INSTALLING AND MONITORING OF THERMAL CONDUCTIVITY SUCTION SENSORS IN A FINE-GRAINED SUBGRADE SOIL SUBJECTED TO SEASONAL FROST

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INSTALLATION AND MONITORING OF THERMAL CONDUCTIVITY SUCTION SENSORS IN A FINE-GRAINED SUBGRADE SOIL SUBJECTED TO SEASONAL FROST

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Abstract

The long term performance of a pavement structure is strongly influenced by the subgrade soil condition. This is particularly true in areas experiencing seasonal freezing and fluctuations in moisture and/or temperature existing within the pavement system. With this fact in mind, proper characterization of fine-grained soils calls for reliable measurements of negative pore-water pressure. Negative-pore water pressure provides one of the stress variables required for understanding unsaturated soil behaviour.

To help understand the aforementioned seasonal variational effects, a pavement section within the primary highway network in the province of Alberta has been instrumented with thermal conductivity suction sensors. The pavement site is a four lane divided highway located in central Alberta. The cross section consists of a 7.32 m wide asphalt concrete pavement with a 3.66 m outside and 2.40 m inside asphalt concrete shoulders. This section was constructed in 1983 and is composed of 130 mm of asphalt concrete surface, 51 mm of asphalt stabilized base, 456 mm of granular base course, and rests on a CL-CI subgrade soil fill in the order of 2 to 3 m. The highway carries traffic of about 539 equivalent single axle loads (ESAL's) per day in one direction.

The pavement section was instrumented with 12 AGWA-II thermal conductivity suction sensors. These sensors are designed to measure both the temperature and soil matric suction within fine-grained soils. The instrumentation consisted of two phases. In the first phase, the suction sensors were calibrated at the University

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of Saskatchewan, Saskatoon, for suctions of up to 400 kPa. This step was necessary to later enable the conversion of the sensor output to suction values. In the second phase, the sensors were installed in three sets of four sensors each. One set is placed within the outside shoulder of the pavement while the other two sets are placed within the outside design lane. Within each set, sensors were placed from 0.78 m to 1.78 m from the top of pavement surface. Temperature and soil suction data has now been collected for five winter months.

1.0 INTRODUCTION

The long term performance of a pavement structure is strongly dependent on the subgrade soil conditions. This is particularly true in areas experiencing seasonal freezing and fluctuations in moisture and temperature existing within the pavement structure. To account for the adverse effects of such factors on the structural adequacy of pavements, it is necessary to have available realistic and reliable strength measures for the layer component materials. With the resilient modulus as a key parameter in such evaluation, it is planned to investigate the seasonal and temperature variational effects on pavement bearing capacity as assessed by non-destructive and other appropriate laboratory test procedures.

The effects of both temperature and water content variations on pavements can be viewed through their influences on the properties of the constituent materials. Such seasonal variations tend to change the strength of the pavement materials so that their resistance to traffic induced stresses are altered (AASHTO 1986, The Asphalt Institute 1982).

It follows that evaluation of the effects of both temperature and water content variations on pavement response is essential to properly rehabilitate existing pavements and design new ones. This necessitates establishing a way for measuring seasonal variations.

In the present work, such evaluation takes the form of establishing seasonal variational changes in the resilient modulus of a representative subgrade soil material that is commonly found within the Alberta Province.

2.0 RESEARCH PROBLEM AND APPROACH

The main theme of the research undertaken concentrates on developing suitable resilient modulus relationships for a typical subgrade soil material that is frequently encountered in Alberta. These models will incorporate the effects of both temperature and water content on pavement structures situated in cold regions.

Specific objectives of the investigation are:

1. Establish temperature and matric suction distributional trends within a typical subgrade material in Alberta.

2. Develop new procedures for determining pavement layer in-situ moduli under different temperature and moisture conditions. This will be accomplished through the use of non-destructive testing and back-calculation techniques

3. Describe currently available laboratory procedures for determining pavement layer moduli.

4. Develop laboratory predictive moduli models for typical Albertan subgrade soils in terms of pertinent soil properties and conditions through dynamic repeated load testing.

5. Correlate laboratory determined resilient moduli relationships with field obtained moduli.

6. Provide guide lines for future implementation of mechanistic - empirical pavement design methodologies.

To achieve the research objectives, a two - phase study was conceived. The first phase will be a field testing program and the second phase will be a factorial laboratory testing program.

This paper will address only the field testing phase.

