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LONG TERM MEASUREMENTS OF MATRIC SUCTION AND SOIL TEMPERATURE USING THERMAL CONDUCTIVITY SENSORS.

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ABSTRACT

Thermal conductivity sensors have enabled the continuous and long-term measurements of matric suction. The performance of these sensors has been upgraded to improve the durability as well as the accuracy of the readings obtained. The function of thermal conductivity sensors for long-term measurements of matric suctions also includes soil temperature measurements. Long-term temperature and matric suction readings were obtained from below two thin membrane pavement sites in Torquay and Bethune, Saskatchewan, Canada from September 2000 until July 2002. An understanding of the soil suction and temperature change behavior of the subgrade throughout the year is obtained from these data. Environmental changes such as the hysteresis of the sensors and the effect of the ambient temperature on the thermal conductivity of the sensors have been found to influence the matric suction readings. Several correction factors have been proposed to eliminate the influence of the ambient temperature and a comparison is made between the correction methods.

INTRODUCTION

The development of thermal conductivity sensors for obtaining long term reliable matric suction measurements is important in understanding the behavior of unsaturated soils. In September 2000, two test installations were made in Saskatchewan, Canada; one located south of Torquay and the other north of Bethune. Sixteen thermal conductivity sensors were installed beneath existing thin membrane system pavements at each site. Thin membrane system pavements consist of compacted native soil forming the subgrade material with a thin layer of asphalt to provide a dust free driving surface. Details regarding the installation procedure and initial readings have been presented by Marjerison et al. (2001).

Data from the thermal conductivity sensors installed at the test sites have been continuously recorded from September 2000 up to the present. A better understanding can be obtained regarding the behavior of the subgrade at various depth throughout the year by using the available temperature and matric suction readings from the thermal conductivity sensors. Corrections for the hysteresis of the sensors as well as the effect of ambient temperature on the thermal conductivity of the sensors have been made and evaluated.

LITERATURE REVIEW

In situ soil suction measurements have been made at several sites in western Canada using thermal conductivity suction sensors. Van der Raadt (1988) monitored matric suctions in five railway subgrades in western Canada and made comparison with other suction measurement methods. Loi et al. (1992) presented matric suction readings from an indoor test track facility under a controlled environment. It was found that long-term stable and reliable matric suction readings in highway subgrades can be obtained using thermal conductivity sensors.

Eighteen thermal conductivity sensors were installed along a section of railway embankment in the Emerson subdivision Trackage, Winnipeg, Manitoba, Canada (Fredlund et al. 1992) and matric suction readings for a period of more than a year were presented. All the readings showed reasonable values in accordance with the amount and period of precipitation as well as the effect of a berm. The sensors were installed using a trench method with extra precaution taken to ensure good contact between the sensors and the soil. The sensors were also installed on an upward slope to prevent water from running along the lead wires and collecting at the sensor tip.

In more recent years, the performance of the thermal conductivity sensors have been improved by using a new ceramic tip with higher porosity, a wide range of pore sizes and greater strength (Shuai and Fredlund, 2000). Improvements were also made in the electronic design. Usage of an integrated circuit (IC) to measure temperature changes inside the ceramic allows both soil temperature and soil suction to be measured. Matric suction readings from the new sensors have been taken on a test cover site in Key Lake, Saskatchewan, Canada and showed a close correlation with precipitation data.

Thermal conductivity soil suction sensor can be subjected to the influences of environmental changes such as wetting and drying cycles and temperature fluctuations (Shuai et al., 2002). Using limited calibration data, an empirical equation can be used to fit the measured calibration curves for the sensors with known hysteresis curves (Feng et al., 2002). The following equation has been proposed to fit to the wetting and drying curves within the suction range of 0 kPa to 1000 kPa,

$$\psi = \left[\frac{b(\Delta V - a)}{c - \Delta V}\right]^{d} \qquad \text{[Eq. 1]}$$

where ψ is the matric suction (kPa), Δ V is the measured rise in the temperature sensor output (mV) and *a*,*b*,*c* and *d* are the fitting parameters related to the main hysteresis loop.

