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INSTALLATION OF SENSORS AND MEASUREMENT OF SOIL SUCTION BELOW THIN MEMBRANE SURFACE PAVEMENTS IN SASKATCHEWAN

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ABSTRACT

The performance of Thin Membrane Surface (TMS) Highways is dependent mainly on the strength of the underlying subgrade soil. The subgrade soil strength, in turn, is a function of the matric suction. An accurate subgrade matric suction profile is required for the prediction of TMS performance. Thermal conductivity sensors and a data acquisition system (DAS) were installed in the subgrades of two separate locations in southern Saskatchewan, Canada. Sixteen sensors were installed in the walls of a trench excavated at each location. Extreme care was taken to seat the sensors so that they had full contact with the soil around the entire sensor, and to backfill and seal around the sensor to eliminate potential flow of water to the sensors. Upon completion of the installations, the sensors were connected to a DAS to continuously monitor the matric suction readings. The resulting matric suction profiles showed that suctions generally decreased with increasing depth. Suction values were lowest in the spring and summer months, and began to increase in the fall of the year. The maximum matric suction values were witnessed in late October to early March depending on sensor depth.

RÉSUMÉ

La performance des Autoroutes à Surface à Membrane Mince (SMM) dépend essentiellement des sols supports sous la surface de la route. D'autre part, la force de ces sols supports est fonction de la succion matricielle. Un profil exact de la succion matricielle des sols supports est nécessaire pour prédire le rendement de la SMM. Des détecteurs de conductivité thermique et un système d'acquisition de données (SAD) ont été installés dans les sols supports en deux emplacements dans le sud de la Saskatchewan, Canada. Seize détecteurs ont été installés dans les parois des tranchées creusées à chaque emplacement. Une attention spéciale a été donnée à l'assise des détecteurs pour que chaque surface de ces détecteurs soit en contact avec le sol, de même les tranchées ont été refermées et scellées avec le plus grand soin afin d'éliminer tout risque éventuel d'infiltration d'eau dans les détecteurs. Après que les installations ont _été complétées, les détecteurs ont été connectés à un SAD pour contrôler de façon continue les données de succion matricielle. Les profils de succion matricielle résultants ont montré que les succions diminuent généralement avec la profondeur. Les valeurs de succion étaient plus basses pendant les mois de printemps et d'été et ont commencé à augmenter au cours de l'automne. Les valeurs maximales de succion matricielle ont été enregistrées entre la fin du mois d'octobre et le début du mois de mars avec des variations selon la profondeur des détecteurs.

1. INTRODUCTION

There are approximately 8600 km of Thin Membrane Surface (TMS) highways in the province of Saskatchewan, Canada. A recent demographic shift in agriculture and other industries in the province has seriously impacted the functionality of these roads. They are deteriorating over time due to repeated heavy loads accelerated by adverse weather conditions.

The TMS highways consist of a soft asphalt mat placed on a subgrade to provide a dust free, mud free driving surface for low volume roads. The subgrade is composed largely of unsaturated soil with a shear strength largely dependent on the pore-water conditions within the soil. The pore-water pressures in highway subgrades are generally negative; this condition is referred to as soil suction. The majority of the strength of the TMS roadways comes from soil suction therefore a methodology is required to accurately predict the performance of the TMS system based on in-situ soil suction at various locations within the subgrade for varying climactic conditions. Such data is necessary to optimize usage of the TMS system while providing valuable design information for future TMS construction projects.

2. MATRIC SUCTION MEASUREMENT

A study was undertaken to measure the matric suction profile within the cross section of the subgrade of a TMS highway using thermal conductivity sensors. The study included the review of matric suction variance resulting from local microclimatic changes. The thermal conductivity sensors utilized for this study were developed through a rigorous research program over several years conducted at the University of Saskatchewan, Saskatoon, Saskatchewan, Canada. The strength, accuracy and durability of the new thermal conductivity sensor used for this study has been significantly improved over previous sensors (Shuai and Fredlund, 1999). These sensors were shown to be accurate in measuring soil suctions between 5 and 1500 kPa with a coefficient of variation of +/- 5 percent. No other soil suction measuring device has been shown to be this accurate so the sensors were considered to be the best method to measure soil suction for this study. A brief description of the new sensor is included in this paper along with data obtained from a field investigation using the sensor.