3.0 PAVEMENT TEST SECTION

Within the framework of the field testing phase, a pavement section that is representative of the primary highway network within the Province of Alberta has been selected for instrumentation. This pavement section is a one kilometer long portion within control section 16:12 on Primary highway 16. The highway is a four - lane divided facility that is located west of Edmonton between highway 22 east of Entwistle and the junction with highway 43, a distance of 51.05 km. The selected pavement section extends from km 18.5 to km 19.5 on the west bound roadway. The mostly westerly 440 m of this section lies in a cut whereas the rest of the section is a fill area. The cross section consists of a 7.32 m wide asphalt concrete pavement (ACP) with 3.50 m outside and 2.40 m inside ACP shoulders, shown in Figure 1. This section of the highway was constructed in 1983 and is composed of 130 mm of asphalt concrete surface, 51 mm of asphalt stabilized base, 456 mm of granular base course and supported by a CL-CI subgrade soil fill varying from 2 to 3 m in height along the section.

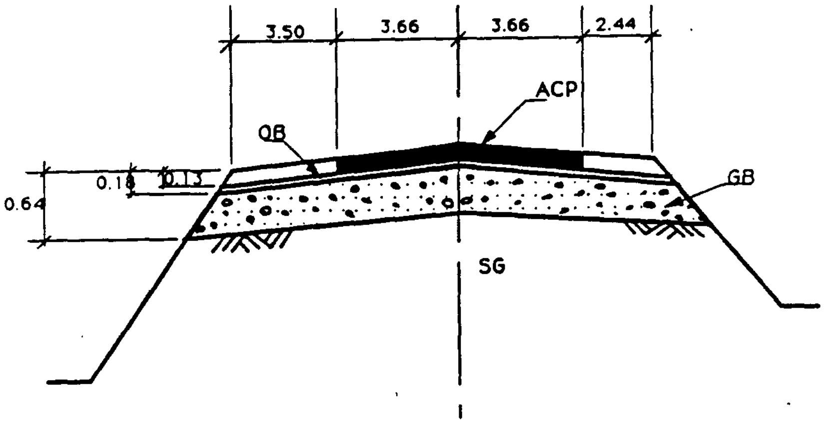
The mixed traffic on this section has two-way AADT of 12656 and consists of about 539 equivalent single axle loads (ESAL's) per day in one direction.

A site approximately 171 m from the beginning of the section was selected as an appropriate location for instrumentation. This particular site showed no visible distress at the time of installation.

4.0 FIELD INSTRUMENTATION

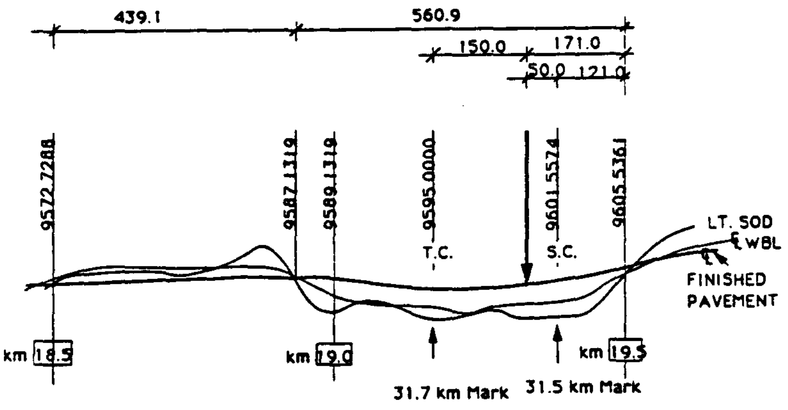
Thermal conductivity suction sensors of the AGWA-II Model, were installed at different depths within the subgrade soil layer in both the outer wheel path and the shoulder areas. This is viewed necessary on the basis of providing an adequate assessment of the water content/density, or strength, changes that a highway will undergo with changes in climatic conditions and seasonal variations.

In the following sections of the paper, the theory of the thermal conductivity sensor, sensor calibration, field installation procedure and method of data collection will be given.



N.B. : all dimensions in meters

FIGURE 1 (a): PAVEMENT CROSS-SECTION



N.B. :

- All Dimensions in Meters
- • FWD Test Locations
- Chainage Points in ft.
- S.C. Single Culvert
- T.C. Twin Culvert

FIGURE 1 (b): SELECTED SITE PROFILE

4.1 Theory of Thermal Conductivity Sensor

Thermal conductivity sensors have been in use by several researcher in the agricultural field since 1971 (Phene et al 1971, 1987). Traditionally, these sensors have been utilized for indirectly measuring soil matric suction, in order to assist in irrigation scheduling. Although these sensors were originally developed for soil science applications, its value in measuring soil suction in fine grained soils has recently been recognized in the area of geotechnical engineering (Wong et al 1989, Sattler 1989, Rahardjo et al 1989). In view of this, the device is considered to be quite useful for the purposes of pavement structural design and rehabilitation.

The AGWA-II thermal conductivity suction sensor used in this study is a commercially available sensor. This sensor consists of a porous ceramic block that contains a temperature sensing element and a miniature heater, shown in Figure 2. The operation of the sensor is based on the principle of heat dissipation in a porous medium. The rate of heat dissipation depends on:

i. the thermal conductivity of the solid matter and of the water,
ii. the mass of the solid and of the water.

