination of Optimum Current and Time*

As described earlier, the sensor testing procedure starts by sending a constant electrical current for a specific time period. In order to generate accurate data, current and time period should be kept constant every time. The quantity of heat generated should be high enough to give a maximum temperature rise and should be low enough to keep the temperature rise on the surface of the sensor to a minimum to eliminate the effect of surrounding soil. The resolution of suction measurements is directly proportional to the difference in temperature rise between wet and dry conditions. Therefore, it is important to have maximum possible temperature rise. However, if the temperature rise is too large, the surface of the sensor will experience a temperature rise. The surface temperature rise produces unwanted heat dissipation into surrounding soil that affects the temperature rise in the ceramic block resulting a reading error.

To find the optimum combination of electrical current and time, several possible combinations were tested while measuring the surface temperature on the sensor using a miniature thermocouple. Among the combinations used, 200 mA current sent over a 60 second period produced surface temperature rise of less than 1 °C for both wet and dry conditions. Therefore, this current-time combination was adopted during the entire calibration process and in the standard sensor monitoring.

4.2 *Calibration Results*

Three sensors from three different batches, designated Sensor-1, Sensor-2, and Sensor-3, were subjected to calibration at GCTS. The three sensors were tested in the SWCC device simultaneously. The top part of SWCC device was modified to have five electrical feed-throughs to accommodate up to

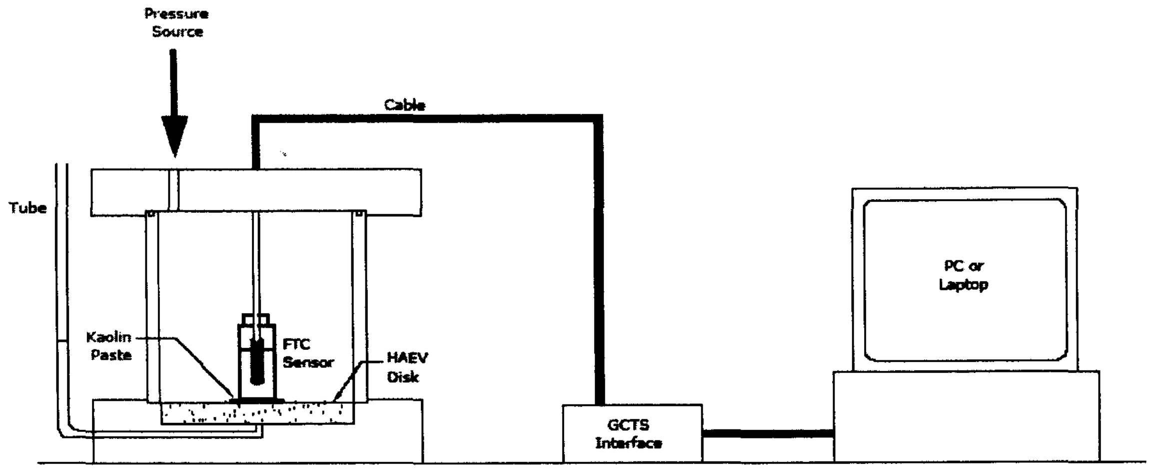

Figure 5. Setup of thermal conductivity sensor in Fredlund SWCC device for calibration.

