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Authorized Reprint 1989 from Geotechnical Testing Journal, September 1989

Calibration of Thermal Conductivity Sensors for Measuring Soil Suction

REFERENCE: Fredlund, D. G. and Wong, D. K. H., **"Calibration of Thermal Conductivity Sensors for Measuring Soil Suction,"** *Geotechnical Testing Journal,* GTJODJ, Vol 12, No. 3, Sept. 1989, pp. 188-194.

ABSTRACT: The accuracy of suction measurements using thermal conductivity sensors is dependent upon their calibration. Therefore, a calibration study was undertaken by using a modified, commercially available, pressure plate extractor. The experimental setup along with the calibration procedure are described. Typical calibration results are presented. In general, results showed reasonable agreement between the calibration curve determined in this study compared to those provided by the manufacturer for matric suction ranging from 0 to 175 kPa. However, large deviations in the calibration curves were observed at suctions above 175 kPa. The sensors were found to be quite sensitive to the changes in matric suction in the range of 0 to 175 kPa. For matric suction above 175 kPa, the sensitivity of the sensor is reduced.

KEYWORDS: soil suction, matric suction, thermal conductivity sensor, pressure plate, calibration

There has been a significant increase in the understanding of the behavior of soil with negative pore-water pressures during the past two decades. However, our ability to measure negative pore-water pressures has not kept pace with theoretical advancements. Consequently, there is a need for devices that can measure soil suction both in the laboratory and in situ. In this way, our knowledge of unsaturated soil mechanics can be put into practice.

The most commonly used devices for measuring soil suction include conventional tensiometers, thermocouple psychrometers, the filter paper techniques, and thermal conductivity sensors. The main limitation associated with the conventional tensiometer is its small range of suction measurement [*1*]. The limitations associated with the psychrometer are related to the fact that the soil must have a relatively high suction and must be in an extremely constant temperature environment [*2*]. The thermal conductivity type sensor appears promising since it is essentially unaffected by salt in the pore-fluid and measures suction over a wider range [*3-5*].

In view of the above considerations, an experimental study was undertaken pertaining to the calibration of thermal conductivity sensors. Thermal conductivity type sensors have been evaluated for geotechnical engineering purposes by a number of investigators. Picornell et al. [*6*] used a commercial thermal conductivity sensor, the MCS 6000, manufactured by Moisture Control System Incorporated to measure the matric suction in an expansive clay soil. Lee [7] undertook a laboratory study on the same type of sensor. In 1984, the MCS 6000 sensor became no longer available commercially. A similar thermal conductivity sensor, the AGWA-II sensor, was manufactured by Agwatronics Incorporated of Merced, CA, and was used in this study. The sensors indirectly measure the matric suction in a soil.

The AGWA-II sensor consists of a porous ceramic tip that contains a sensing unit that can be used as a miniature heater and a temperature sensor. The sensor operates on the principle of heat dissipation of a porous medium that can be desaturated when the water phase goes into tension [*8-10*]. Basically, the operation of the sensor depends on the rate of heat dissipation in a rigid structure, porous medium. The water content of the medium is a function of matric suction. The thermal conductivity of the porous medium can be measured by supplying a controlled amount of heat at the center of the porous medium and measuring the temperature change at the same point after a fixed period of time. The temperature change can be calibrated to matric suction.

Calibration is recognized as a first and fundamental step towards the use of this type of sensor. The accuracy and reproducibility is dependent upon the calibration of the sensor [*11*]. Each AGWA-II sensor purchased from the manufacturer is supplied with a linear calibration consisting of an intercept value and a slope.

It was felt, however, that an independent, more detailed study of the sensor calibration should be undertaken. The purpose of this paper is to describe the experimental setup and the calibration procedure, to examine the response of the sensors, and to present typical calibration results.

Apparatus for Calibration of the Sensors

The experimental setup for calibrating the AGWA-II sensors is illustrated in Fig. 1. A schematic of the major components is shown in Fig. 2. The calibration setup consisted of a pressure plate extractor with a ceramic plate, a temperature control box, and a thermal conductivity readout device. The readout devices were either the AGWAMETER (that is, a handheld meter) or the Hewlett-Packard data acquisition system. The data acquisition system comprised of an HP 3421A data acquisition/control unit, a SIPS board (that is, a sensor interface and power supply unit), and a desktop microcomputer. Both the AGWAMETER and the SIPS board are available from Agwatronics Incorporated.