The new thermal conductivity sensor consists of: a porous ceramic block containing numerous pore sizes; a heating device; a temperature sensing device; an epoxy jacket; and, connecting wire (Figure 1). Prior to use the sensors require calibration using a commercially available pressure plate apparatus. The calibration determines the electric current output for a given a given matric suction value so that a calibration curve for each sensor can be developed. Once this procedure is complete the sensor can be used to indirectly measure matric suction in a variety of soil types.

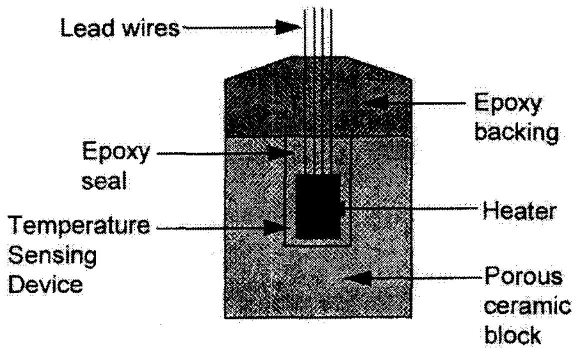

Figure 1 Sketch of New Thermal Conductivity Sensor

One of the many advantages of the thermal conductivity sensors is their compatibility with a data acquisition system (DAS). The DAS used for this study was supplied by Campbell Scientific Inc. of Edmonton, Alberta, Canada, and consisted of: datalogger (CR10X); multiplexer (AM416); Constant Current Sink and Amplifier; power supply (PS12); communication system (COM200 and COM100); and, system software (PC208W).

The CR10X is capable of storing up to 60,000 data values which is paramount when data is being taken at remote locations. It has the ability to provide real time information at desired intervals and its set up facilitates communication between the datalogger and base station by direct communication, via telephone or by cellular communication.

The AM416 multiplexer facilitates acquisition of data from multiple sensor installations through control of the numerous sensor readings scanned by the datalogger. Acquisition of readings from the various sensors is accomplished through the use of mechanical relays in the multiplexer which are used to switch the desired sensor signals through the system. The Constant Current Sink and Amplifier is utilized by the DAS to ensure precision of the heating voltage for the sensor. It also compensates for varying lengths of sensor cable wires.

The power supply for the system was a 7.0 ampere.hour (Ahr) sealed rechargeable battery with a 12 Volt charging regulator. This was supplemented with a 26 Ahr battery and the power source for the entire system was provided by a solar panel. Communication with the system for purposes of data acquisition and for sending instructions to the datalogger was accomplished through the use of a cellular communication system consisting of a modem, transceiver and cellular antennae. The entire DAS was tested in the laboratory to ensure reliability prior to any field installations.

3. FIELD PROGRAM

3.1 Site Selection

Specific objectives of this study were:

1. Develop a practical installation procedure for the new thermal conductivity sensors to facilitate acquisition of appropriate data.
2. Evaluate the ability of the new sensor to measure matric suction in highway subgrades at remote locations on a continuous basis.
3. Evaluate the DAS utilized in conjunction with the new sensor.
4. Verify that suction readings can be obtained and evaluated within the context of unsaturated soils.

To achieve these objectives two sites in southern Saskatchewan, Canada were selected as locations for the installation of the new sensors (Figure 2). A third site was also selected as an alternate for installation pending budget acquisition. These sites were on TMS highways with the first located on Highway No. 354 (Site 1) approximately 3.5 km north of Bethune, Saskatchewan, Canada and the second located on Highway No. 350 (Site 2) approximately 8.6 km south of Torquay, Saskatchewan, Canada. The alternate site (Site 3) was located on Highway No. 34 south of Bengough, Saskatchewan, Canada.

