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# MEASUREMENTS AND ANALYSIS OF TEMPERATURE AND SOIL SUCTIONS BELOW THIN MEMBRANE SURFACES (TMS) IN SASKATCHEWAN

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ABSTRACT: This paper presents data obtained from the installation of thermal conductivity, matric suction sensors in the subgrades of Thin Membrane Surfaces in Saskatchewan. Extensive temperature and matric suction data were collected from 16 sensors installed in two sites at Torquay and Bethune for a period from September 2000 until July 2002. By plotting temperature and soil suction with time, it was possible to observe that the effect of a change in temperature on the change in suction. A correlation was observed between increasing temperature and decreasing matric suction with the minimum matric suction values being recorded at the maximum temperatures. Observations were made on the change in temperature and matric suction with depth and location. The study focuses on spring break-up when the bearing capacity of the soil is low. By plotting the freezing profile, the maximum depth of frost penetration and the duration when the pavement is most susceptible to spring break-up, can be estimated.

RÉSUMÉ: Ce papier est l'extension des données obtenues et analysées de l'installation des détecteurs conductivité thermique, des détecteurs de succion matricielle dans les sols supports sous les Surfaces à Membrane Minces dans Saskatchewan. Les données de la température vastes et de succion matricielle recueillis de 16 détecteurs installés dans deux sites à Torquay et Bethune pour une période du 2000 septembre jusqu'à ce que le 2002 juillet est présenté. En traçant la succion du sol de température avec le temps, une observation est faite en ce qui concerne l'effet dans le changement de température au changement dans la succion. Une corrélation peut être trouvée entre augmenter de température avec diminuer de succion matricielle avec les valeurs de succion minimum étant enregistrée aux températures maximums. Les observations sont aussi faites en ce qui concerne le changement dans la température et succion matricielle avec la profondeur et la distance. Le focus est donné sur la période de rupture de printemps où la capacité portant est à son plus bas. En traçant le l'isotherme de 0°C aux diverses profondeurs et le divers temps, un profil glacial du site est obtenu. De ce profil glacial, la profondeur maximum de pénétration de gelée de même que la durée où le trottoir est le plus susceptible pour la rupture de printemps peut être estimée.

## 1. INTRODUCTION

In September 2000, two test installations were made in Saskatchewan, Canada; one located south of Torquay and north of Bethune. Sixteen thermal conductivity sensors were installed beneath existing thin membrane system pavements at each site. Details regarding the installation procedure and initial readings were presented by Marjerison (2001).

Data from the thermal conductivity sensors have been continuously recorded up to the present. By using the available temperature and matric suction readings from the thermal conductivity sensors, a better understanding can be obtained regarding the bearing capacity of the thin membrane system roads and its dependency on the local climatic conditions.

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. With the arrival of spring, thawing occurs within the subgrade of the road. An increase in pore-water pressures in the subgrade (i.e., matric suction decreases) occurs and subsequently the shear strength and bearing capacity of the road decreases. During the spring period, loaded trucks are not allowed to use the low volume roads in order to prevent damage due to the weakness of the pavement structure.

The current practice for imposing road bans is quite subjective and is heavily based on the past experience of the engineers in charge of the roads. Ambient temperature readings provide limited information and do not accurately reflect the freezing and thawing mechanism occurring in the subgrade. The installation of thermal conductivity sensors provide both temperature and soil suction measurements from within the subgrade. The analysis and usage of the data can provide means of optimizing the implementation of road bans as well as giving a better understanding of the freezing and thawing mechanism.

## 2. INSTALLATION OF THE THERMAL CONDUCTIVITY SENSORS

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.

Installation of the sensors, as well as the data acquisition system, involved excavating a 2.4 meters by 1.08 meters trench from the centerline to the side slope of the highway. Sensors were imbedded at a depth of 1000mm from the east face of the trench and 700mm from the north face of the trench. All the sensors were successfully seated at that depth with the exception of a couple of sensors at both sites where problems were encountered during augering. A good sensor to soil contact was obtained during installation by ensuring that the end of the hole was flat and that the diameter of the hole was similar to that of the sensor. Initial readings were taken before the sensors were backfilled to ensure that the sensors had not been damaged during insertion. The backfill behind the sensors consisted of 150mm of native soil followed by expanding insulation for the remainder of the hole. Once the installation of the sensors was complete, the trench was backfilled with native soil. A compacted soil layer was placed to within 150mm of the finished pavement surface. A polyethylene moisture barrier was placed near ground surface followed by the remainder of the excavation backfill. The pavement was then repaired using hot mix bituminous asphalt for the Bethune site and a cold mix asphalt followed by a seal coat patch repair for the Torquay site.