The pressure plate extractor is commercially available from Soilmoisture Incorporated of Santa Barbara, CA. The pressure plate

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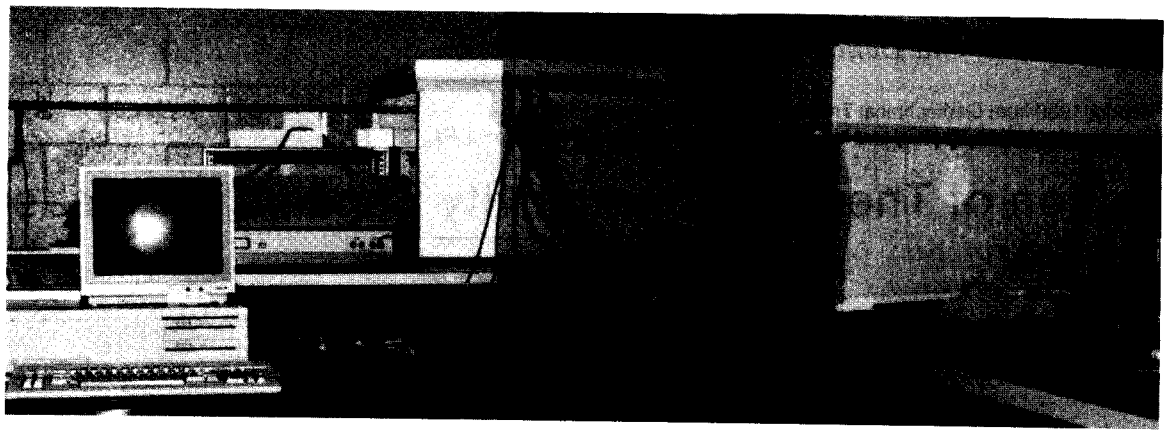
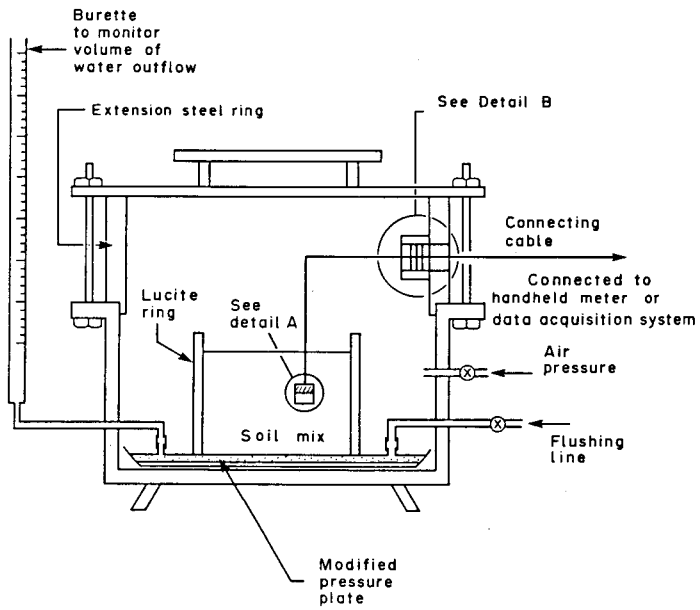
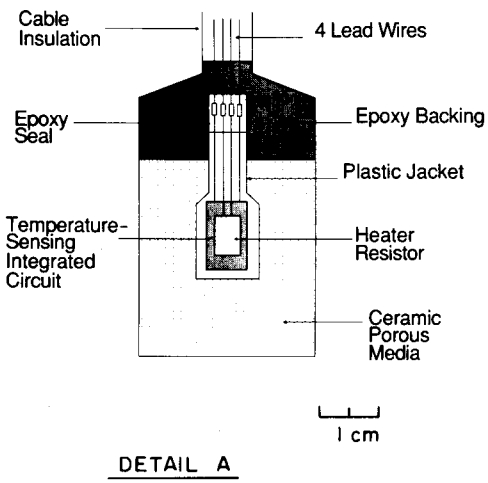