The sites were selected at locations where it was predicted that the temperatures would be the greatest and would increase the quickest. This was at locations on north/south roadways, on the downward slope of a south-facing hill and on the west side of the highway. These criteria would ensure that the sites would begin the spring thaw at the earliest possible time, relative to the portion of highway located north and south of the site, by maximizing the influence of direct sun weather conditions at the sites.

The subgrade at Site 1 and Site 2 consisted of a low plastic clay till soil classified as "CL" based on the Unified Soil Classification System. Sixteen of the new thermal conductivity sensors were installed at each site.

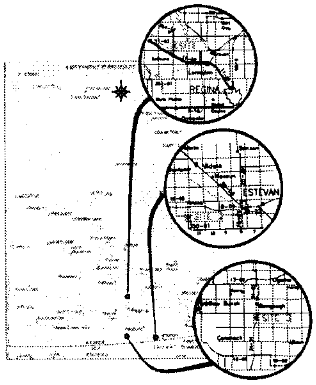

Figure 2 Location Plan For Proposed and Alternate Sites

3.2 Installation Procedure

The new thermal conductivity sensors had to be inserted directly into the subgrade of the highway. To facilitate the installation a trench, with dimensions of 1.08 m wide and approximately 2.4 m deep, was excavated in the highway with a backhoe. The excavation started at a distance of 2.0 m west of the highway centreline and extended from that point through the highway shoulder and sideslope. The trench size permitted installation of the sensors in the east and north face of the excavation.

Each sensor was installed by initially augering a 32 mm diameter pilot hole to within 100 mm of the required sensor depth. The remainder of the sensor hole was constructed with a 28 mm diameter auger which was nearly identical to the diameter of the sensor. The 32 mm pilot hole was utilized to make the actual sensor insertion less difficult. The 28 mm diameter auger was used to drill the final portion of the sensor hole to ensure that there would be good soil to sensor contact after insertion. Once the sensor hole was completed it was cleaned using compressed air to ensure that loose debris did not affect the installation. The sensors were then inserted into the hole using a custom-built insertion tool. Care was taken during the insertion procedure to ensure that the sensor was seated at the proper depth fully in contact with the back of the hole.

Following insertion each sensor was verified by taking an initial reading and comparing the reading to the individual sensors calibration curve. This was done prior to backfill to ensure that the sensor had not been damaged during installation. The sensor hole was then backfilled with 150 mm of native material from auger cuttings which was compacted with a wooden tamping dowel during the backfill procedure. The remainder of the hole was backfilled with low expanding foam. Low expanding foam was used to ensure that all possible avenues, existing from the sensor installation, for contamination of the sensor readings by water flow were eliminated. It was imperative that good soil to sensor contact be maintained between the sensor tip and surrounding soil to ensure that continuity of the water phase between the sensor and the soil was maintained preventing erroneous results from occurring.

Following installation, the individual sensors were connected to the multiplexer of the DAS. At Site 1 the multiplexer was located with the rest of the DAS at the west property line of the highway right of way. This required the length of the sensor cable leads to be extended by approximately 15.0 m (they were initially fabricated with 7.0 m leads). The required length for the sensor cables at Site 1 had been predetermined during the initial stages of the study and as such the cables had been extended prior to bringing them to site. A heat shrink splice was used around all extension connections to provide a water tight seal to prevent corrosion of the connection. The spliced cable and sensor was then verified in the laboratory. The heat shrink splice of the cable connections was undertaken at the University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

The entire DAS was placed in a custom built stainless steel enclosure and was buried to a depth of approximately 300 mm. Figure 3 shows the installed stainless steel enclosure containing the DAS. The stainless steel enclosure was utilized to protect the system from vandalism and the effects of the environment.