The influence of ambient temperature on the thermal conductivity of water affects the matric suction measurements of the thermal conductivity sensors. Shuai et al. (2002) took into account the effect of thermal properties of water and developed a correction for the ambient temperature as follows:

$$\Delta T(t,T_0) = \Delta T(t,T_1)\frac{0.0014t + 0.5743}{0.6065}\Delta T(t,T_1) \qquad \text{[Eq. 2]}$$

where $\Delta T(t,T_0)$ is the rise in sensor core temperature that was measured at the ambient temperature during calibration (T_0) at time t and $\Delta T(t,T_1)$ is the field measured sensor core temperature rise at ambient temperature (T_1) at time t. Nichol et al. (2003) suggested that the thermal conductivity of the sensor should account for the thermal conductivity of the dry ceramic, the sensor water content and the interconnectedness of the water phase. By making several approximations, the estimated correction factor shown in Figure 1 was used to convert the field measured sensor core temperature rise to the measured sensor core temperature rise during calibration. The ambient temperature correction proposed by Nichol et al. (2003) takes into account matric suction while the correction proposed by Shuai et al. (2002) is constant for all matric suctions.

TEST SITES

The thermal conductivity matric suction sensors installed in the subgrade consist of a porous ceramic block with a heating device and an embedded temperature sensing circuit. The sensors are calibrated to determine the electric current output for a specific matric suction. The individual sensors are connected to a multiplexer that in turn, is connected to a data acquisition system. The multiplexer facilitates the acquisition of data from the sensors and communication with the system was accomplished through the use of a transceiver and a cellular antennae.

The two sites selected for the installation of the thermal conductivity sensors were thin membrane systems (TMS). The first site was located on Highway No. 345, approximately 3.5 km north of Bethune and the second site was located on Highway No. 350, approximately 8.6 km south of Torquay.

There were 16 sensors installed at each site and the spatial distribution of the sensors is shown in Figure 2. Sensors were placed and labeled based on a vertical grid, starting from the centerline of the highway to the side slope. The majority of the sensors were placed under the inner and outer wheel path of the highway which had the highest traffic activity. Grid 1 with 5 sensors and Grid 2 with 4 sensors were located in the inner and outer wheel paths, respectively. Grids 3 and 4, each with 3 sensors were located on the shoulder and Grid 5 with only one sensor was on the side slope.

The presented data shows temperature and soil suction readings obtained from the thermal conductivity sensors for the period of September 2000 to July 2002. For the Bethune site, the data for the period from March 15, 2001 to May 3, 2001 was unavailable due to contamination of the data acquisition system with melt-water. However, the problem was later rectified and data collection was continued. In addition to the temperature and soil suction readings from the sensors, ambient (surface) temperature readings were also collected and presented for the period of December 2000 to July 2002. The purpose of the ambient temperature readings was for comparison with the soil temperature and soil suction readings. It is observed that both the temperature and soil suction readings bear a relationship to the ambient temperature with a dependence on the location of the sensors.

Readings were taken daily at an interval of 4 hours with the exception of the winter months when readings were taken at an interval of 12 hours. This was due to the inability of the sensors to obtain readings once the sensors were frozen.

PRESENTATION OF RESULTS

Figure 3 shows the soil temperature readings at various depths along the same vertical grid in the Torquay site. Vertical Grid 1 is located under the wheel path of the highway, nearest to the centerline of the road. Readings for Sensor 1-1 show the readings nearest to the surface of the road while subsequent plots are for readings from sensors seated at an increasing distance from the surface. Sensor 1-5 is located at the deepest depth of 2.2 meters. From these curves, it can be observed that the fluctuations in soil temperature readings decrease with increasing depth and the overall plots become smoother. The maximum values for the temperature readings decrease while the minimum values increase. Readings from Sensor 1-5 shows that there is no freezing occurring at that depth. The overall soil suction readings are higher for the sensor at a deeper depth where no freezing is occurring compared to the sensor readings at a shallower depth which are experiencing freezing. This behavior is related to the migration of moisture to the freezing front which will decrease the soil suction prior to freezing. The same migration of moisture would in turn increase the soil suction values for the sensors located at a greater depth. Figure 3 also shows a shift in the graph towards the right and this is due to the delayed response of the soil to a change in the ambient air temperature.