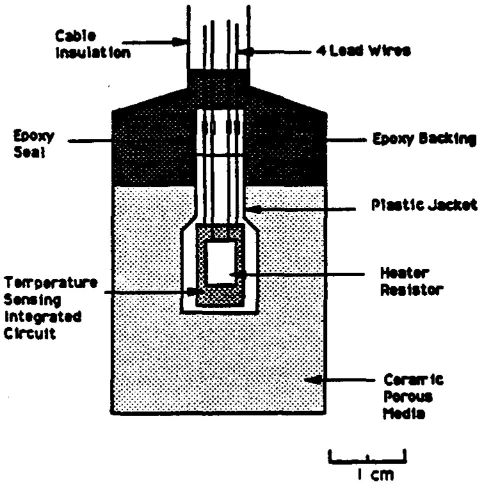


FIGURE 2 : AGWA - II SENSOR

The thermal conductivity of air is small and can be neglected. Since for a particular sensor, the mass of the solid matrix is constant, the rate of heat dissipated within the solid matrix will also be constant. Therefore, changes in the rate of heat dissipated in the sensor is proportional to the water content of the sensor.

When a sensor is inserted into a soil, water will move between the sensor and the soil until stress equilibrium is attained. The equilibrium water content of the sensor is an indication of the suction in the sensor and in the soil. Thus, the sensor indirectly measures the heat - dissipation capacity of the water content in the sensor tip. This is usually achieved by supplying a controlled amount of heat at the centre of the ceramic block, through the heating element, and then measuring the temperature rise at the same point after a fixed period of time. The change in temperature is a function of the water content which can be converted to matric suction through calibration.

4.2 Description of Apparatus and Calibration Procedure

The AGWA-II sensors were calibrated at the University of Saskatchewan. The experimental setup used for calibration is shown in Figure 3 (a). This setup consists of a 1500 kPa pressure plate extractor, a 25.4 cm diameter ceramic plate with a sheet - rubber backing, an insulated enclosure and a data acquisition system. The pressure plate was modified by adding a circular extension ring to the pressure chamber. Twelve circular holes were drilled along the side wall of the extension ring; these holes were required for the sensor cable to be brought outside the pressure chamber to be hooked up to the data acquisition system. Brass rings, along with split metal pieces and split rubber gaskets were arranged in such a manner that air leakage around the lead wires of the sensors could be eliminated. The air leakage was prevented by the rubber gaskets which were compressed to expand against the side of the hole and against the perimeter of the lead wire as the brass rings were tightened. The ceramic plate of the pressure extractor which has an air entry value of 500 kPa was also modified by installing an additional outlet. This modification was intended for the purpose of removing any entrapped or diffused air that may accumulate beneath the ceramic plate. The insulated enclosure was used to contain the entire pressure plate extractor in order to maintain the ambient temperature within the box at about 0.5 degree Celcius of mean room temperature. The data acquisition system used in calibration consists of a CR10 data logger, an AM32 multiplexor, an external D.C power source, a lap top PC computer and a computer software, the PC208. The software was used for programming the data logger. This system was used to record the response of the sensors in terms of ambient temperature and temperature differences.

A calibration soil mix that is composed of 10 percent Ottawa fine sand and 90 percent silt was used to provide contact between the thermal conductivity sensor tip and the ceramic plate. Good contact is essential to provide continuity between the water phase in the porous block and in the high air entry ceramic disk.

The ceramic plate was soaked in water for several days to ensure saturation. The AGWA-II sensors were also soaked in water to bring them to saturation. The calibration soil mix, prepared in a slurried form, was placed on the ceramic plate and contained in a lucite ring. The initially saturated sensors were directed through the extension ring holes and then the tips were pushed into the slurry mix. The spaces around the sensors lead wires were sealed by tightening the brass rings. The pressure plate was then closed, air pressure was applied and the whole assembly was checked for leakage.

After no leakage was ensured, calibration was carried out in matric suction increments of 50 kPa, starting from 0 kPa and going to a maximum of 400 kPa. This gave a nine point calibration curve for each sensor. At each pressure increment level, the response of each sensor was monitored until equilibrium was achieved. The sensor response for 0 and 50 kPa was monitored every half an hour. This time interval was increased to one hour for the subsequent pressure increments. Generally, equilibrium was achieved within a 2-day time period for each suction level.