FIG. 1—*The data acquisition system along with the experimental calibration setup.*





extractor was modified by adding an extension steel ring to the pressure chamber such that the height of the chamber was increased by about 10 cm (Fig. 2). Twelve holes (but could be any number) were drilled along the sidewall of the extension ring for the purpose of carrying the lead wires to the data acquisition system. These holes were slightly larger than the tip of the sensor. Brass rings, along with split metal pieces and split rubber gaskets were arranged in such a manner that air leakage around the lead wire of the sensor could be eliminated. The air leakage was prevented by the rubber gaskets, which were compressed as the brass rings were tightened. The detailed arrangement of various components are shown in Fig. 3. The ceramic plate of the pressure plate extractor was also modified by installing an additional outlet as shown in Fig. 2. With this modification, diffused or entrapped air that accumulated beneath the ceramic plate could be flushed with water through one of the outlets. The ceramic plate was 25.4 cm in diameter and 0.6 cm in thickness with an air entry value of 300 kPa.

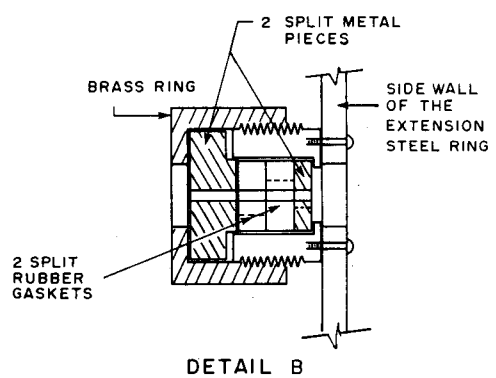


FIG. 2—*Schematic showing the detail of the components forming the seal around the sensor lead wires.*

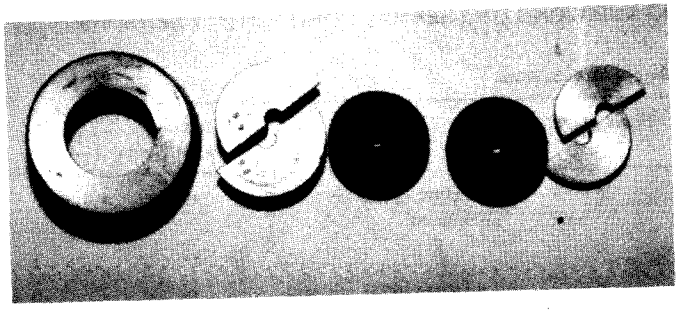


FIG. 3—*Pressure plate setup for calibrating thermal conductivity sensors.*

A temperature control box made of lucite and Styrofoam® was used to contain the entire pressure plate extractor (Fig. 1). The ambient temperature within the box could be maintained to within ±0.5°C of a value near the room temperature.

Soil Mixture Around the Sensor

The purpose of the soil is to provide a contact between the thermal conductivity sensor tip and the ceramic plate. Intact soil around the sensor will remove inaccurracies in calibration resulting from poor contacts. A preferred material for the purpose of calibrating the thermal conductivity sensors is a soil that possesses a low shrinkage potential and a high water-holding capability. Such a soil is likely to remain intact without developing cracks even at relatively high matric suctions. It is difficult to obtain a naturally occurring soil that meets both of these criteria. In view of this, a series of trial and error experiments were conducted in an attempt to establish a special calibration soil mixture. The experiments involved using varying percentages of a fine Ottawa sand and a naturally occurring silt.

A grain size analysis for the selected calibration mixture is presented in Fig. 4. The calibration mixture is shown to contain 55% sand, 40% silt, and 5% clay size particles. This corresponds to a mixture of 10% fine Ottawa sand and 90% silt.

Figure 5 shows a plot of water content versus matric suction for the selected calibration mixture. The air entry value of the soil is approximately 17 kPa. The results of two mixtures of the Ottawa sand and silt tested for calibration purposes are shown in Table 1. It was desirous to have a mixture with a low air entry value. A calibration soil mixture of 10% fine Ottawa sand and 90% silt was felt to be the preferred material and was subsequently used for all sensor calibrations.