The next analysis examines the response of the soil temperature and soil suction readings to a change in location. Readings from sensors located at the same depths along a horizontal plane were compared. To study the effect of the location of the sensors along the horizontal grid as seen in Figure 4 for Torquay, an approximate horizontal grid is used. The approximate horizontal grid starts with Sensor 1-3 which is nearest to the centerline of the road and is followed by Sensor 2-8, Sensor 3-11, Sensor 4-14 and finally Sensor 5-16 which is located on the side slope. Although the locations of the sensors are not exactly at the same depth, their locations are approximately the same and can be used for comparison.

Sensors 1-3 and 2-3 are seated at almost an equal depth and the overburden load from the traffic together with the similar boundary conditions explains why the soil temperature readings from Sensor 1-3 and 2-3 are similar. The curves shown for Sensor 1-3 and Sensor 2-8 overlap with each other. Other sensors located further from the centerline indicate a slight decrease in maximum temperature readings and higher minimum readings. This is probably due to the decrease in overburden pressures for the sensors located on the shoulders and side slopes of the road where a decrease in overburden pressure reduces frost penetration. There are no differences in the number and magnitude of temperature fluctuations and no lateral shift in the temperature peaks. This shows that there is essentially no change in ambient air temperature along the horizontal plane across the roadway.

Sensor 5-16 for Torquay (See Figure 5) does not experience freezing because of its location on the side slope. The side slopes are generally covered with snow banks during the winter period and tend to retard frost penetration. Thus, the lack of moisture migration to the freezing front in Sensor 5-16 causes the overall soil suction values to be much higher than those of Sensor 1-3 where freezing occurs (as seen in Figure 5).

Figure 6 compares the matric suction values obtained from the wetting and drying graphs with no correction factor used and with correction factors proposed by both Shuai et al. (2002) and Nichol et al. (2003). An increment of 10 days is used on the x-axis. Below the ambient temperature during calibration (i.e., 23^0C), matric suction values without any temperature correction are above both the corrected values. At temperatures above 23^0C, the opposite is observed with uncorrected matric suction readings are lower than both the corrected values. Corrected matric suction values using the method proposed by Nichol et al. (2003) are consistently between the uncorrected matric suction values and the matric suction obtained using the method proposed by Shuai et al. (2002). This trend is noticed in both the drying and wetting curves.

The corrected values for the drying curves are still lower than the uncorrected matric suction on the wetting curve. Hysteresis of the sensors has a more significant influence on the matric suction readings then the ambient temperature effects.

Shuai and Fredlund (2002) found the new thermal conductivity sensor to be reasonably sensitive and accurate in measuring soil suction in the range from 5 kPa to 1500 kPa. Nichol et al. (2003) observed a long-term sensor drift in the data obtained from a waste rock pile mine site located in Cluff Lake in northern Saskatchewan that is attributed mainly to the effect of relaxation or alteration of the ceramic over time by the pore-water solution. Suction values obtained from Sensor 1-5 and 3-12 for Bethune (See Figure 7) indicates that even at low suction values (approximately 20 kPa), there are no evidence of sensor drift. The same situation was observed from readings obtained at an indoor track facility (Loi et al.) where no long term sensor drift was detected at low matric suctions. This indicates that the environment beneath a pavement does not lead to long-term sensor drift as observed in results by Nichol et al. (2003).

CONCLUSION

Long-term matric suction and soil temperature readings obtained from the thermal conductivity sensors placed at various depths and locations in the subgrade of a thin membrane pavement have proven to be reasonable and consistent. Although the sensors undergo freezing at temperatures lower than 0^0C, acceptable measurements recommence once the sensors thaw. The thermal conductivity sensors perform as indicators of when the ground freezes and thaws.