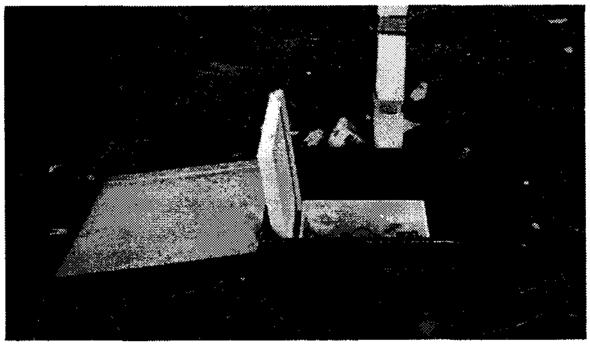

Figure 3 Stainless Steel Enclosure For The DAS

At Site 2 the need for sensor cable extensions was eliminated by separating the multiplexer from the rest of the DAS by placing it in a separate protective enclosure in the sideslope of the highway. The protective enclosure consisted of a 600 mm diameter fiberglass well casing with an expanded metal mesh platform for seating the multiplexer. The protective enclosure had a stainless steel cover for easy access complete with locking latch for protection from vandalism. Figure 4 shows the protective enclosure for the multiplexer at Site 2 containing 16 sensor cables connected to the multiplexer. The multiplexer at Site 2 was connected to the DAS located at the highway property line with cables trenched to the DAS. The DAS at Site 2 was placed in a stainless steel enclosure identical to the one utilized at Site 1.

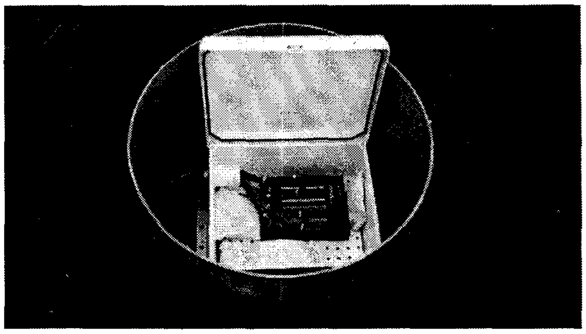

Figure 4 Protective Enclosure For Multiplexer at Site 2

All the leads at both sites ran along the bottom of the trench for connection to the multiplexer. Following this the sensor cable leads and power source cables were placed inside standard PVC pipe in the trench bottom. This was done to further protect any connections in the cables from corrosion from soil water conditions. The trench was then backfilled with the excavated soil and compacted in 150 mm lifts. A polyethylene moisture barrier was placed at a depth of 150 mm from the finished highway surface to help prevent moisture infiltration into the subgrade of the compacted excavation. Following this the backfill was brought to approximately 50 mm from finished surface with native material. The remainder of backfill consisted of 50 mm of hot mix asphalt at Site 1 and 50 mm of cold mix asphalt covered with a sand seal at Site 2.

3.3 Field Measurement of Matric Suction

The thermal conductivity sensors were installed during September of 2000. The calibration of the sensors had been previously completed at the University of Saskatchewan, Saskatoon, Saskatchewan, Canada and was not part of this study. The calibration results from the sensors however, were used to determine the matric suction from the sensor readings.

The sensors were initially dry prior to installation. They were installed in five vertical grids throughout the cross section of the subgrade. Figure 5 is a highway cross section showing the location of the sensors in the highway subgrade. Grid 1 was located under the inner wheel path, Grid 2 under the outer wheel path, Grid 3 under the shoulder/sideslope and Grids 4 and 5 in the sideslope of the highway. The deepest sensor was at 2.2 m and the shallowest sensor was installed at 0.3 m. The specific sensor locations were chosen to obtain a representative matric suction profile over the entire highway cross section.