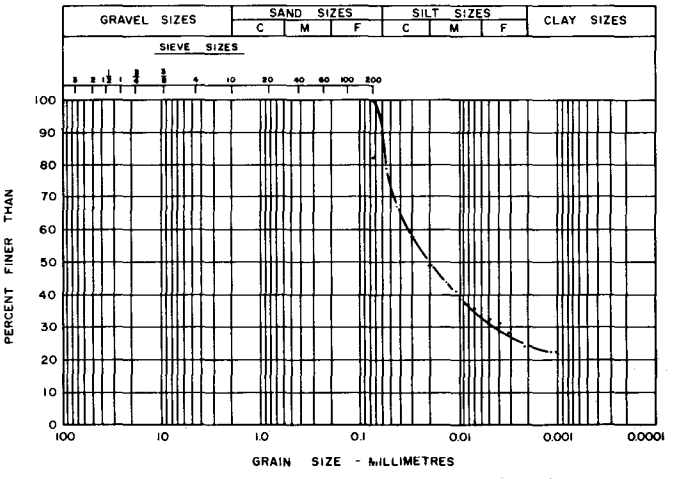


FIG. 4—*Grain size distribution curve for the calibration soil mixture.*

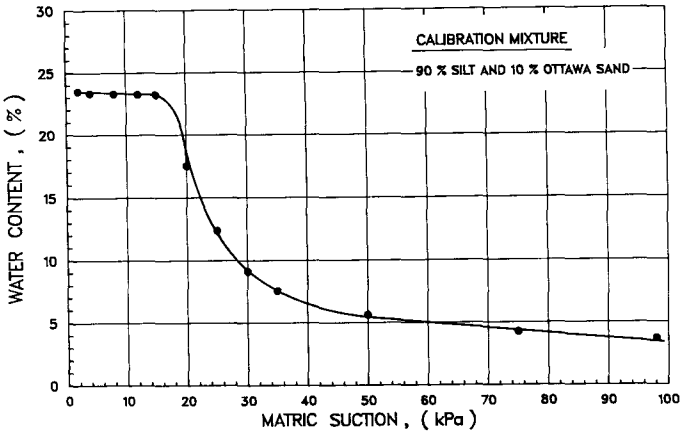


FIG. 5—*Soil-water characteristic curve for the calibration soil mixture.*

Test Procedure for Calibrating the Sensors

The AGWA-II sensors were calibrated using the modified pressure plate extractor. The general principle of operation of the pressure plate extractor is described in ASTM Test Method for Capillary-Moisture Relationships for Coarse and Medium-Textured Soils by Porous-Plate Apparatus (D 2325) and ASTM Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure Membrane Apparatus (D 3152). Basically, a continuous hydraulic flow is maintained between the saturated ceramic plate and the wet calibration soil containing the sensors. When air pressure is applied to the pressure chamber, a differential pressure is created across the ceramic plate. This differential pressure is equal to the matric suction in the soil at equilibrium. The bottom of the plate is maintained at atmospheric pressure. The water within the calibration soil, which was initially at a matric suction less than the differential applied pressure across the ceramic plate, will begin to flow out through the drain tube. The water outflow will cease when equilibrium is established with respect to the applied air pressure.

It is essential to assure that the ceramic plate was initially saturated. Therefore, the ceramic plate was initially submerged in a water bath for several days. Deaired water was then introduced into the pressure chamber and forced through the plate by applying an arbitrary air pressure (for example, 100 kPa) to the chamber. Air pressure was subsequently increased to the air entry value of the ceramic plate and maintained at least for 2 h. If the ceramic plate was adequately saturated, no air bubbles were detected from below the ceramic plate. If air bubbles were observed, it was generally an indication that either the ceramic plate was cracked or that there were some improper connections between the pressure plate and rubber membrane. In either case, the problem was identified and rectified before conducting the calibration test.

TABLE 1—*Summary of the calibration tests.*

Calibration Test	Sensor Used	Pressure Increment	DAS[a]	Hand Held[b] Unit	Calibration Material	Outflow Measurment
A	865, 887, 899, 900, 901, 902, 904, 905, 906, 907, 909, 911	0, 50, 150, 300	x	x	soil mixture (80% silt and 20% sand)	no
B	865, 887, 899, 900, 901, 902, 904, 905, 906, 907, 909, 911	0, 100, 200, 250	x	x	soil mixture (80% silt and 10% sand)	no
C	865, 887, 899, 900, 901, 902, 904, 905, 906, 907, 909, 911	0, 175, 225, 250, 300	...	x	soil mixture (90% silt and 10% sand)	no
D	650, 652, 662, 709, 716, 726, 733, 861, 868, 870, 872, 897	0, 50, 100, 175, 200, 250, 300	...	x	soil mixture (90% silt and 10% sand)	yes
E	480, 512, 516, 554, 563, 685, 714, 722, 727, 782, 833, 859	0, 10, 25, 50, 100, 150, 200, 250, 300	...	x	soil mixture (90% silt and 10% sand)	yes
F	368, 374, 379, 385, 419, 422, 423, 425, 427, 667, 698, 723	0, 100, 150, 175, 200, 250, 300	...	x	soil mixture (90% silt and 10% sand)	no
G	304, 312, 372, 375, 378, 424, 426, 549, 701, 711, 715, 736	0, 100, 150, 200, 300	...	x	soil mixture (90% silt and 10% sand)	no

[a]Data acquisition system.
[b]Agwameter.