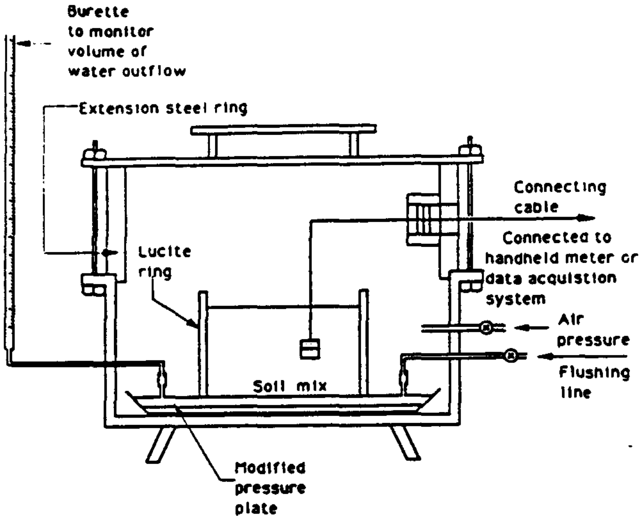


FIGURE 3 : CALIBRATION APPARATUS

4.3 Calibration Data

Figure 4 shows typical time response curves for the AGWA-II sensors for changes in applied suction during calibration.

The values of the delta T's at equilibrium for each applied pressure increment and the corresponding suction are used to plot the calibration curve for each sensor. These calibration curves were found to be nonlinear. Using the PC 208 software, second degree polynomial curves were found to suitably describe the behaviour of the calibration data. This is depicted in Figure 5.

4.4 Installation of the AGWA-II Sensors

The relative locations and depths of the twelve sensors that were installed for this project are as shown in Figures 6 (a) and (b). Previous experience had been that the most critical zone in which suction readings should be obtained is located within the upper 1.20 m of the subgrade soil layer. This within the depth of frost of 2.0 m that is frequently encountered within the Province of Alberta. With this in mind, it was decided to have the sensors installed at depths of 0.15, 0.30, 0.60, 0.85 and 1.15 meters from the top of the subgrade layer. Because of the practical difficulty involved in maintaining these depths for all sensors, a 5 to 15 % variation was considered acceptable. This is shown in Figure 6 (b).

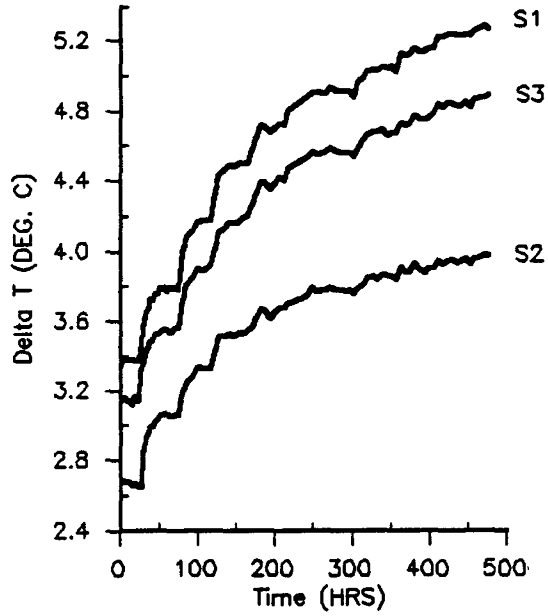


FIGURE 4: TIME RESPONSE CURVES (SENSORS 1,2,3)

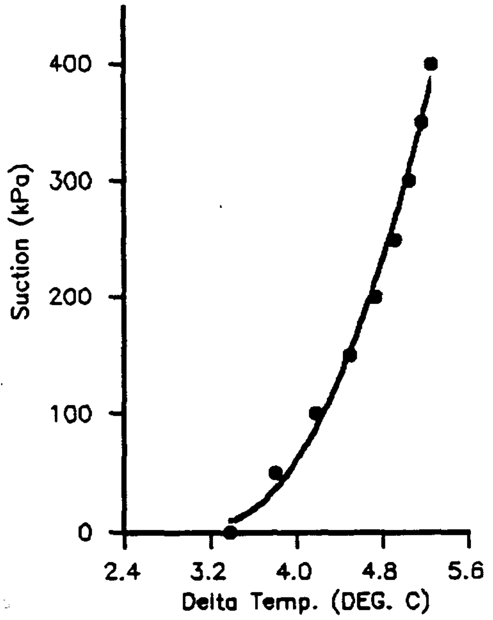


FIGURE 5: CALIBRATION CURVE (SENSOR 1)

A major concern about using the AGWA-II sensors is the installation procedure. It was noted before that a good soil-to-sensor contact is essential to obtain reliable suction measurements. This consideration coupled with the fact that the AGWA-II sensors are quite fragile, necessitates extreme care to be exercised when these sensors are being installed so as not to break them. One acceptable procedure for installing such sensors in the field involves excavating a trench or boring a large - diameter borehole to the required depth following which the sensors were to be installed into the side of the excavation by hand. But since a public highway is involved, this procedure was deemed to be too disruptive. As a result, an alternative method for installation was selected. A procedure that was used for installing some of these sensors in a project near Regina were adopted. The steps involved in this procedure were as follows (Klimochko 1990):

1. A hole 125 mm in diameter was bored through the asphalt concrete pavement and into the subgrade approximately 300 mm above the required depth that the sensor was to be placed at. This was done using a drill rig.