The frequency chosen for sensor readings was dependent on the time of year and whether the sensor had reached equilibrium with the soil. For example the frequency was readings every hour until equilibrium was reached, every four hours during the fall and spring of the year and every twelve hours during the winter period.

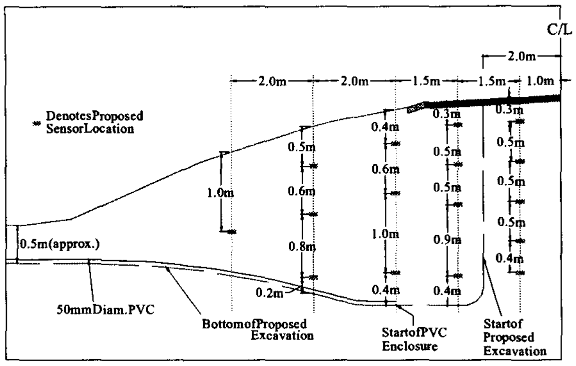

Figure 5 Cross Section Showing Sensor Locations

4. PRESENTATION OF DATA AND ANALYSIS OF RESULTS

Extensive matric suction data have been collected from two sites in Saskatchewan, Canada. Data from Site 1 during the period of March 15, 2001 to May 3, 2001 is unavailable due to contamination of the DAS from melt-water. Therefore the findings obtained from Site 1 will be discussed only briefly and not in as much detail as the results obtained at Site 2. The data obtained from Site 2 will be presented in detail as it is continuous throughout the entire study period. The suction data are presented in graphical format according to a particular sensor depth range with only one depth range plotted per graph. The depth ranges are 0.3 m to 0.5 m, 0.8 m, 1.0 m to 1.3 m and 1.8 m to 2.2 m. Graphical representation of the 0.3 m to 0.5 m depth range are shown in Figure 6 and Figure 7 and the graphical representation of the 1.0 m to 1.3 m depth range are shown in Figure 8 and Figure 9. The results from the remaining two depth ranges are discussed however no graphical representation of the data obtained are included.

4.1 Site 2 – South of Torquay, Canada

The subgrade at Site 2 is constructed with oxidized glacial till. The highway cross section consists of approximately 40 mm of asphalt concrete overlying the subgrade. The sensors were installed on September 15, 2000.

4.1.1 Discussion of Field Data

The time until equilibrium between the sensor and the soil was reached was dependent on the sensor characteristics and existing soil conditions. Equilibrium for all sensors appears to be complete by the middle of October with the exception of T 4-13. This sensor exhibited erratic behaviour from the time of the initial reading through the entire study period.

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Freezing and thawing conditions in the soil varied with sensor depth and sensor location within the subgrade. For example the shallow depth range experienced freezing conditions in early November and thawing conditions in late March while only one sensor in the maximum depth range noted freezing conditions. This was sensor T 1-4 which was located at a depth of 1.8 m under the inner wheel path of the highway. Also of note at this site was the fact that sensor T 5-16 did not experience freezing conditions even though it was located at a depth of only 1.0 m. Sensor T 5-16 was located in the highway sideslope and experienced significant snow cover which provided insulation from the cold temperatures while sensor T 1-4 was located under the driving surface which would have no snow cover and where frost penetration would be the greatest.

The general trend for the majority of the sensors exhibited a steady increase in suction magnitude through the fall and winter or until the soil around he sensor became frozen. Maximum suction was reached later in the year as the sensor depth was increased. The recorded suction in shallow sensors peaked around November 10, 2000, while the recorded suction in deeper sensors peaked near the middle of March. This could be due to the frost penetration drawing moisture upwards causing suction at greater depths to increase. This trend continued until spring temperatures were experienced in March of 2001.

In the spring, the sensors that were in frozen ground showed a steady increase in matric suction as the ground began to thaw. The suction values reached a peak and then dropped very rapidly as the spring "break up" took place. Following this rapid drop the suctions tended towards a more constant suction value later in the spring, beginning in late April 2001 for the shallow sensors, and early May 2001 at deeper locations.