After saturating the ceramic plate, the calibration mixture was placed on the ceramic plate in a slurried form and contained inside a lucite cylinder. The initially saturated sensor was directed through a hole in the extension steel ring, and then the tip was pushed into the mixture. The sensors had been saturated by submerging the tip in deaired water for about two days. The space around the lead wire of each sensor was sealed by tightening the brass rings. The pressure chamber was closed, and air pressure was applied to the mixture. The water within the mixture was allowed to drain through the saturated ceramic plate in response to the applied pressure. The response of each sensor was monitored until equilibrium was achieved. The above procedure was repeated for various applied air pressures. The monitoring was carried out using either the data acquisition system or the handheld Agwatronic meter. For Tests A and B (Table 1) both the data acquisition system and the handheld meter were used. A summary of numerous calibration tests are shown in Table 1.

During the calibration procedure, water was regularly flushed below the ceramic plate in order to remove any diffused, entrapped air. Water was circulated through one of the outlets and allowed to drain from the other outlet (Fig. 2).

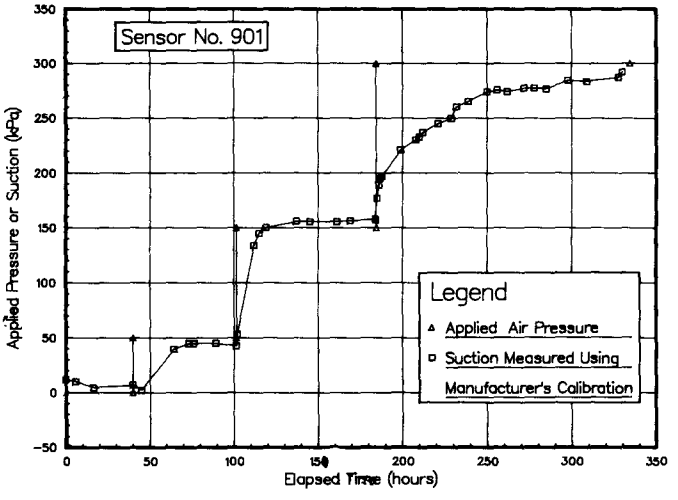
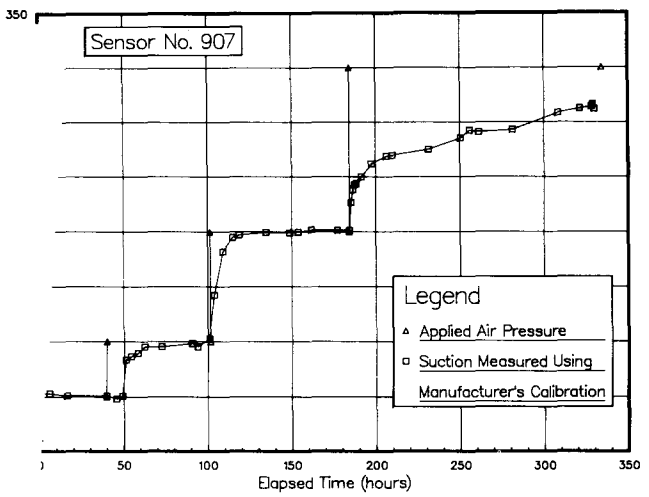


FIG. 6—*Time response of Sensor 901 to changes in applied air pressure.*

Presentation and Discussion of the Response of the Thermal Conductivity Sensors

Figures 6 and 7 show typical time response curves for the AGWA-II sensors for changes in applied air pressure during the calibration process. In general, the results indicate that the equalization time for the sensors increases with increasing applied pressure. For an applied pressure below 150 kPa, the equalization time was in the order of 50 h for the calibration mixtured used.

