Monitoring Soil Suction in an Indoor Test Track Facility

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Tests on a full-scale pavement were conducted in an indoor controlled environment, the pavement track testing facility operated by the Saskatchewan Department of Highways and Transportation. The tests were conducted to evaluate the performance and reliability in using thermal conductivity sensors to measure matric suction in the subgrade under field conditions. Thermal conductivity sensors were installed at various locations and depths to monitor the matric solutions under the pavement structure. The thermal conductivity sensors were found to produce reliable and stable readings of the in situ matric suction over a long period of time. The effects of repetitive wheel loadings as well as ponding of the side slopes were investigated.

Highway embankments are elevated earth structures. The subgrades of the embankment are nearly always unsaturated. A knowledge of the negative pore-water pressures is necessary to the understanding of the behavior of the subgrade soils with respect to shear strength, volume change, and flow (*1*,*2*).

Thermal conductivity sensors appear to be a promising device for measuring matric suction. Two types of thermal conductivity sensors are currently available. One type uses a thermocouple; the other uses an integrated circuit as the temperature-sensing device. The integrated circuit-type sensors were used in this research program. A cross-sectional diagram of an integrated circuit–type thermal conductivity sensor is presented in Figure 1. The thermal conductivity sensor uses an indirect method for measuring matric suctions on the basis of thermal conductivity of a standard porous ceramic. The development of the thermal conductivity sensors has been discussed by Fredlund (*3*).

OBJECTIVE OF RESEARCH

The objectives of this program were as follows:

1. To evaluate the use of thermal conductivity sensors for measuring matric suctions in pavement subgrades over a long period of time,
2. To evaluate the effect of repetitive wheel loadings on the pavement structure and on the in situ matric suctions in the subgrade, and
3. To evaluate the response of the pavement structure and the in situ matric suctions of the subgrade to the ponding of water against the sideslopes of the embankment.

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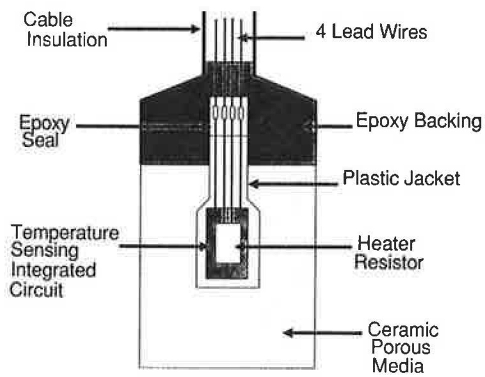

FIGURE 1 Cross-sectional diagram of integrated circuit–type thermal conductivity sensors.

When a new sensor is being evaluated for its acceptability in measuring matric suction, it is important that laboratory studies be done on the sensor before its installation in situ. Many laboratory studies have been done on the thermal conductivity sensors, and their performances have been quite promising (*4*). It is fitting that the sensors be installed in the indoor test track for a study of their performance because this facility has a controlled environment. An evaluation can then be done on the acceptability of using these sensors in situ installations in highway subgrades.

DESCRIPTION OF TEST TRACK FACILITY

The test track facility of the Saskatchewan Department of Highways and Transportation is located in Regina, Saskatchewan, Canada. The facility is housed in a fully insulated, dome-shaped, ribbed-plywood building. The circular track is 15.84 m in diameter and is divided into five segments. These are labeled as Segments 0, 1, 2, 3, and 4 in Figure 2.

Segments 0, 2, 3, and 4 have concrete barrier walls that confine the track. Segment 1 has an unconfined outer sideslope that allows for the simulation of a typical shoulder with a sideslope embankment configuration. Only Segment 1 was instrumented for this study.

The test track carries normal dual-wheel tires mounted on a single-arm, twin parallel I-beam gantry. The lateral position of the wheels can be varied to simulate actual field conditions, because vehicles tend to wander across the width of the driving lane. The system can apply loads of up to 54 kN and can operate at speeds up to 32 km/hr. In this program, a wheel

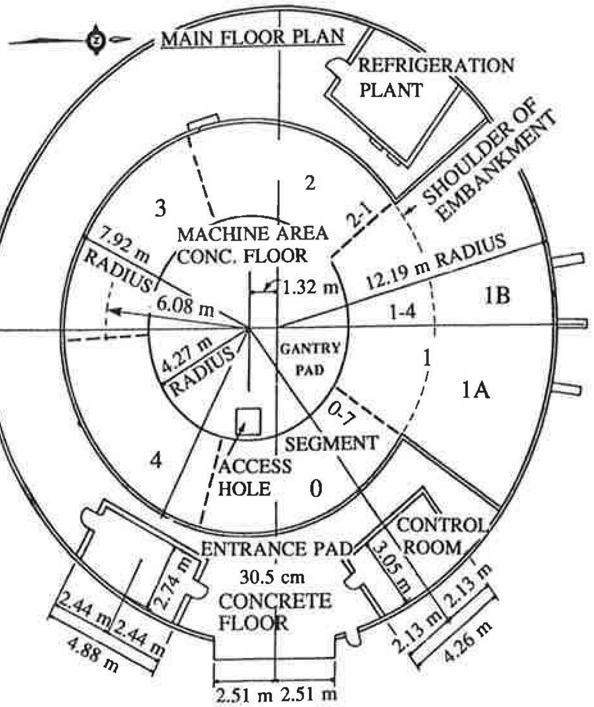

FIGURE 2 Plan of Saskatchewan Department of Highways and Transportation test track facility.

load of 40 kN and a tire pressure of 350 kPa were used with a speed of 6 to 7 km/hr.