At temperatures below the calibration temperature (i.e., 23^0C), the corrected and uncorrected matric suction values bear the following relationship:

Uncorrected < Corrected (using Nichol et al., 2003) < Corrected (using Shuai et al., 2002)

For temperatures above calibration, the corrected and uncorrected matric suction values bear the following relationship:

Corrected (using Shuai et al., 2002) < Corrected (using Nichol et al., 2003) < Uncorrected

The method proposed by Nichol et al. (2002) takes more factors into consideration in the temperature correction and is recommended as being the superior method to use.

The presence of long-term sensor drift appears to be dependent on the situation where the thermal conductivity sensors are subjected to rather than the performance of the sensors.

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LIST OF FIGURES

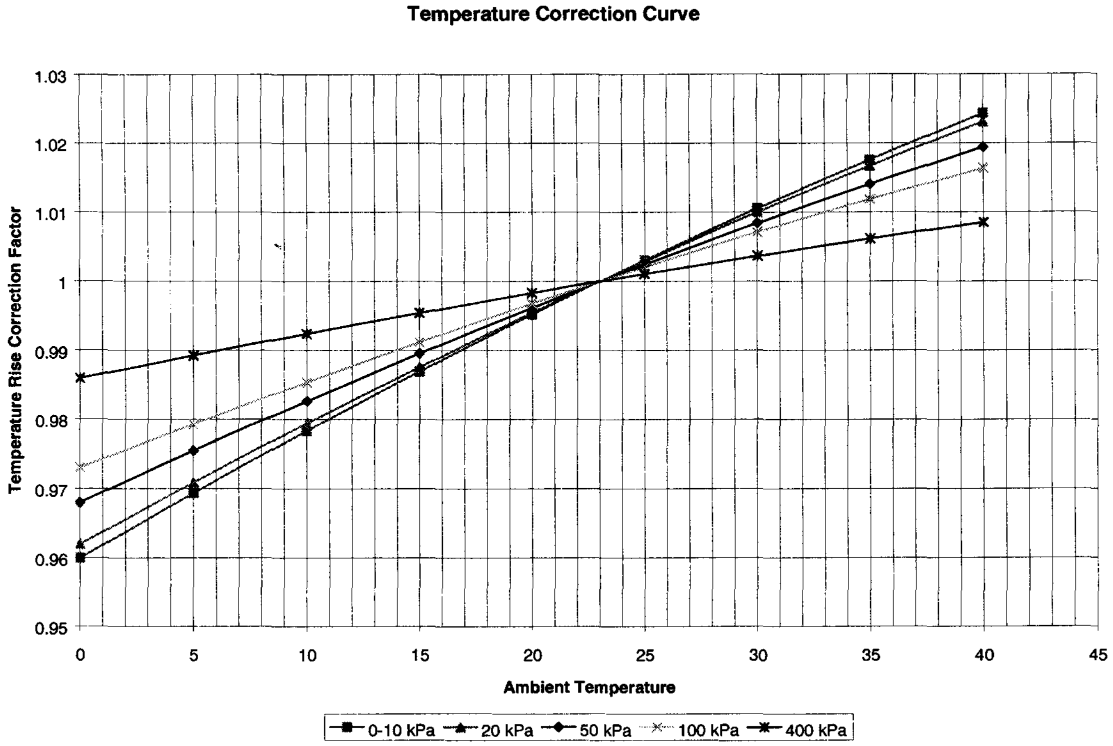


FIGURE 1 Correction factor for ambient soil temperature. The field measured thermal conductivity sensor core temperature rise is multiplied by the correction factor to obtain the core temperature rise that would have been measured at 23^{0}C (after Nichol et al., 2003).