The equalization time of each sensor is influenced by the presence of the calibration mixture, which acts as an interface material between the embedded sensor and the ceramic plate. The interface material requires a period of time before reaching a suction equal



7—*Time response of Sensor 907 to changes in applied air pressure.*

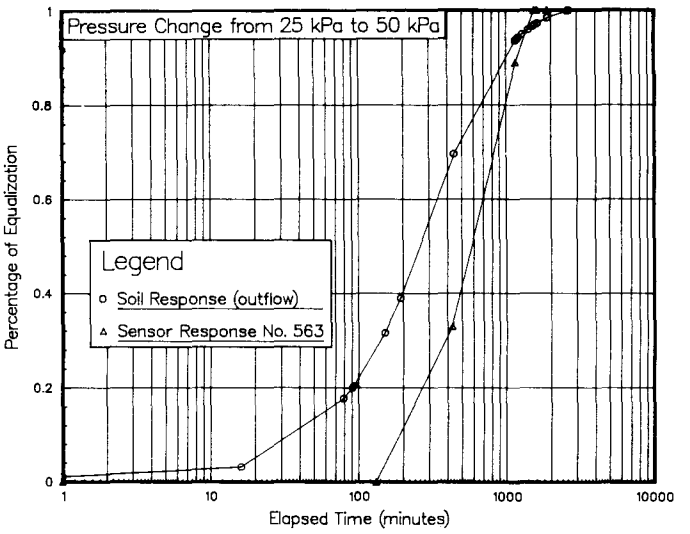
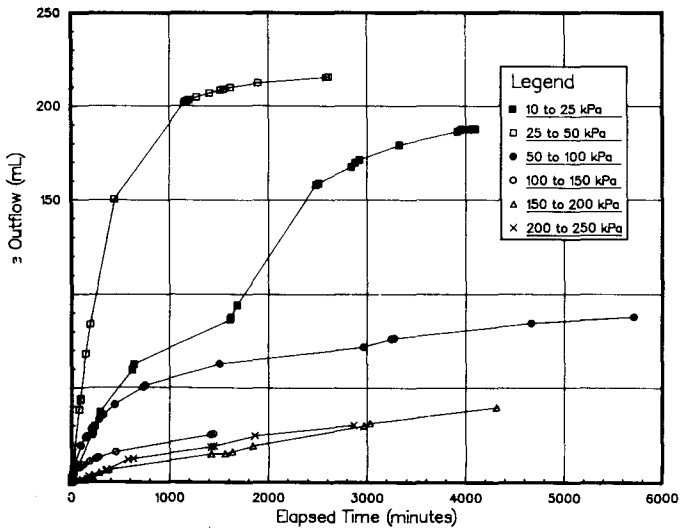


FIG. 9—*Comparison of the response of the calibration soil mixture and sensor.*

to the applied air pressure. The rate at which the calibration mixture reaches equilibrium depends on such factors as the coefficient of permeability and thickness of the ceramic plate, as well as the coefficient of permeability and height of the calibration mixture [*12*].

In an attempt to better define the response of each sensor, the volume of water outflow from the calibration mixture was measured along with the response of the sensor. A summary of the outflow curves at different applied pressures is presented in Fig. 8. The results show that the calibration mixture reaches equilibrium more rapidly at low applied pressures with a relatively large volume of outflow. However, at higher applied pressures the equalization time increases considerably with a significant reduction in the volume of outflow. The increased equalization time is attributed to a reduction in the coefficient of permeability of the soil mixture at higher suctions.

A typical comparison of the response of the calibration mixture and that of the sensor to a change in pressure is shown in Fig. 9.



IG. 8—*Water outflow curves for several applied air pressures.*

The water outflow started as soon as the applied pressure was increased from 25 to 50 kPa. However, the sensor showed a time lag of approximately 120 min in reading suction changes. This is not a fixed time lag since this value depends on the location of the sensor tip in the calibration mixture. Sensors located near to the surface of the calibration mixture should experience a shorter time lag compared to those situated at a greater depth into the mixture.

Typical equalization times for the calibration mixture and the sensor are presented in Fig. 9. The results indicate that it takes approximately 50 h for the calibration mixture to reach equilibrium when the pressure was increased from 25 to 50 kPa. On the other hand, it only required about 30 h for the sensor to reach equilibrium for the same pressure range. The shorter equalization time indicates that the sensor comes to equilibrium once the suction is established at the depth of the sensor in the soil.