One factor that played a role in the location of each test site was the influence of direct sunlight conditions. The sensors were installed at locations where the temperatures would be the highest. This involved placing the sensors on a north/south roadway, installing the sensors on the north side of a downhill grade facing south and installing the sensors on the west side of the south bound lane. By so doing, the influence of direct sunlight conditions would be maximized to ensure that the subgrade soil would begin its spring thaw earliest relative to other portions of the highway.

## 3. LOCATION OF SENSORS

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 1. 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.

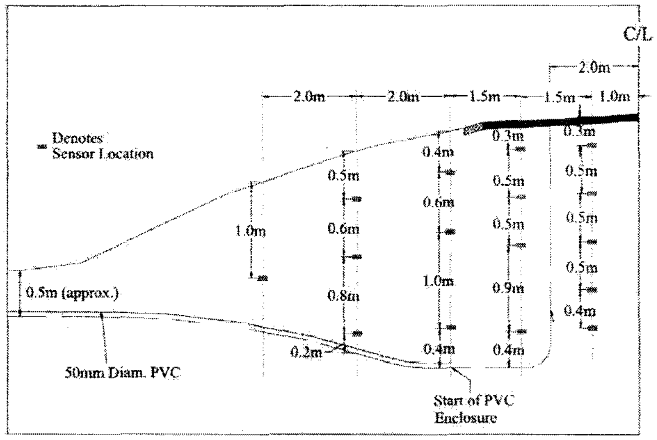

Figure 1. Location of thermal conductivity sensors for Torquay and Bethune (after Marjerison, 2001)

## 4. ANALYSIS OF THE TEST SITE RESULTS

Figure 2 shows the change in ambient temperature, soil temperature and soil suction readings versus time for Sensor 1-1 in Torquay. Sensor 1-1 is located at a depth of 0.3m in the subgrade directly under the inner wheel path. There is a time span of 100 days along the x-axis with temperature and soil suction readings starting on September 15, 2000. The ambient temperature readings started on December 13, 2000. The readings from the thermal conductivity sensors correspond closely to the ambient temperature readings. There appears to be a close relationship between changes in ground surface temperature and the temperatures in the ground. Depending on the location of the thermal conductivity sensors, the soil temperature can be seen to be less variable than the temperature at ground surface. While the soil temperature fluctuations are less, the temperatures reflect the ground surface temperatures.

Temperature readings below 0 degrees Celsius could not be measured with the sensors. The unknown fraction of the unfrozen water, together with the higher thermal conductivity of ice, makes the sensor readings difficult to interpret. In order to place the graph for the suction values at a position where comparisons with the soil temperature and ambient temperature can be made, a different scale was used along the second y-axis. The selected scale allows the suction readings to go into the negative soil suction although these are not realistic.

The soil suction data indicates that the soil suction readings bear an inverse relationship to the change in temperature readings. When the temperature readings are at a maximum value, the soil suction readings are at a minimum value and vice versa. This seems reasonable, particularly during the freezing and thawing of the soil. During freezing, water turns to ice and the soil suction would be expected to increase. On the other hand, when the ground thaws, water is released from its frozen state and the soil suction readings should decrease. An explanation for this phenomenon is not completely clear for conditions when freezing and thawing are not occurring.

The portion between the two congruent lines shown in Figure 2 shows the readings taken during the first spring after the installation of the sensors for the period from April 3, 2001 to July 12, 2001. By enlarging that region, the change in ambient temperature and soil temperature with time can be clearly seen (Figure 3). The readings from the sensors exhibit lower amplitudes than the ambient temperature readings; however, the overall change in readings is similar. For a time span of 10 days, the soil suction readings have approximately the same fluctuations as the temperature readings (but are in an opposite direction). This behavior is consistent with the overall observation that a change in soil suction is inversely proportional to a change in temperature.

Figure 4 shows the 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 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 4 also shows a shift in the graph towards the right and this is due to the delayed response of the soil to the change in ambient temperature.