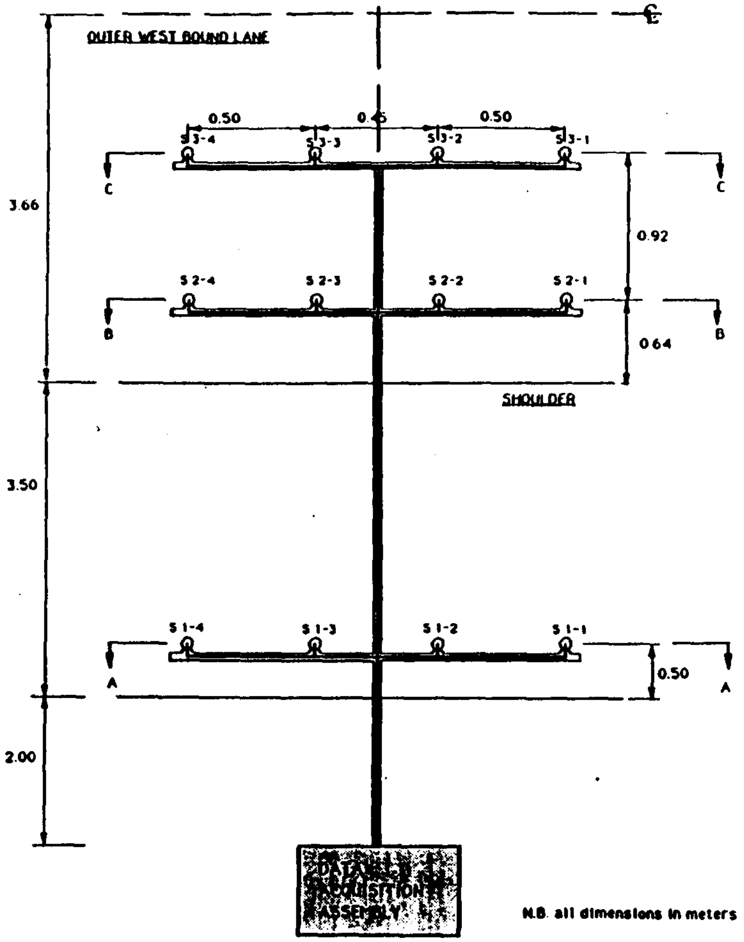


FIGURE 6 (a): INSTRUMENTATION LAYOUT

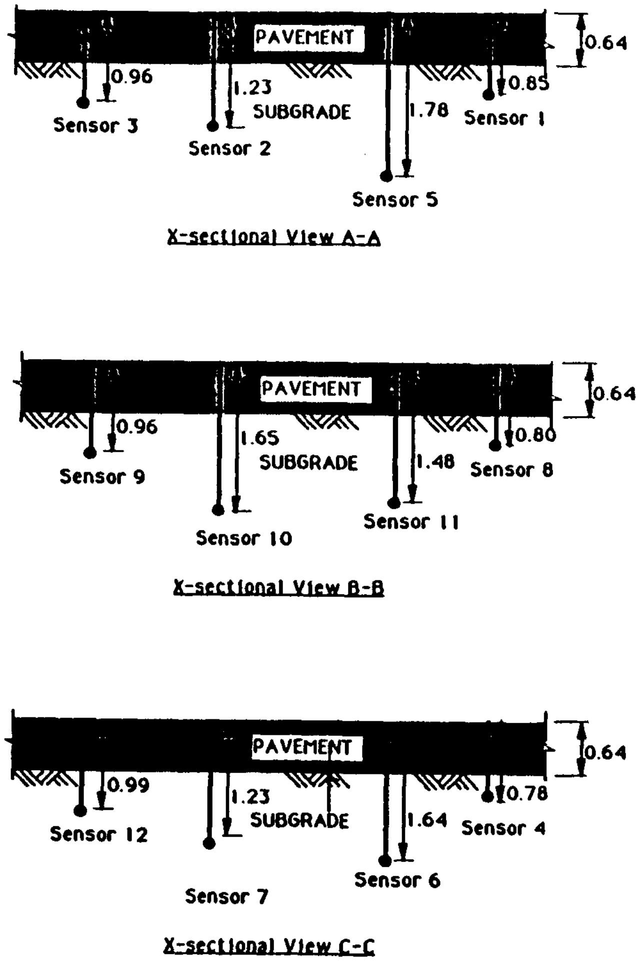


FIGURE 6 (b): SENSORS DEPTH LOCATIONS

2. A 75 mm diameter Shelby tube was pushed to obtain a soil sample extending from the bottom of the borehole down to the depth at which the sensor was to be placed. This was also expected to produce a flat surface for installing the sensor.