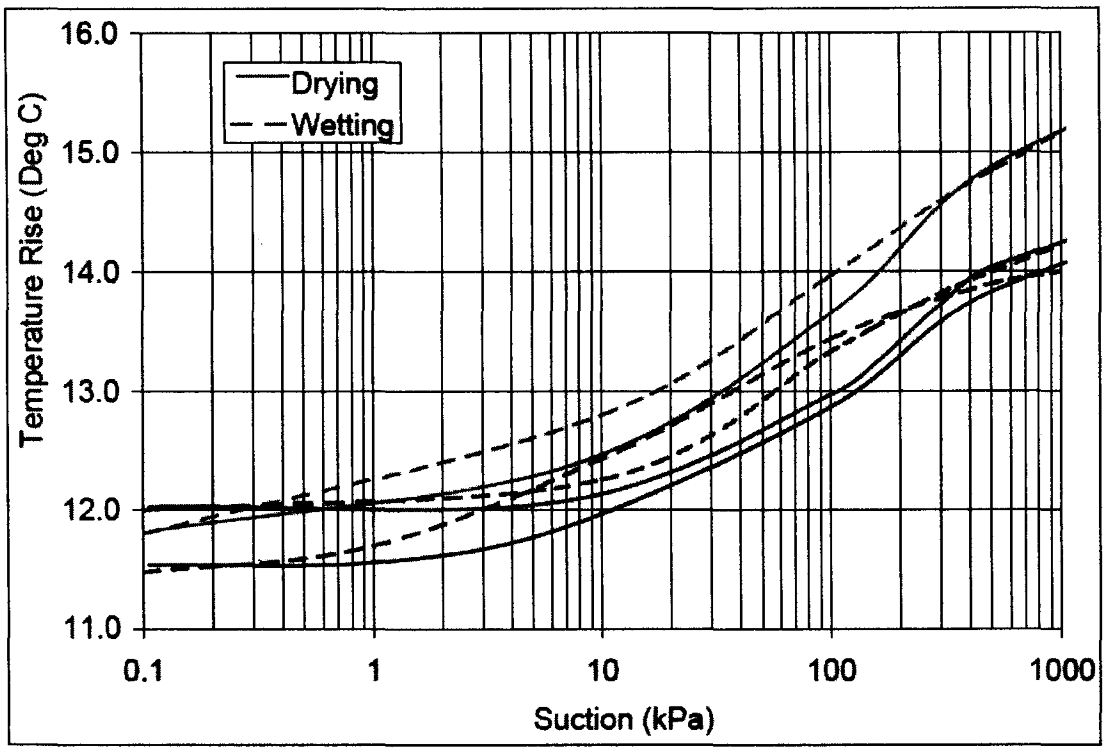

Figure 6. Actual calibration curves obtained for the three sensors.

five sensors. Then the three installed sensor cables were connected to GCTS datalogger as shown in Figure 5. Note: For clarity, Figure 5 shows only one sensor.

The test results, ΔT values, are presented in Table 2. The ambient temperature fluctuated between 21 and 28 °C during the calibration process. As mentioned earlier, a temperature correction was applied to ΔT using the procedure suggested by Nichol et al. 2003. The standard temperature was considered as 23°C for the purpose of temperature correction.

The generated calibration curves are shown in Figures 6. Even though the curves are not identical, they are somewhat comparable to each other. More comparisons and error analyses of the calibration curves will be performed as more data points are available in the future. Based on the existing data, actual resolution of suction measurements was computed. The details are presented in the following section.

4.3 *Resolution of measured suction*

Based on the calibration data, the resolution of suction measurements was computed using the resolution of temperature measurements, T_{res}, 0.004 °C. Since the calibration curve slope changed significally depending on the suction range, three ranges were identified: 1 – 10 kPa; 10 – 100 kPa;

Table 2. Sensor calibration data.

Sensor	Applied Suction	Drying		Wetting	
		ΔT*	ΔT_{corr}**	ΔT	ΔT_{corr}
	kPa	°C	°C	°C	°C
Sensor-1	0.1 (wet)	11.747	11.760	11.747	11.760
	7	12.328	12.321	12.720	12.806
	96	13.554	13.598	13.870	13.948
	500	14.768	14.843	14.768	14.843
	1,000,000 (dry)	16.102	16.137	16.102	16.137
Sensor-2	0.1 (wet)	11.971	11.969	11.971	11.969
	7	12.019	12.027	12.169	12.260
	96	12.865	12.918	13.229	13.315
	500	13.918	13.995	13.918	13.995
	1,000,000 (dry)	14.996	15.076	14.996	15.076
Sensor-3	0.1 (wet)	11.462	11.475	11.462	11.475
	7	11.807	11.815	12.402	12.506
	96	12.764	12.817	13.353	13.440
	500	13.714	13.790	13.714	13.790
	1,000,000 (dry)	14.792	14.873	14.792	14.873

*ΔT is the maximum temperature rise in the center of ceramic block corresponding to the applied suction.
**ΔT_{corr} is the corrected maximum temperature rise based on the method presented by Nichol et al. 2003.