Calibration of the Thermal Conductivity Sensors

Typical calibration curves for AGWA-II sensors are shown in Figs. 10 and 11 together with the corresponding calibration curves provided by the manufacturer. The calibration curves were obtained by relating the applied air pressure to the corresponding sensor output at equilibrium. The results indicate that the response of the sensors are nonlinear and that the calibration curves can be approximated by a bilinear form. The breaking point for the calibration curve was found to be at about 175 kPa for most sensors. As shown in Figs. 10 and 11, the response of the sensors measured between a matric suction range of 0 and 175 kPa are in good agreement with the calibration curves applied by the manufacturer. However, deviations between the calibration results commenced at about 175 kPa and became more pronounced with increasing suctions. The nonlinear response characteristics of the sensors are believed to be related primarily to the pore-size distribution in the sensor tip.

The slope of each calibration curve gives an indication of the sensitivity of the sensor to a change in matric suction (that is, kPa/mV). For matric suction less than 175 kPa, the slopes are relatively flat compared to those above 175 kPa (Figs. 10 and 11). A flat cali-

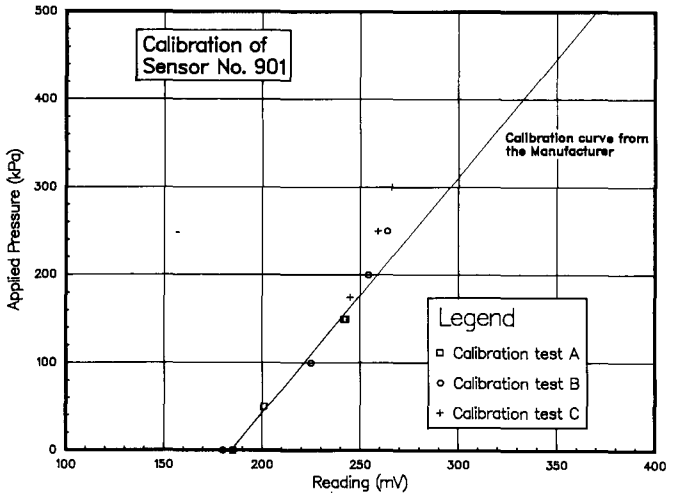


FIG. 10—*Calibration curve for Sensor 901.*

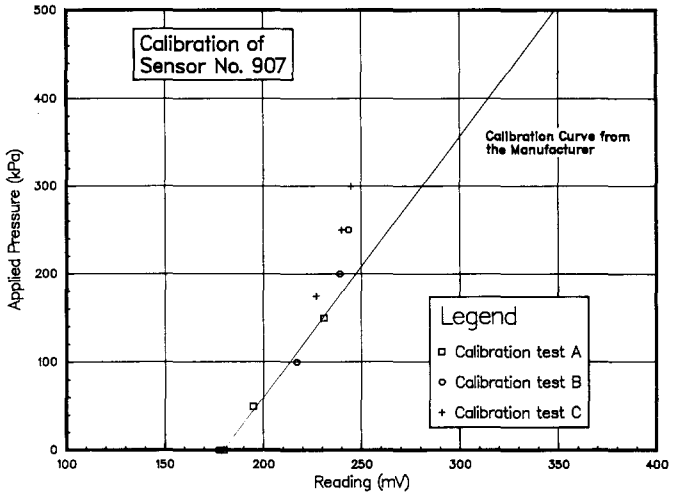


FIG. 11—*Calibration curve for Sensor 907.*

TABLE 2—*Summary of the calibration results.*

Group 1: Sensors Purchased in 1984		Group 2: Sensors Purchased in 1986/87	
Sensor Number	Slope Below the Breaking Point, kPa/mV	Sensor Number	Slope below the Breaking Point, kPa/mV
304	26.469	480	3.333
312	20.000	512	3.750
368	15.957	516	3.333
372	23.000	549	2.429
374	16.304	554	2.500
375	18.182	563	2.830
378	17.391	650	3.127
379	16.483	652	2.307
385	17.341	662	3.333
419	5.260	667	3.448
422	4.444	685	2.941
423	4.762	698	2.020
424	4.651	701	2.290
425	3.947	709	2.326
426	4.854	711	2.632
427	5.769	714	2.564
		715	2.439
Average slope = 12.28 kPa/mV		716	2.040
Standard deviation = 7.79 kPa/mV		722	2.000
		723	2.564
		726	2.219
		727	2.273
		733	2.165
		736	2.500
		782	2.469
		833	2.564
		859	2.344
		861	2.259
		865	3.030
		868	2.542
		870	3.297
		872	2.221
		887	2.564
		897	3.297
		899	2.976
		900	2.830
		901	2.695
		902	3.084
		904	3.127
		905	2.299
		906	2.633
		907	2.963
		909	3.191
		911	2.174
		Average slope = 2.69 kPa/mV	
		Standard deviation = 0.44 kPa/mv	