3. A hole at the bottom of the Shelby spoon sample cavity was then punched for fitting the sensor into. A sledge hammer and a rod whose end was equipped with an adapter similar in diameter and length to that of the sensor was used. Care was taken not to make the punched hole any deeper than necessary. The length corresponding to the required depth of the tip of sensor, was marked on the installation rod. By driving the rod to the marked length, a punched hole with an exact depth was obtained. This was done to ensure that the bottom of the sensor when inserted would be in full contact with the soil.

4. The sensor was inserted using a special wire rod. This rod was approximately 9 mm in diameter with one end bent out 90 degrees, approximately 40 mm and then bent again so as to form the letter "c". The sensor was held against the wire rod by pulling back on the electrical cable while it was being guided into the punched hole located in the bottom of the Shelby sample cavity. After the sensor was inserted into the punch hole, the technician pushed gently on the insertion rod to ensure that good sensor-to-soil contact was made. The recommendation to install the sensors in saturated condition was not followed because of the time constraint during the installation phase. The compromise would be that sensors would come to equilibrium rather slowly.

5. After the sensor was installed in the punch hole, dry powdered kaolin was backfilled into the hole to approximately 75 mm above the sensor. The fact that the kaolin backfill was dry is important in that it was done so as to ensure that the backfill be void - free to provide for a good sensor-to soil contact. It is to be noted, however, that one disadvantage of using dry kaolin is that it is not at the same moisture equilibrium as the surrounding clay soil in the vicinity of the sensor. This might result in some moisture transfer which in turn could affect the sensor readings in the process. However, it was believed that the advantage of the void-free backfill far out weighs the disadvantage of the soils being at different moisture contents. Moreover, with time the dry kaolin will come to equilibrium with the surrounding clay.

6. The remainder of the hole up to the top of the subgrade was backfilled with a crumbly clay material similar to that at the site. The moisture content of this backfill material was appreciably less than that existing in the in situ material. The dryer soil was used to overcome the backfilling problem.

7. After all the sensors were installed at the desired depths and locations, a series of trenches for laying the cable from

each sensor to the location of the data acquisition box were cut into the pavement to a depth of approximately 50 mm. The data acquisition system was placed in a water-tight box, at 2.0 m from the outside shoulder edge on the north side slope.

8. After the cables from the sensors were laid in the trenches, the trenches were backfilled with a granular material and were topped off with some cold-mix patching material.

9. The ends of the electrical cables coming out of the trenches were then connected to the appropriate terminals of the AM32 multiplexor residing inside the data acquisition box. The PC208 software was used to download the program that will commence data monitoring and collection.

5.0 DATA COLLECTION AND MONITORING

The same data acquisition system used during the calibration phase was used for the field monitoring phase. Two external batteries for powering up the system were used to replace the D.C power supply. The whole assembly was placed in a water tight container. This is done to prevent moisture from getting inside the box and damaging both the data logger and the multiplexor. The PC208 software was used to program the CR10 unit to record temperature and moisture suction measurements every two hours. This is synchronized to reflect real time (instantaneous) measurements.

The installation of the twelve thermal conductivity gauges was completed on November 7th, 1990. Since then monitoring and collection of both temperature and matric suction data have been performed on a regular basis. A four - week period was found adequate for site visits to retrieve the data. This is determined in view of the fact that the external batteries should be recharged once every month to maintain the data being collected.

Temperature and suction data collected between Nov.7, 1990 and Apr.6, 1991 have been processed and plotted in Figures 7 and 8.

6.0 INTERPRETATION AND DISCUSSION OF FIELD RESULTS

Figures 7 and 8 display the variations of temperature and soil suction with time at various depths and locations within the subgrade layer. It is to be noticed that all sensors appear to respond in a similar manner. As the temperature decreases from above freezing to below freezing, matric suction drops sharply and then increases rapidly to approximately the same values. This observation is in good agreement with the findings of a recent laboratory study aimed at investigating the suitability of thermal conductivity sensors for measuring negative pore-water pressures in a freezing (Fredlund et al 1991). This phenomenon is attributed mainly to the tendency of the water within the porous block of the sensor to maintain a constant temperature during the phase transformation.