4.1.1.1 Results based on Horizontal Location

4.1.1.1.1 0.3 to 0.5 m Depth Range

There are four sensors located in the 0.3 m to 0.5 m depth range at both sites. They are located under the inner and outer wheel paths respectively, under the shoulder and under the sideslope of the highway. The sensors located in the 0.3 m to 0.5 m depth range at Site 2 show the sensor located under the shoulder of the highway (T3-10) having a higher recorded suction value than the sensors located under the pavement for similar depths. This trend continued until early November when the soil around the sensors began to freeze (Figure 6). These results were different than those obtained at Site 1 where suctions under the pavement were higher than those in the shoulder or sideslope of the highway. The lower suction values recorded in the shoulder at Site 1 would explain why many shoulder failures are noted on the TMS highways. The difference in this trend at Site 2 is perhaps due to higher infiltration rates through the asphalt mat of the TMS highway at Site 2, causing lower suctions to be recorded.

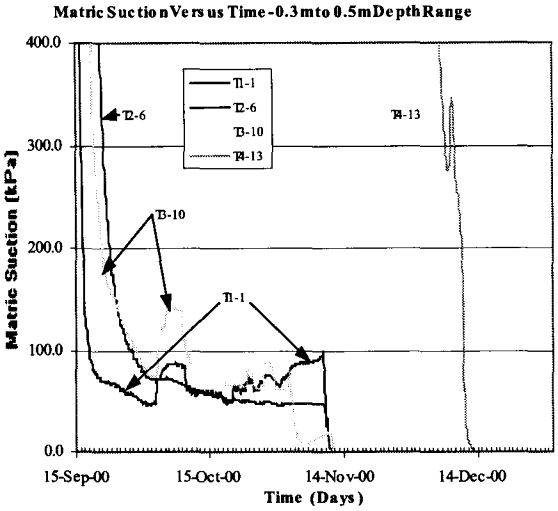

Figure 6 Matric Suctions For 2000 As Soil Freezes

Thawing of the ground around the sensors at this depth was noted in the middle of March. There was significant fluctuation in sensor readings in the early spring with readings levelling off somewhat by the end of April (Figure 7). The fluctuation in the suction readings noted in March was due to the fluctuation in ambient temperatures experienced at that time which affected the shallow sensors significantly more than the deeper sensors.

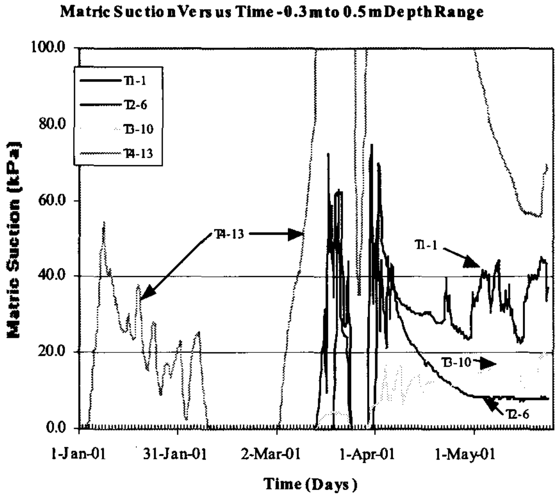

Figure 7 Matric Suctions For 2001 During Spring Thaw

4.1.1.1.2 0.8 m Depth Range

There are two sensors located in the 0.8 m depth range and they are located under the inner and outer wheel paths respectively. The sensors located at the 0.8 m depth range at both sites exhibited similar characteristics in terms of trends in suction and magnitude of suction. Both sites had nearly constant suction readings after equilibrium was reached with only minor fluctuations recorded between individual readings. At the end of October the suctions increased until the soil began to freeze. The main difference between the two sites for the 0.8 m depth range was the magnitude of the suction prior to the soil becoming frozen. For example the maximum suction achieved at Site 2 (110 kPa) was nearly double that of Site 1 (56 kPa). This could be explained by the fact that Site 2 had significantly lower initial moisture contents than Site 1 which could indicate that the local micro-climactic conditions are drier overall than those at Site 1.