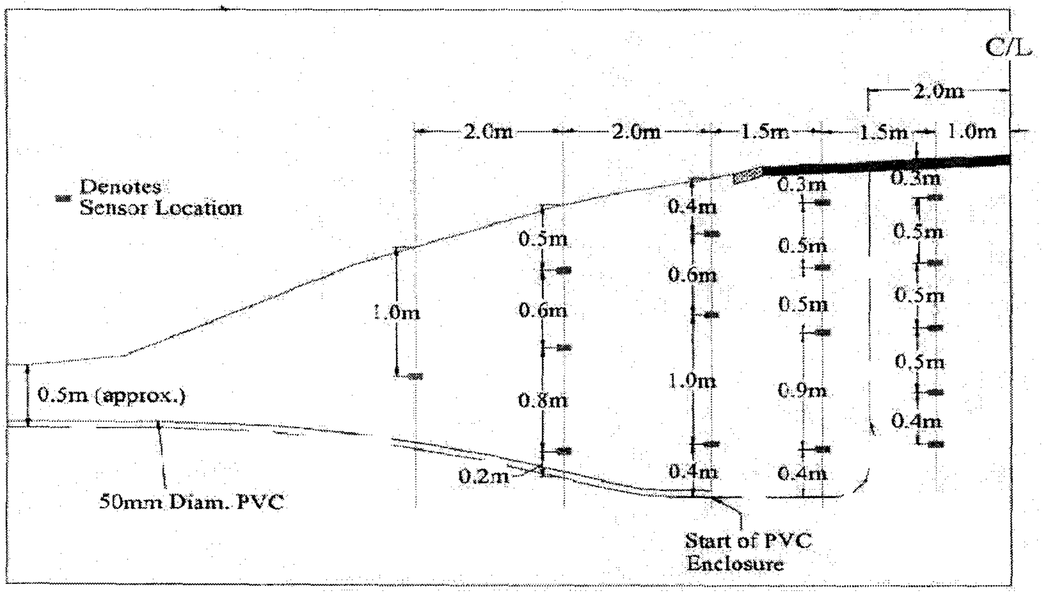


FIGURE 2 Location of the sensors.

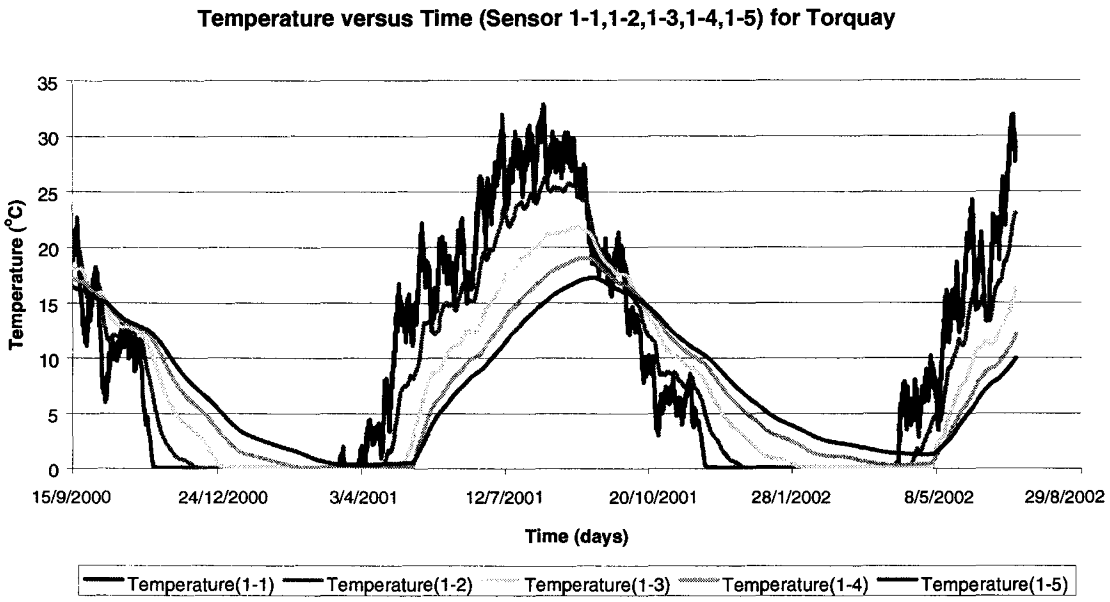


FIGURE 3 Soil temperatures versus time for sensors along vertical grid 1 in Torquay.