The trend observed from Figure 4 at Torquay is similar to the results shown in Figure 5 at Bethune. In Figure 5, vertical Grid 2 is directly under the outer wheel path. There are 4 sensors starting with Sensor 2-6 which is nearest to the surface of the road, ending with Sensor 2-9 which is the deepest. Due to the seepage of meltwater into the data acquisition system during the first spring break up, data during the period from March 15, 2001 to May 3, 2001 is not available. However, after the problem was rectified, the data obtained shows the same trend as the data obtained from Torquay where no problems were encountered. Once again, the sensor located nearest to the road surface (Sensor 2-6) exhibited higher fluctuations. As the depths of the sensors increased, the response of the sensors to a change in ambient temperature became less pronounced and more delayed in time. The shift of the graph towards the right with increasing sensor depth shows that different depths in the subgrade experience freezing or thawing at different times.

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 6 for Torquay and Figure 7 for Bethune, 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 location of the sensors is not exactly at the same depth, their location is 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 loads from the traffic together with the similar boundary conditions explains why the temperature readings from Sensor 1-3 and 2-3 (as seen in Figure 6 for Torquay and Figure 7 for Bethune) are similar. The curves shown for Sensor 1-3 and Sensor 2-8 for both locations 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 discourages frost penetration.

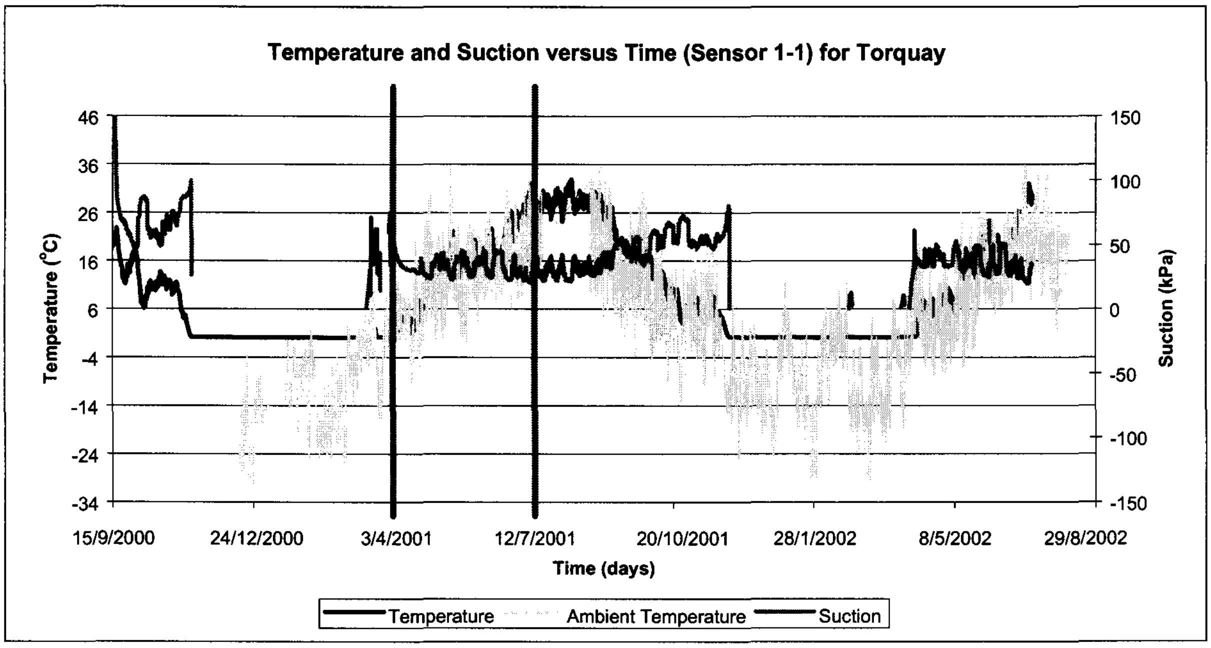

Figure 2. Temperature and suction versus time for sensor 1-1 in Torquay

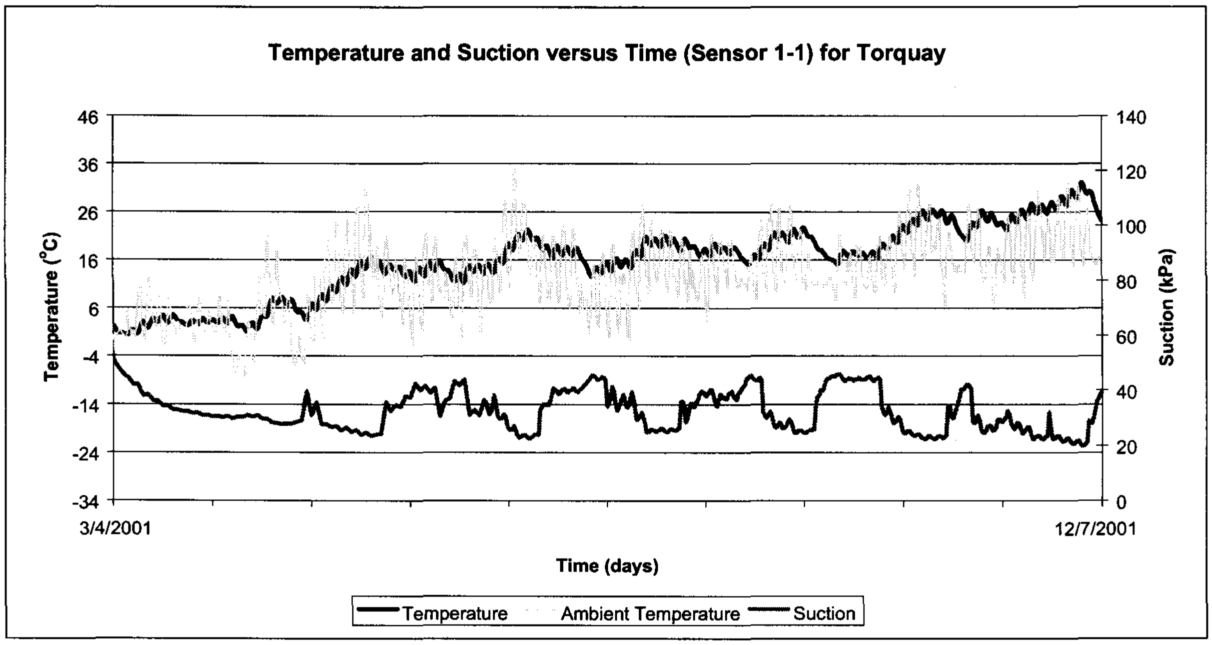

Figure 3. Temperature and suction versus time for sensor 1-1 in Torquay within a period of 100 days