4.1.1.1.3 1.0M TO 1.3 M DEPTH RANGE

There are five sensors located in this depth range at Site 2 and they are located in the inner and out wheel paths, the shoulder and the sideslope or the highway. All the sensors in this depth range appeared to reach equilibrium with the soil in early October of 2000. The shape of the graphical presentations of the results for these sensors appear similar until the ground becomes frozen (Figure 8). The main difference in the curves is the magnitude of suction at the individual sensors.

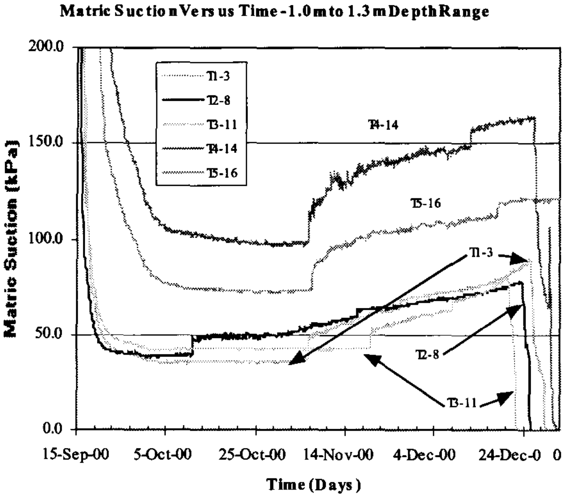

Figure 8 Matric Suctions For 2000 As Soil Freezes

Similar to sensors at other depths, the results show a trend where the sensors reached equilibrium with the soil, followed by a gradual increase in suction to a maximum value prior to the soil becoming frozen. The trend is similar at Site 1 however the maximum suctions recorded are much lower than those recorded at Site 2. For example Sensor B 4-14 (Site 1) shows a maximum suction of approximately 37 kPa while the corresponding sensor T 4-14 (Site 2) shows a maximum suction of approximately 163 kPa reached prior to the ground becoming frozen. Site 2 also shows suction readings significantly higher in the sideslope of the highway than in the shoulder or under the pavement.

Only one sensor (T 5-16) location did not freeze during the study period at Site 2 unlike the case at Site 1. Sensor T 5-16 suction readings increased steadily from late fall to a maximum value of approximately 120 kPa at the end of December. The recorded suction at this sensor then decreased steadily until the end of the study period. The results for the remainder of the sensors in this depth range indicated that the ground began to thaw in late March; the corresponding suction values show an initial increase to a maximum value in late April. The recorded suctions then decreased steadily and then levelled off towards the end of May (Figure 9).