and 100 – 1000 kPa. Within a range, the ratio of change in suction to change in temperature rise, ΔT, gives the change in suction per unit change in ΔT. Multiplying this quantity by the temperature resolution, T_{res}, gives the resolution of suction that can be achieved in each respective range as given in Equation 1. The resolution of suction measurements (ψ_{res}) computed for the three calibration curves are presented in Table 3.

$$\psi_{res} = (\psi_{max} - \psi_{min})/(\Delta T|_{\psi max} - \Delta T|_{\psi min})T_{res} \quad (1)$$

where ψ_{max} = maximum suction in a given range; ψ_{min} = minimum suction in the given range; $\Delta T|_{\psi max}$ = temperature rise at ψ_{max}; $\Delta T|_{\psi min}$ = temperature rise at ψ_{min}; and T_{res} = 0.004 °C.

5 RESPONSE TIME AND ACCURACY

The maximum accuracy that can be achieved with the sensor is governed by the resolution of the measurements. According to the data presented in Table 3, the maximum possible accuracy of the sensor depends on the suction range as well as the type of curve, drying or wetting. The values of resolution for drying and wetting curves in respective suction ranges are not significantly different and can be considered comparable. The reason for this is that the slopes of the drying and wetting curves are similar.

For the low suction range, 1 to 10 kPa, the average possible accuracy is 0.11 kPa or 2.1% of the average measured suction. Within the other two ranges, 10-100 kPa and 100-1000 kPa, the average possible accuracy is 0.7 % of measured suction.

During the calibration process, the sensors were repeatedly tested once the equilibrium point has adequately passed. Theoretically, the repeated temperature measurements should record the same value to obtain the maximum possible accuracy. However, the real results contain random errors, which will decides the actual accuracy of the measurements that can be achieved with the sensor.

Table 3. Resolution of suction measurements based on sensor calibration data.

Sensor	Suction Range	Resolution of Suction, ψ_{res}		Resolution as Percent of Average Measured Suction	
		kPa		%	
	kPa	Drying	Wetting	Drying	Wetting
Sensor -1	1-10	0.06	0.03	1.02	0.62
	$10-10^2$	0.30	0.32	0.55	0.58
	10^2-10^3	2.18	2.76	0.40	0.50
Sensor -2	1-10	0.20	0.12	3.62	2.25
	$10-10^2$	0.47	0.34	0.85	0.62
	10^2-10^3	2.60	3.65	0.47	0.66
Sensor -3	1-10	0.08	0.04	1.50	0.67
	$10-10^2$	0.40	0.36	0.72	0.66
	10^2-10^3	2.81	5.45	0.51	0.99
Average	1-10	0.11	0.06	2.05	1.18
	$10-10^2$	0.39	0.34	0.71	0.62
	10^2-10^3	2.53	3.96	0.46	0.72

5.1 *Response Time*

The last two data points obtained after the equilibrium of Sensor-1 at 7, 96, and 500 kPa were analyzed to obtain an idea on actual accuracy of measurements. The data and computed values are presented in Table 4. Also, shown in Table 4 is the estimated time for equilibrium. The response time of the senor is the time required to reach equilibrium condition once the sensor is subjected to a change in suction. According to Table 4, the response time of the sensor ranged between 2 to 5½ days depending on the applied suction. This response time seems considerably long for a sensor to be able to use in the field. However, the actual expected response time in the field is 5.3 times faster due to the increased contact surface area. During the calibration process, only the bottom surface of sensor is in contact with the HAEV disk. But in the field, both the bottom surface and side surface are to be in contact with the surrounding soil. The effective surface area of sensor in the field is 5.3 times greater than the effective surface area during the calibration. In addition the water migration through low permeable HAEV disks can contribute to the long response time in the laboratory. Therefore, the response time of the sensor is estimated in the range of 4 to 6 hours.