SUBSOIL PROFILE AND INSTALLATION OF INSTRUMENTATION

Segment 1 was constructed with a sideslope of 4:1 and was divided into two sections: Section 1A and Section 1B.

In Section 1A, the foundation material consists of 300 mm of sand underlain by 900 mm of highly plastic Regina clay. The upper 300 mm of the Regina clay was compacted to 100 percent maximum standard ASSHTO density. The lower 600 mm of the Regina clay was compacted to 95 percent maximum standard AASHTO density. Below this structure was another 500 mm of Regina clay, which was nominally compacted.

The foundation soil in Section 1B was made up of 1200 mm of a glacial till from the Indian Head area. The upper 600 mm of the till was compacted to 100 percent maximum standard AASHTO density. The lower 600 mm of the till was compacted to 95 percent maximum standard AASHTO density. This section was also underlain by 500 mm of nominally compacted Regina clay.

The Regina clay has a liquid limit of 66.5 percent, a plasticity index of 34.0 percent, and standard AASHTO maximum dry density of 1.410 mg/m^3 at the corresponding optimum water content of 28.0 percent. The Indian Head till has a liquid limit of 34.5 percent, a plasticity index of 14.4 percent, and standard AASHTO maximum dry density of 1.765 mg/m^3 at the corresponding optimum water content of 17.0 percent.

Both sections 1A and 1B were placed on 200 mm of sand with an embedded plastic membrane. On the top, both sections were overlaid with 40 mm of hot-mix asphaltic concrete.

Nineteen thermal conductivity sensors were installed in Section 1A and 1B. The locations of the 19 sensors are shown in Figure 3. The installation of the sensors proceeded as follows. First, a 76-mm-diameter hole was drilled vertically to within 50 mm of the intended level of the sensor. A smaller hole, the size of the sensor (which is 25 mm in diameter) was then drilled from the base of the 76-mm-diameter hole. The hole was cleaned using compressed air before the sensor was gently pushed into place in the smaller hole. This mode of installation ensured good contact between the sensor and the soil. The hole was backfilled in layers with cuttings from the drilling operation and was compacted with a compaction hammer.

The sensors were installed dry in each of the prepared drill holes. There were, however, some exceptions. Before the sensors were installed in some of the deep holes (e.g., Sensors

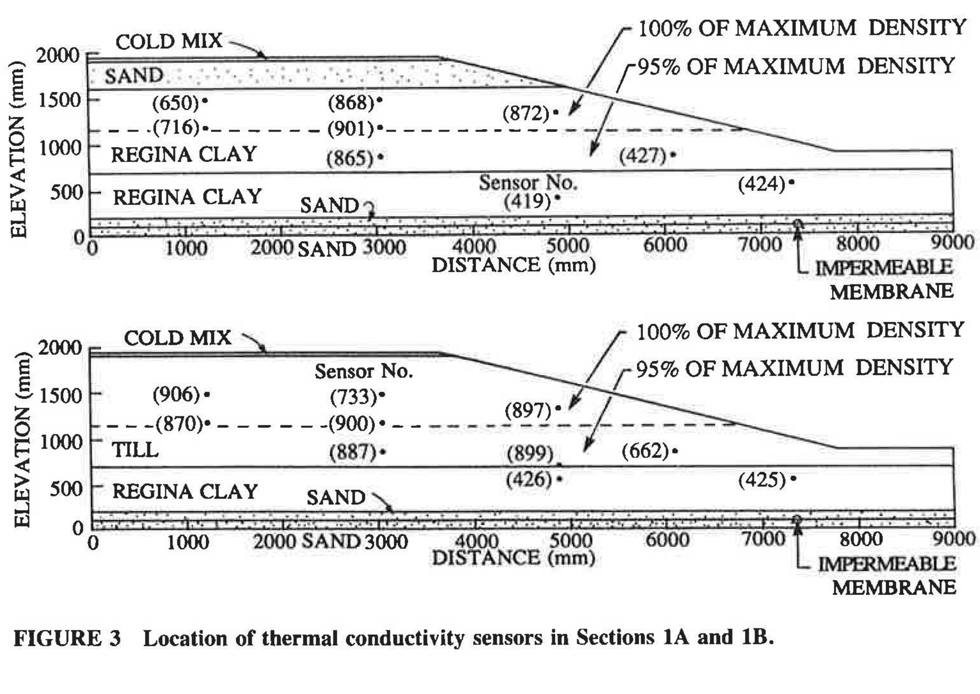

FIGURE 3 Location of thermal conductivity sensors in Sections 1A and 1B.