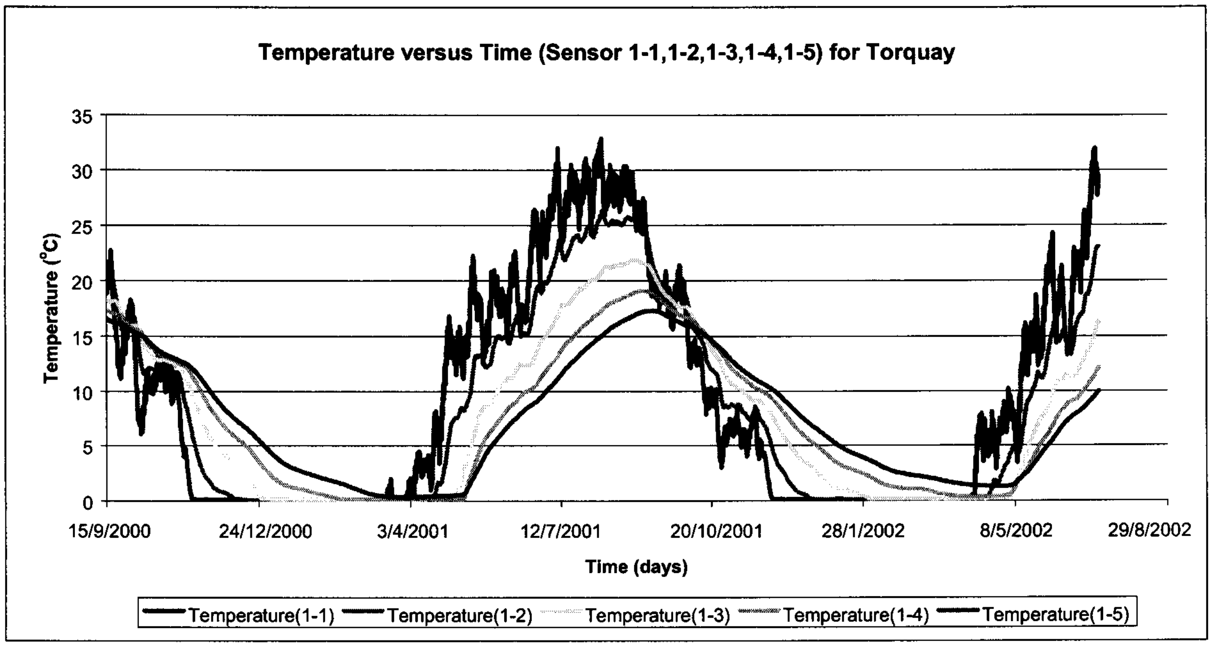

Figure 4. Temperature versus time for sensors along vertical Grid 1 in Torquay

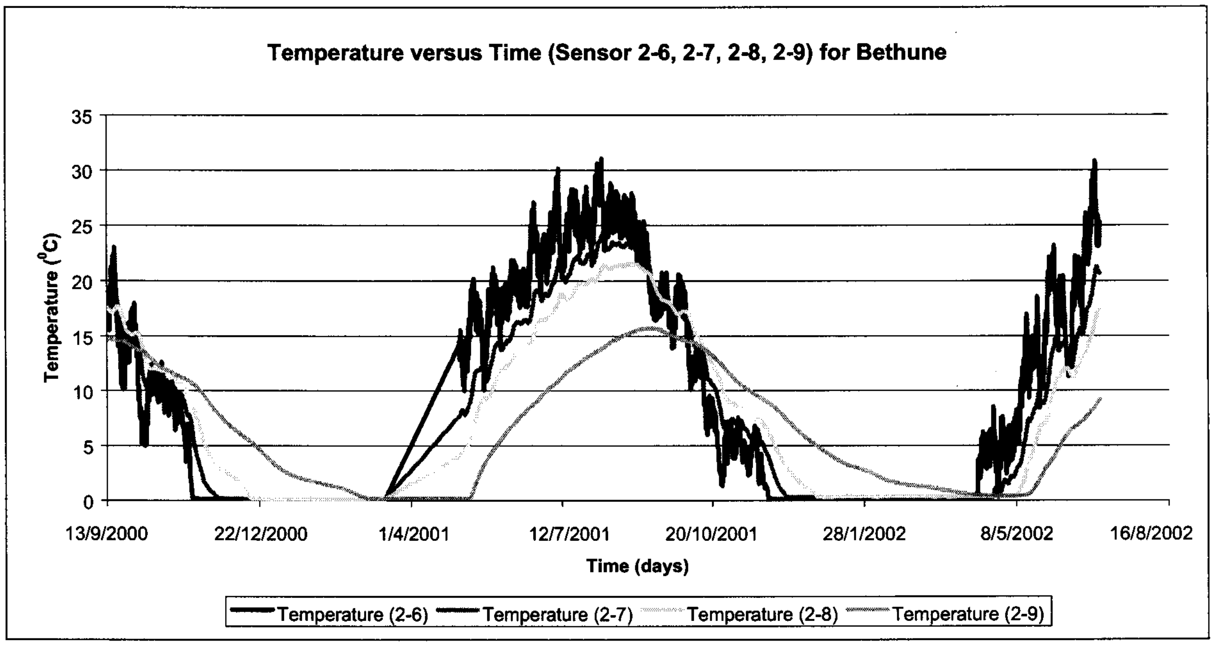

Figure 5. Temperature versus time for sensors along vertical Grid 2 in Bethune