5.2 *Error Analysis*

The actual accuracy of the suction measurements depends on the repeatability of the measurements. Table 4 is prepared based on the data obtained from Sensor-1. The last two data points taken after attaining equilibrium were considered in the error analysis. The equilibrium time was determined based on the ΔT versus elapsed time plots. The readings taken from Sensor-1, after applying 500 kPa pressure starting from 96 kPa, are plotted against elapsed time in Figure 7. The plot indicates that the equilibrium was reached in about 5.5 days. For the purpose of determining the relative error, the last two data points that lie beyond the equilibrium point were considered as repetitive measurements. The deviation of two points from the average (T_{dev}) was considered as the error of the measurement at that suction value. The error of measurement was computed using Equation 1, but now replacing T_{res} with T_{dev}. The results were expressed as a percentage of measured suction, which will be the accuracy, in the last column of Table 4.

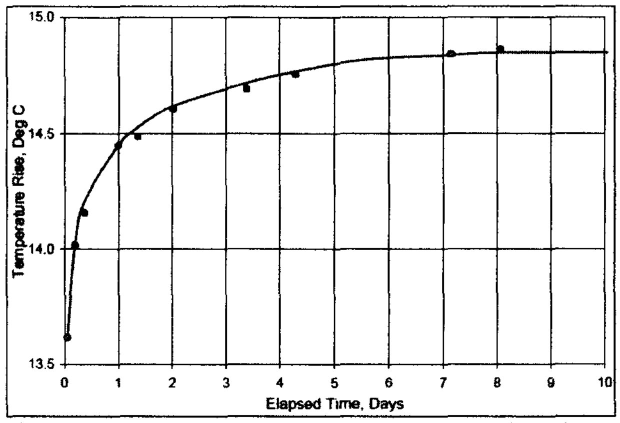

Figure 7. Measured temperature rise in Sensor-1 while changing from 96 kPa to 500 kPa.

The error analysis performed above was a simple analysis based only on a few data points available at the time of analysis. A better estimate of the error could be obtained with multiple repeated readings. However, since the maximum error found here is 2.7%, the accuracy of the measurements is specified as less than 5% of the measured suction.

Table 4. Actual accuracy computed from repeated data points

Measured Suction	Estimated Time for Equilibrium	Elapsed Time	ΔT_{corr}	Mean ΔT_{corr}	Deviation from Mean, T_{dev}	T_{res}	Maximum Possible Accuracy*	Absolute Error	Error as a Percentage of Measured Suction
kPa	Days	Days	°C	°C	°C	°C	kPa	kPa	%
7	2.0	3.7	12.307	12.314	± 0.007	0.004	0.11	0.19	2.7
		4.7	12.321						
96	3.5	4.8	13.618	13.608	± 0.010	0.004	0.39	0.94	1.0
		5.8	13.598						
500	5.5	7.1	14.824	14.834	± 0.010	0.004	3.96	9.76	2.0
		8.0	14.843						

* Maximum possible accuracy is the average accuracy presented in Table 3.

6 GENERAL APPLICATIONS

The suction sensors are widely applicable in variety of engineering as well as soil science applications. In mining operations, the suction measurements are required for modeling seepage and contaminant movement in tailings and mine waste. Installation of durable filed suction sensors could provide valuable data for several years for a reasonable cost. Also, such suction measurements are useful in determining strength parameters for slope stability analysis (Fredlund and Rahardjo 1993)

Another main application of sensors is to obtain suction measurements beneath highway pavements. The strength of highway pavement systems is mainly dependent on temperature and moisture conditions beneath the pavement. Data from suction sensors installed in a highway test section can be effectively used in pavement design. The new 2002 pavement design guide includes provisions for using suction values in the design process.

Another application is in the area of handling expansive soils associated with engineering construction projects. The potential for expansion can be quantified and monitored by obtaining field suction values.

7 CONCLUSIONS

The Fredlund thermal conductivity sensor is an improved, reliable sensor compared to the sensors that were available in the past. The durability and accuracy of the sensor have been enhanced by using special weatherproof material and adopting state-of-the-art digital design.

The calibration curves can be determined by five data points obtained at 0.1 (wet), 10, 100, 500, and 1,000,000 kPa (dry) suction values. Both drying and wetting curves are required to interpret the field data accurately. Individual sensor calibrations with more data points can be performed for increased accuracy. Two corrections, temperature and hysteresis, should be applied to reading when reducing data.

Low maintenance and ability to automate the monitoring program are very helpful when the sensors are to be installed in remote locations.

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