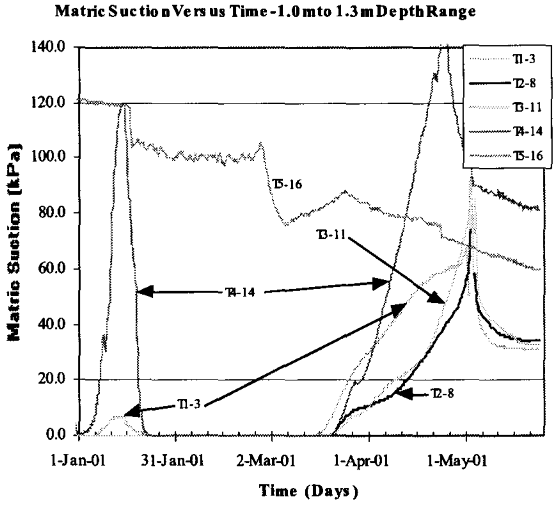

Figure 9 Matric Suctions For 2001 During Spring Thaw

4.1.1.1.4 1.8M TO 2.2 M DEPTH RANGE

There are also five sensors located in this depth range at both sites. Two are located under the inner wheel path, one under the outer wheel path, one in the shoulder and one in the sideslope of the highway. The time for the individual sensors to reach equilibrium varied from late September to early November. Similar to the results of other depth ranges, there was initially a constant suction recorded for a period of time, followed by a steady increase in late fall to a maximum value in late March. The recorded suction values decreased somewhat during the spring period and this trend continued until the end of the study period on May 31, 2001. Similar to the other depth ranges the higher suctions were recorded at Site 2.

Only one sensor (T 1-4) indicated freezing conditions in the ground surrounding the sensor. Thawing at this location was recorded near March 10, 2001.

4.1.1.2 RESULTS BASED ON VERTICAL LOCATION OF SENSOR

The data from both sites indicates a trend of decreasing suction with increasing depth of sensor. Once equilibrium

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was achieved between the soil and the sensor the recorded suctions indicate the highest suction measured at the shallow depth and the lowest suction recorded at the deepest sensor on any given vertical grid in the highway cross section. Also noted was the greater intensity of fluctuation between individual readings for the shallow sensors. This is due to the fact that the shallow sensors are more prone to the effects of local climactic conditions such as temperature variations and local precipitation than sensors at greater depths.

The effect of freezing conditions was also witnessed during the study period. The ground located immediately under the pavement froze first. This would be the expected response because the traffic on the highway would tend to accelerate the freezing conditions in the highway subgrades. Deeper sensors recorded maximum suction values later in the year prior to thawing conditions. This is due to water being pulled from below to the freezing zone leading to an increase in suction with the decrease in moisture.

Stress distribution of traffic wheel loading is maximum at the surface and decreases with depth. Therefore the recorded suction values to a depth of 0.8 m under the inner and outer wheel paths of the highway are integral to understanding the available subgrade strengths. This provides the basis of a mechanistic surfacing structure design.

Based on this premise the results from Site 2 indicate that a minimum design suction value of approximately 35 kPa would be reasonable for this material. The alternative to this could be to restrict heavy traffic from the highway until early November when a design suction of between 50 kPa and 60 kPa could be used. The heavy traffic could continue utilizing the highway until suction readings indicated that thawing conditions were underway in the spring.

5. SUMMARY AND CONCLUSIONS

An installation procedure for placing the new thermal conductivity sensors in TMS subgrades has been developed and described. The new thermal conductivity sensor functioned very well during the study period indicating that long term and continuous data acquisition from remote locations is possible over a wide range of suction values. The suction results obtained were generally consistent with respect to expected trends in suction values.

The DAS utilized in conjunction with the sensors facilitated effective and efficient data acquisition. Severe weather conditions did not affect the functionality of the system. The communication system used in conjunction with the DAS proved to be very effective in obtaining data from remote sites via wireless communication. Modifications to the stainless steel enclosure and the installation at Site 1 should help to prevent future problems with contamination of the DAS from spring wetting conditions. These modifications include elevating the enclosure, minor drainage work adjacent to the enclosure and ensuring that water tight fittings are used on the enclosure.

The suction readings obtained through the use of the new thermal conductivity sensor can be analyzed in the context of unsaturated soils. The available subgrade strengths can be estimated based on in-situ soil suction.

Greater fluctuation between sensor readings was witnessed in sensors located at shallow depths due to the effects of local climactic conditions. Seasonal variation is evident in the recorded suction values with the maximum values recorded during the winter months and minimum values recorded during the spring of the year. The deeper sensors experienced maximum suction values a variable length of time after the shallower sensors. The time of year of maximum recorded matric suction is a function of the depth of the sensor and the local climactic conditions.

6. ACKNOWLEDGEMENTS

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