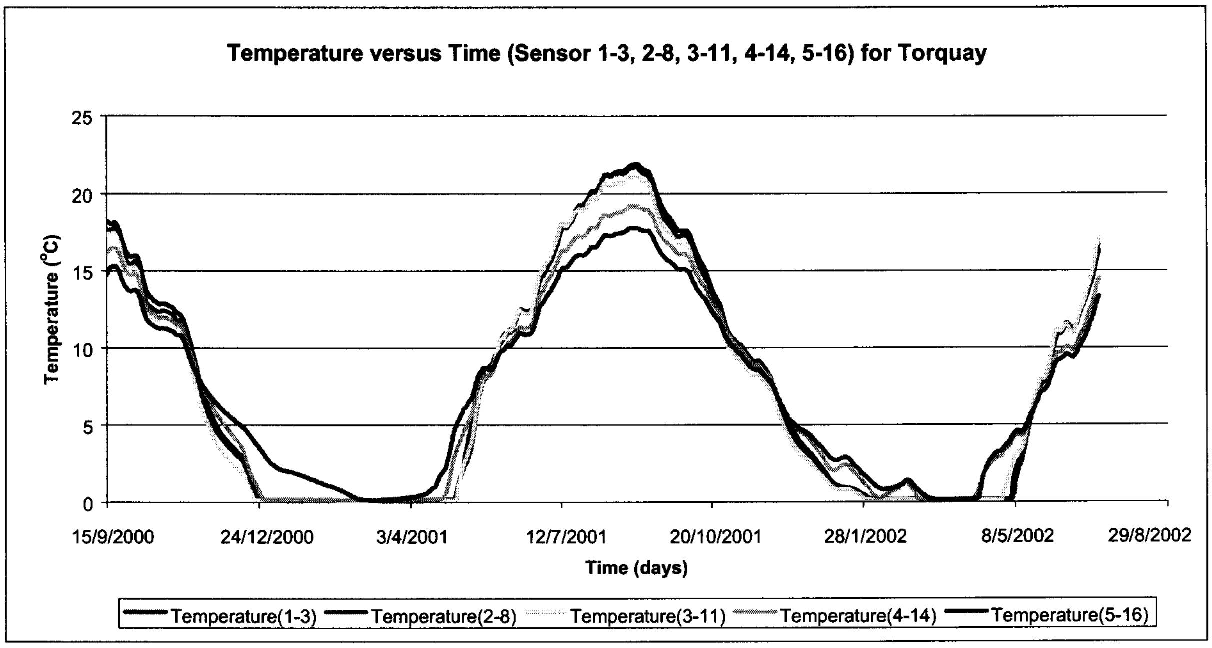

Figure 6. Temperature versus time for sensors along the same horizontal plane in Torquay

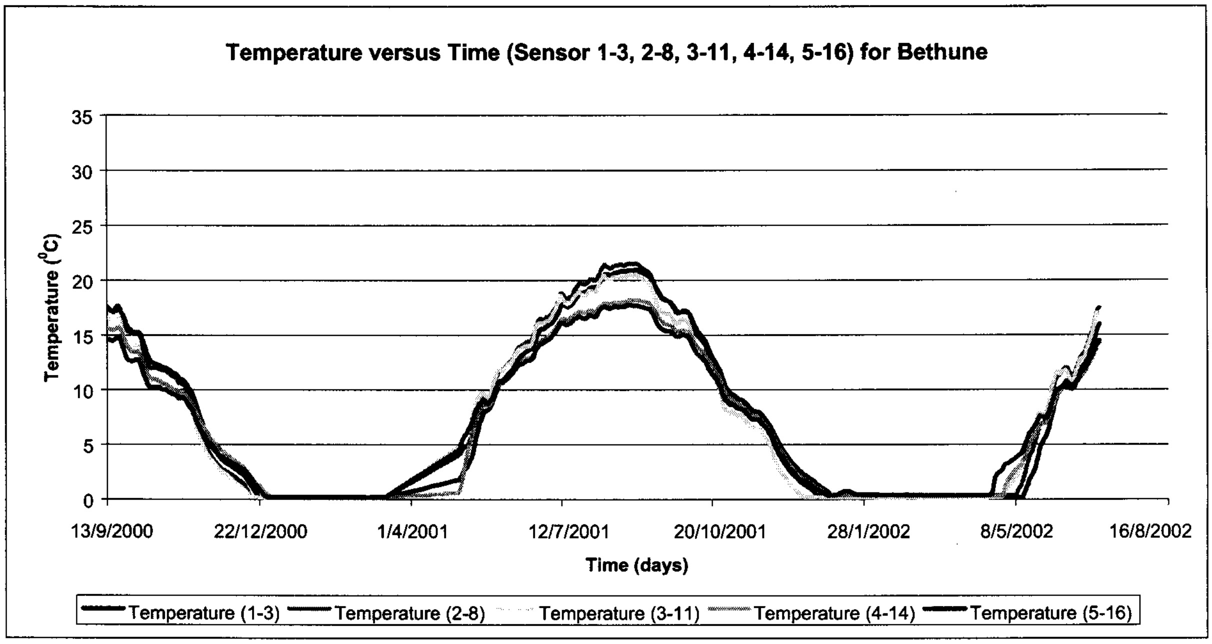

Figure 7. Temperature versus time for sensors along the same horizontal plane in Bethune