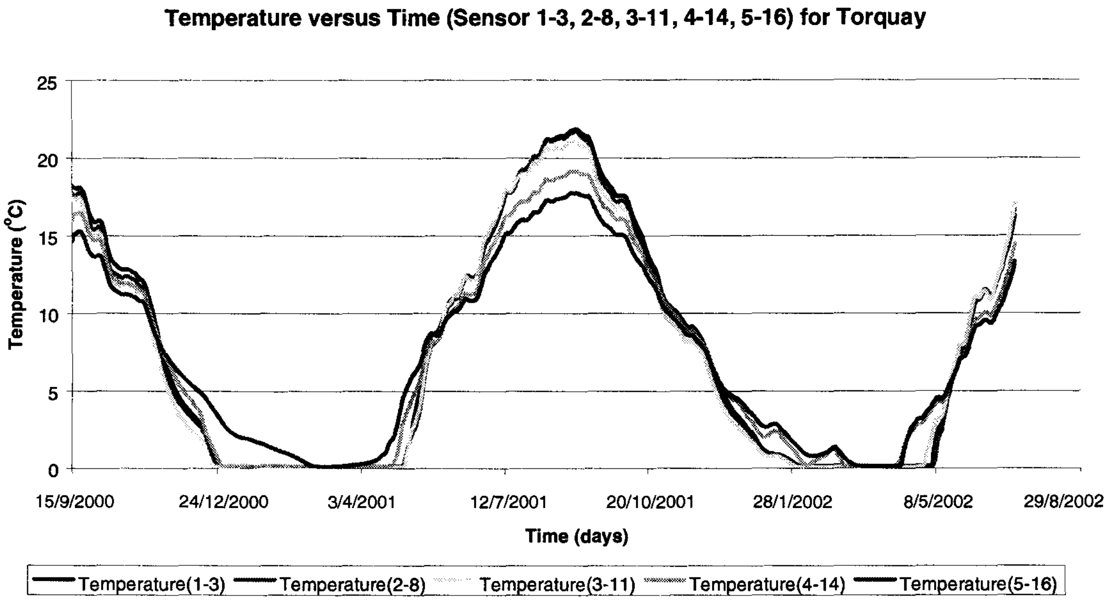
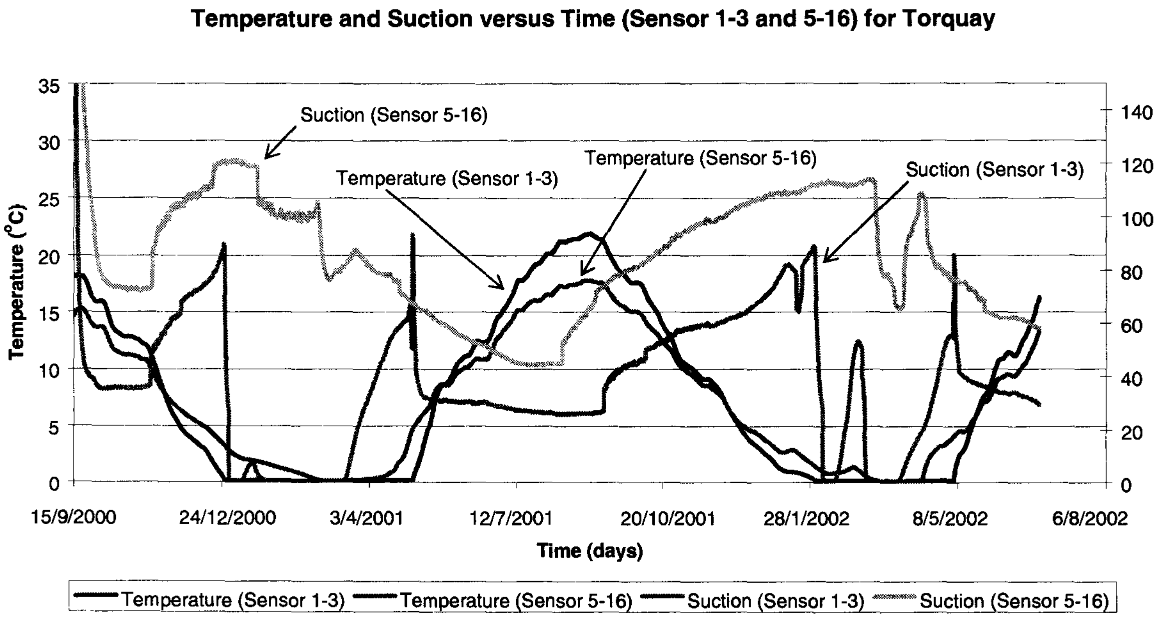