bration curve implies a small change in matric suction relative to a large change in sensor output. Therefore, the sensor is relatively sensitive to the changes in matric suction in the range from 0 to 175 kPa. On the other hand, a steep calibration curve implies a large change in matric suction with a small change in sensor output, thereby rendering the sensor less sensitive to matric suction change above 175 kPa.

A summary of the calibration slopes in the lower suction range of the sensors calibrated in this study is given in Table 2. This table presents calibration results for two distinct groups of sensors. These two groups were from different shipments supplied by the manufacturer. The first group of sensors, which was purchased in 1984, gives an average slope of 12.28 kPa/mV and a standard deviation of 7.79 kPa/mV. A high standard deviation value implies a large variation in pore-size distributions among the sensor tips. As indicated in Table 2, the calibration slopes of the second group of sensors are more uniform and flatter compared to those of the first group. The average slope and the standard deviation were found to be 2.69 and 0.44, respectively. The second group of sensors was purchased between 1986 to 1987.

The stability and reproducibility of a sensor are also illustrated in Figs. 10 and 11. Calibration Tests A and B were conducted continuously for a period of about 1 1/2 months using the same sensors but with different pressure increments (Table 1). The calibrated sensors were then used to measure the soil suction in undisturbed soil specimens for about 1 1/2 months. Upon the completion of these suction measurements, the same set of sensors was recalibrated in calibration Test C, which continued for approximately one month. The results show that the sensor outputs were consistent

for all three calibration tests. The sensor response appears to be stable with respect to time. In other words, there appears to be no significant drift in the response of the sensors over the period of approximately four months.

The presented calibration curves were obtained using a desorption process. It would be expected that the calibration curve might differ slightly for sorption because of hysteresis. The effect of hysteresis on calibration has not been evaluated in this study but is felt to be quite small.

Summary and Conclusions

A laboratory procedure for the purpose of calibrating thermal conductivity sensors is described. The calibration setup consists of a modified pressure plate extractor, a modified ceramic plate, a temperature control box, and a readout device. The procedure described and the apparatus used are shown to be suitable for calibrating thermal conductivity sensors.

The equalization time for the sensors was examined along with the behavior of the calibration mixture in an attempt to better understand the response of the sensors. The results indicate that the equalization times for the sensor and the calibration mixture increase with increasing applied pressure. The results show that the calibration curves for the AGWA-II sensors are bilinear with a breaking point at about 175 kPa. Good agreement was generally found between the calibration curve obtained in this study compared to that provided by the manufacturer for matric suctions ranging from 0 to 175 kPa. Deviations from the manufacturer's calibration occurred around 175 kPa because of the nonlinear response characteristics of the sensors. The sensors were found to be reasonably sensitive to changes in matric suction in the range from 0 to 175 kPa. The authors recommend that users of thermal conductivity sensors should calibrate each sensor before their usage. The calibration procedure should involve a sufficient number of applied pressures (for example, 7 pressures) in order to define nonlinearities in the calibration curve. The results also indicate that the sensor output is relatively consistent and stable with time.

Acknowledgments

This study was sponsored by the Saskatchewan Highways and Transportation Department in cooperation with the Department of Civil Engineering, University of Saskatchewan. The authors would like to acknowledge this financial support and the assistance of Mr. R. A. Widger, Director of Geotechnical Materials Branch, Saskatchewan Highways and Transportation. The authors would like to thank Mr. G. Putz for his assistance in setting up the data acquisition system and Mr. A. Ho for his help in conducting some of the calibration tests. In addition, the authors also would acknowledge help from the Agwatronics, Merced, CA. We recognize that Agwatronics have been carrying these sensors through a development phase, and we have been pleased to be of assistance in their development.

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