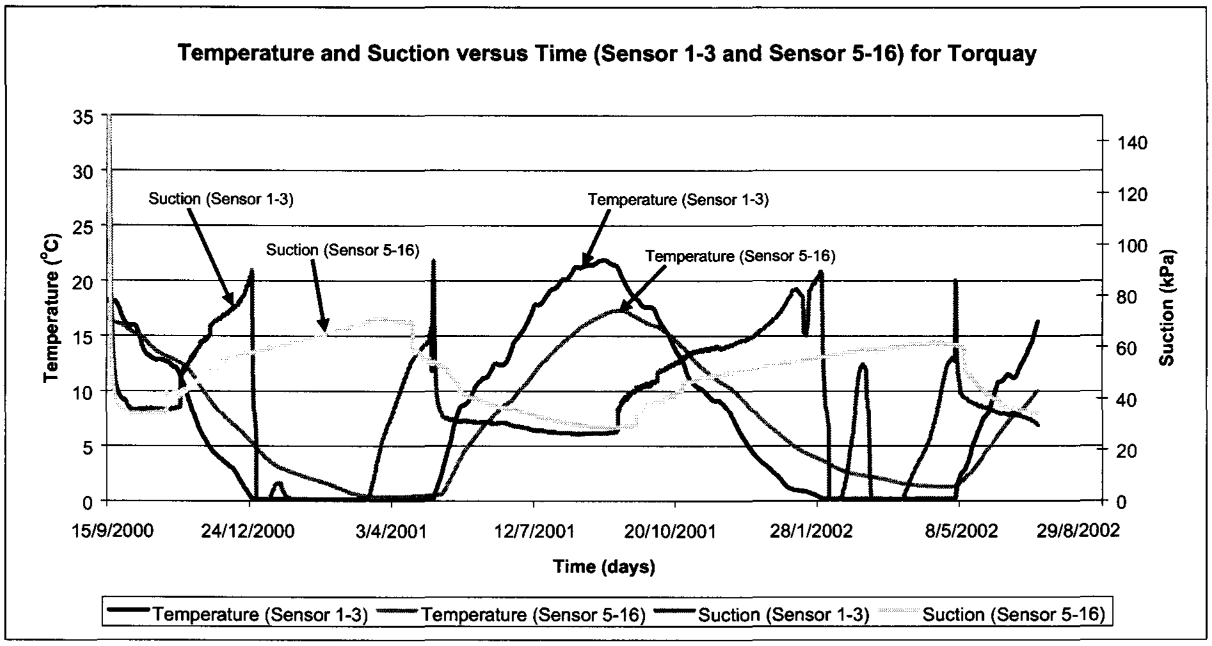

Figure 8. Comparison between temperature and suction readings from sensor 1-3 and sensor 5-16 in Torquay

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 temperature along the horizontal plane across the roadway.

Sensor 5-16 for Torquay as seen in Figure 8 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 8).

## 5. FREEZING PROFILES

During the arrival of spring, thawing occurs from the surface of the road downwards. Since the soil in the subgrade beneath the pavement is still frozen, the increase in pore-water pressure brought about by thawing is not allowed to dissipate. The shoulder of the road, which is generally covered with snow retards frost penetration and causes the increased pore-water pressures to be trapped within the subgrade. The increase in pore-water pressure decreases the soil suction which in turn, decreases the shear stress and bearing capacity of the subgrade.

Thin membrane system roads such as those at the Torquay site and the Bethune site are sufficient during much of the year, but when spring breakup occurs, the bearing capacity of the roadway is insufficient. When there is a decrease in bearing capacity of the road caused by spring breakup, a limit needs to be placed on the loads that can be applied to the road. Road bans are imposed on 8 axle trucks in Saskatchewan, Canada during this period to prevent excessive damage to the roads. However, in order to achieve a balance between maintaining the roads and preventing severe economic losses to the agricultural industry, a maximum period of 40 days has been set for road bans.

The decision on when to impose the road bans, as well as lift the road bans, can be assisted with information obtained by the test sites instrumented with the thermal conductivity sensors. As an example, the sensors directly under the vertical Grid 1 for the site in Torquay, can be used to illustrate the freezing profile that can be obtained for the first spring breakup. The soil freezing profile as seen in Figure 9 was obtained by assuming that the subgrade freezes at 0°C and the soil in the subgrade is homogeneous.