FIGURE 4 Soil temperatures versus time for sensors along horizontal grid 1 in Torquay.



Temperature and Suction versus Time (Sensor 1-3 and 5-16) for Torquay

FIGURE 5 Comparison between soil temperature and suction readings from sensor 1-3 and sensor 5-16 in Torquay.

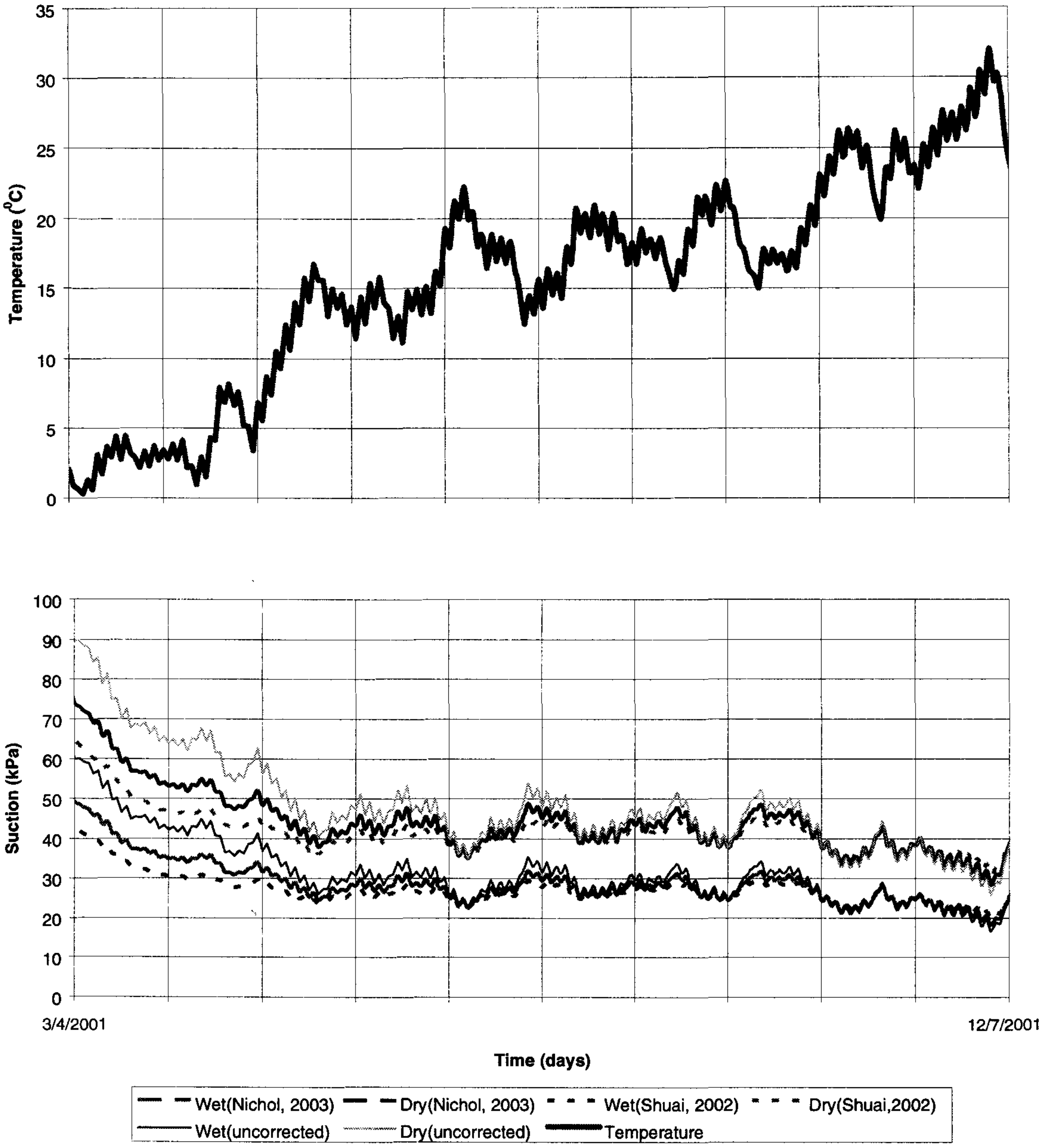