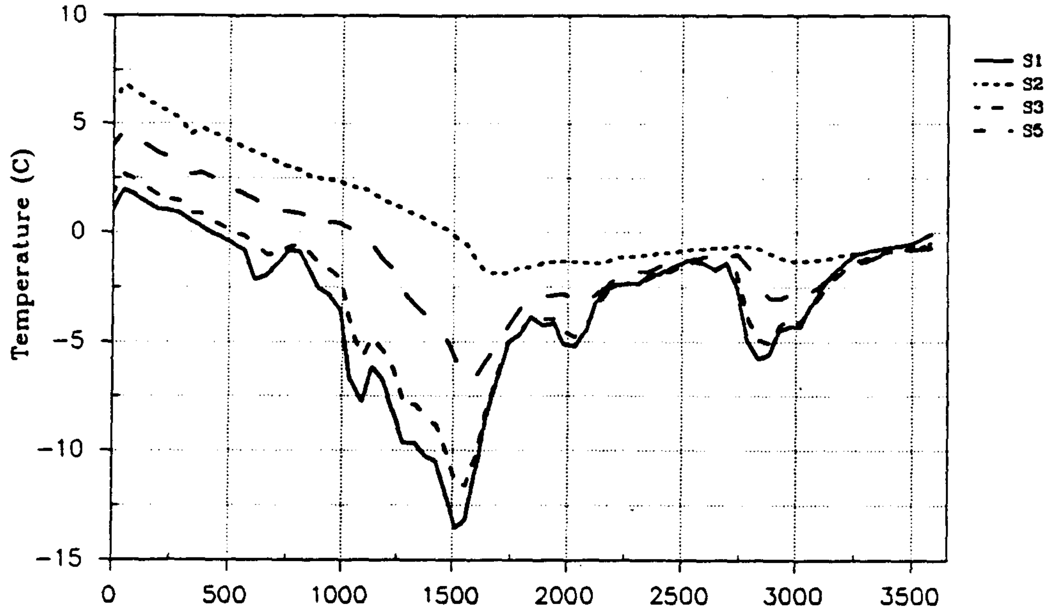


FIGURE 7(A): VARIATION OF TEMPERATURE WITH TIME FOR SENSORS 1,2,3,5

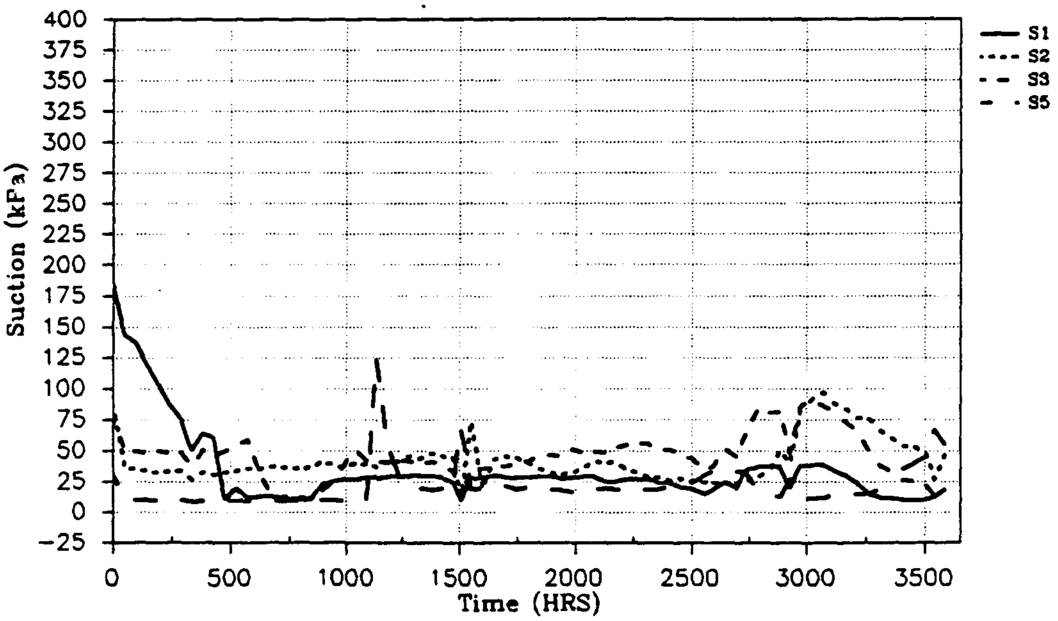


FIGURE 7(B): VARIATION OF MATRIC SUCTION WITH TIME FOR SENSORS 1,2,3,5

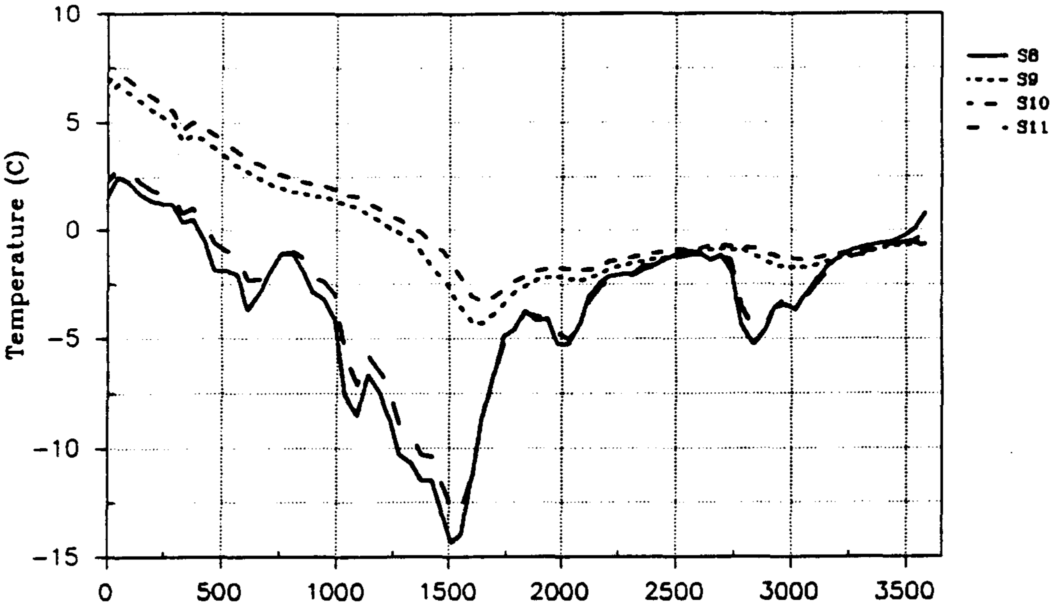


FIGURE 8(A): VARIATION OF TEMPERATURE WITH TIME FOR SENSORS 8,9,10,11

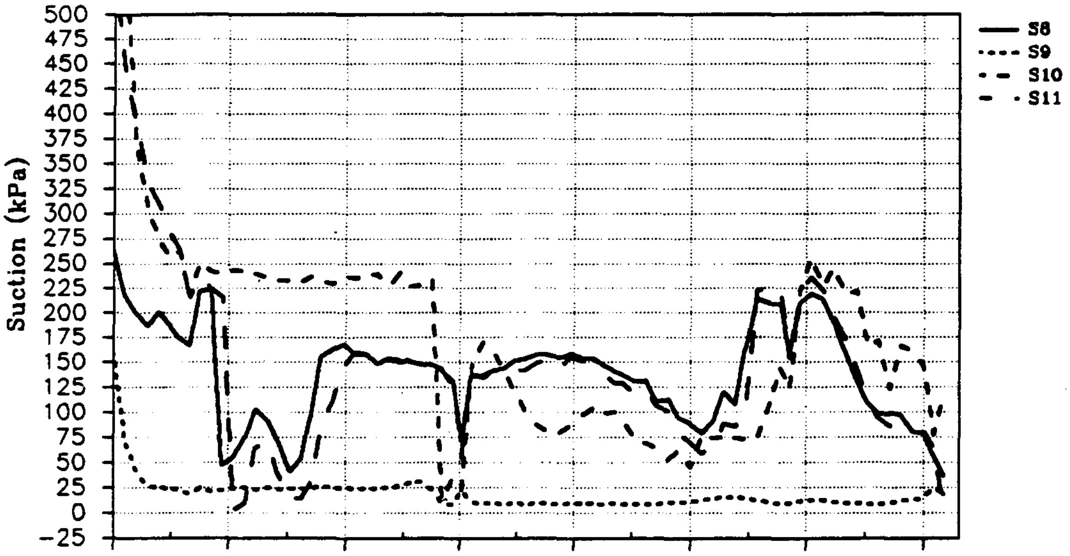


FIGURE 8(B): VARIATION OF MATRIC SUCTION WITH TIME FOR SENSORS 8,9,10,11

This is demonstrated by the sudden drops in soil suction readings as the temperature decreases to zero degrees Celcius. On the other hand, the rapid increase in suction observed after that can be attributed to the fact that major proportion of the water in the sensor has frozen. This means higher apparent suction values due to the greater thermal conductivity of ice as compared to water.

From Figures 7 (b) and 8 (b), it is evident that there are more variations in suction readings obtained from within the west bound lane than from the outside shoulder. The reason for this is still unknown.

7.0 SUMMARY AND CONCLUSIONS

This paper is aimed at documenting the research efforts pertaining to the use of thermal conductivity sensors for monitoring temperature and moisture variations within a typical subgrade material that is commonly found in Alberta. In particular, the emphasis is on identifying and quantifying the seasonal variational factors that affect the pavement structural capacity. This involved instrumenting a pavement section on a Primary Highway with twelve thermal conductivity suction sensors at various depths.

A practical installation procedure has been developed to cater for the fragile materials of the thermal conductivity sensors. This procedure was built on some guidelines that have been used before in a similar installation near Regina.

An automated data acquisition system for monitoring the sensors response has also been developed. This system consists of a data logger, a multiplexor, two D.C. batteries, a relay driver and a 10V D.C. voltage regulator. This system has been used successfully for monitoring the response of the sensors. Data retrieval and reduction have been in effect since installation in November 1990.

Results obtained so far supports findings that has been reported by other researchers. The AGWA-II thermal conductivity sensors have been confirmed as potential devices for measuring soil matric potential under freezing and non-freezing environmental conditions. These test methods coupled with the use of non destructive pavement tests and/or laboratory tests are expected to be useful tools for better design and rehabilitation of flexible pavement structures situated in areas subjected to seasonal frost.

The results presented in this paper are still preliminary and further interpretation at a later time is expected.

ACKNOWLEDGMENTS

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