The depth of the freezing profile is plotted on the y-axis while the x-axis shows the change in the freezing profile with time. The time span on the x-axis is 20 days. To analyze the first spring breakup experienced at the Torquay site, the freezing profile between October 25, 2000 and April 3, 2001 is shown. It was assumed that the soil freezes at 0°C and since the thermal conductivity sensors are not able to measure temperatures in the negative temperature range, the freezing profile is shown by the 0°C isotherm.

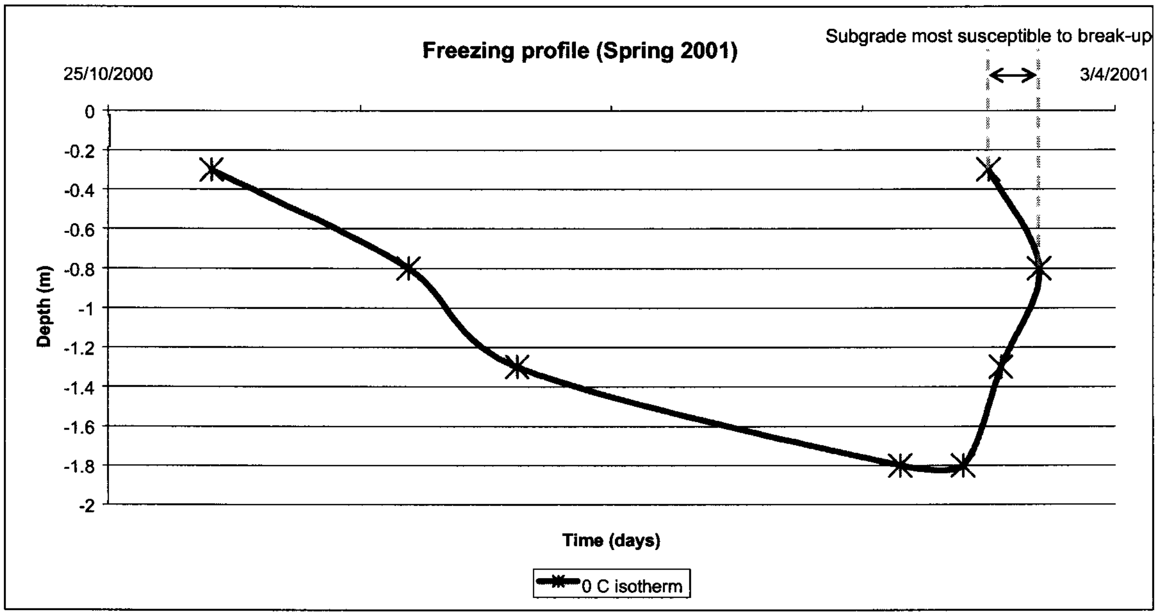

Figure 9. Freezing profile in Torquay for spring 2001

From the freezing profile it can be observed that the maximum depth of frost penetration for the Torquay site prior to the spring break up in 2001, was approximately 1.8 meter. The period where the subgrade was most susceptible to spring break up can be obtained from the right hand section of the curve. This is the period when thawing is occurring on the road surface but the underlying subgrade remains frozen. In order to prevent damage to the road during this period, heavy loads should be kept off the road until the subgrade completely thaws and the pore-water pressures are allowed to dissipate and return to negative values.

## 6. SUMMARY AND CONCLUSION

From the temperature and soil suction readings obtained from Torquay and Bethune test sites, the response of the subgrade to ambient temperatures can be observed. The horizontal location across the roadway, has a minor effect on the readings obtained compared to the vertical locations. Soil suction readings are generally inversely proportional to the temperature readings with maximum soil suctions being achieved at minimum temperatures and vice versa. The readings from the sensors correspond well to changes in ambient temperature and the magnitude of the amplitudes decreases with increasing depth. A freezing profile can be obtained from the readings obtained from the thermal conductivity sensors.

The viability of installing thermal conductivity sensors in a remote location to obtain continuous, long term reliable readings has been demonstrated. Apart from the initial installation, almost no maintenance has been necessary and the data can be transmitted via a transmitter and wireless cellular antennae. The data obtained has various usages, providing a better understanding of the freezing and thawing mechanisms in the subgrade, obtaining more information on the behavior of freezing and thawing of soils and also by improving road design and maintenance practices. The freezing profile obtained from the data can be used to optimize the implementation of road bans by providing a more objective decision making procedure.

## 7. REFERENCES

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