FIGURE 6 Soil temperature and comparison of matric suction values obtained from the wetting and drying curves with no correction factor used, with correction factor proposed by Shuai et al. (2002) and with correction factor proposed by Nichol et al. (2003).

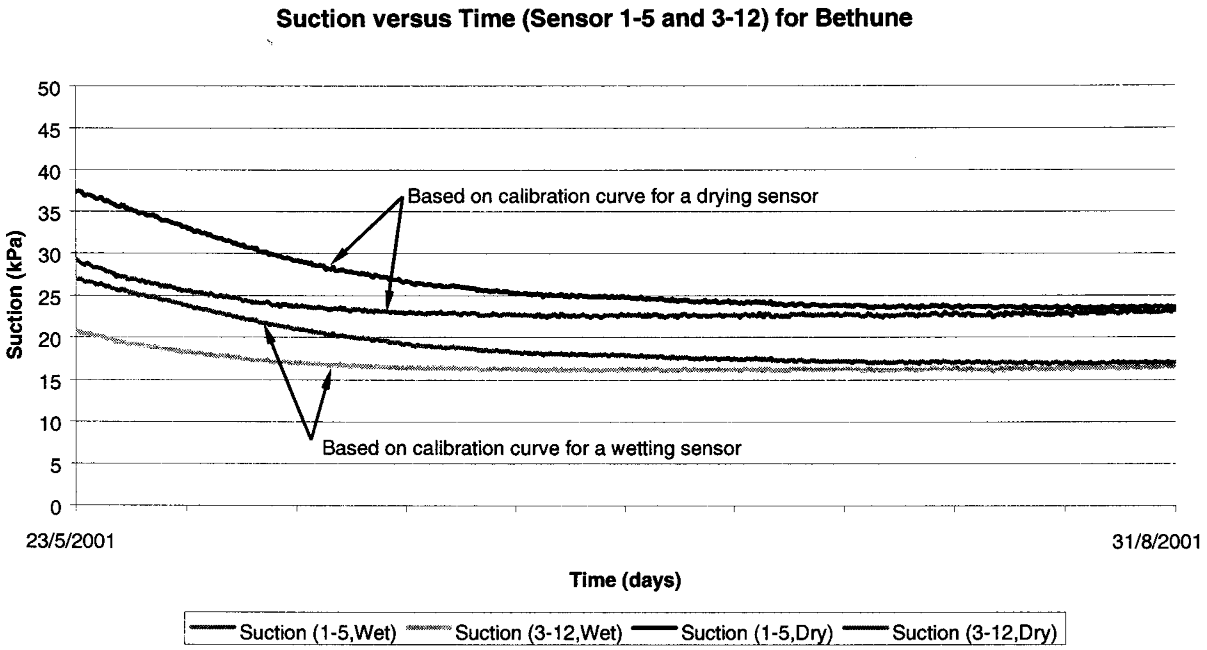


FIGURE 7 Matric suction versus time for sensor 1-5 and 3-12 for Bethune.