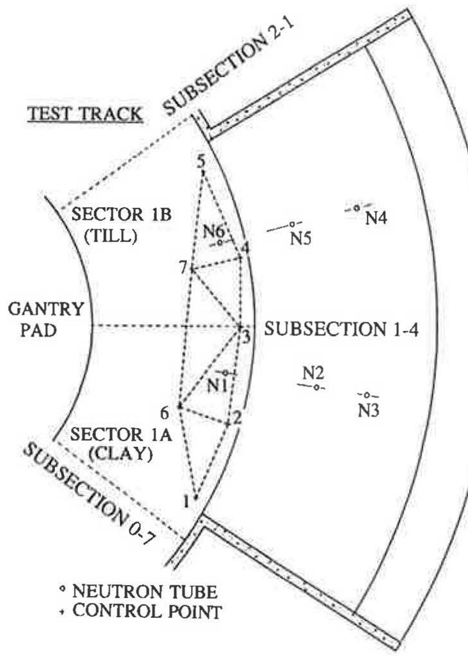

FIGURE 4 Location of neutron tubes and survey control points.

419, 427, 424, 426, and 425), some water was added to the hole. This unfortunate procedure was adopted at the discretion of the on-site engineer because of the difficulty of installation at those depths.

Six neutron tubes were installed for water content measurements. Seven survey control points, each consisting of a 100-mm-long nail driven through the pavement surface, was established to monitor movements. The locations of this instrumentation are shown in Figure 4.

DESCRIPTION OF TESTS

Installation of the thermal conductivity sensors was completed on July 15, 1987. Suction readings were taken immediately and monitoring was continued for more than a year before the first wheel load test. The wheel load test consists of running the dual wheels at speed of 6 to 7 km/hr. The load on the dual wheels was 4000 kg (9000 lb), and the tire pressure was 350 kPa (50 psi). During the initial monitoring period, an automated data acquisition system was used to read the thermal conductivity sensors on an hourly basis.

The preliminary wheel load test was commenced on July 27, 1988. During this period the automated data acquisition system was programmed to record matric suction readings at the 100th, 200th, 400th, 800th, and 1,600th passes of the wheels. However, at the 58th pass excessive deformation of the subgrade occurred in Section 1B (till section) near the interface with Segment 2. The test was terminated to allow for the repair of the track.

Wheel load tests were resumed on October 17, 1988. This test continued to 613 passes, and excessive deformations of up to 25 mm were evident near the end of Section 1B.

Water was introduced into the ditch in Sections 1A and 1B. It took approximately 66 min to raise the water level to within 150 mm below the upper sand layer of Section 1A. In other words, no water was allowed to enter the upper sand layer just below the asphaltic pavement in Section 1A. The water level was checked frequently to ensure that it was maintained at the required level.

The area was drained on January 16, 1989, by pumping water from the flooded area. The water was discharged outside the building. Draining was completed in about 60 min.

A second wheel load test was performed on February 15, 1989. In this test, excessive deformations occurred in Section 1B. Excessive deformations also occurred at the boundary of Sections 1A and 1B after about 155 wheel passes. The deflection and the rebound of the pavement was as much as 20 mm.

PRESENTATION OF RESULTS

Long-term, stable measurements were obtained from the thermal conductivity sensors. Some typical data obtained over a monitoring period of 1 year are presented in Figures 5, 7, and 8. These data were collected before the wheel loading tests and the infiltration test.

The data presented in Figure 5 were from sensors installed in the Indian Head till subgrade in Section 1B. The sensors were initially air-dried and were installed in dry holes. The average water content of the till measured at that time was 11 percent. This water content is lower than the as-built water content of 18 percent, indicating that significant drying of the subgrade had occurred since the section was constructed. A water content of 11 percent corresponds to a matric suction value of about 110 kPa (Figure 6). The sensors took in water from the surrounding soil, and the matric suction of the sensors decreased until equilibrium was established between the sensors and the soil. With the exception of Sensors 897 and 733, stable consistent matric suction values of about 50 to 100 kPa were recorded. The higher matric suction values recorded by Sensors 897 and 733 could be due to the soil's being drier at these locations or to faulty functioning of the sensor. Sensor 897 was near the exposed sideslope, and Sensor 733 was near the edge of the pavement, fairly close to the exposed sideslope. Water may have been lost from the soil at these locations because of evaporation, resulting in increased matric suction values.

The data presented in Figure 7 were from sensors installed in the Regina clay subgrade of Section 1A. Again these sensors were installed in an air-dried state into dry holes. The long-term equilibrium matric suction values recorded by the sensors installed in the Regina clay subgrade of Section 1A were from about 400 to 500 kPa. These measurements were near the upper limit of the range of the sensor. The average water content measured was 15 percent, which was much lower than the as-built water content of 28 percent. This confirmed that significant drying of the subgrade had occurred since the section was constructed.

Sensor 865 recorded a consistently lower matric suction value of between 200 and 250 kPa. This could be due to the soil's being wetter at the location of Sensor 865. Sensor 650 recorded matric suction values of approximately 400 to 425 kPa over about 250 days. The matric suction then decreased to a value of about 200 kPa and remained at that value for about 100 days before increasing and approaching the initial record value of about 400 kPa. Sensor 650 was located just

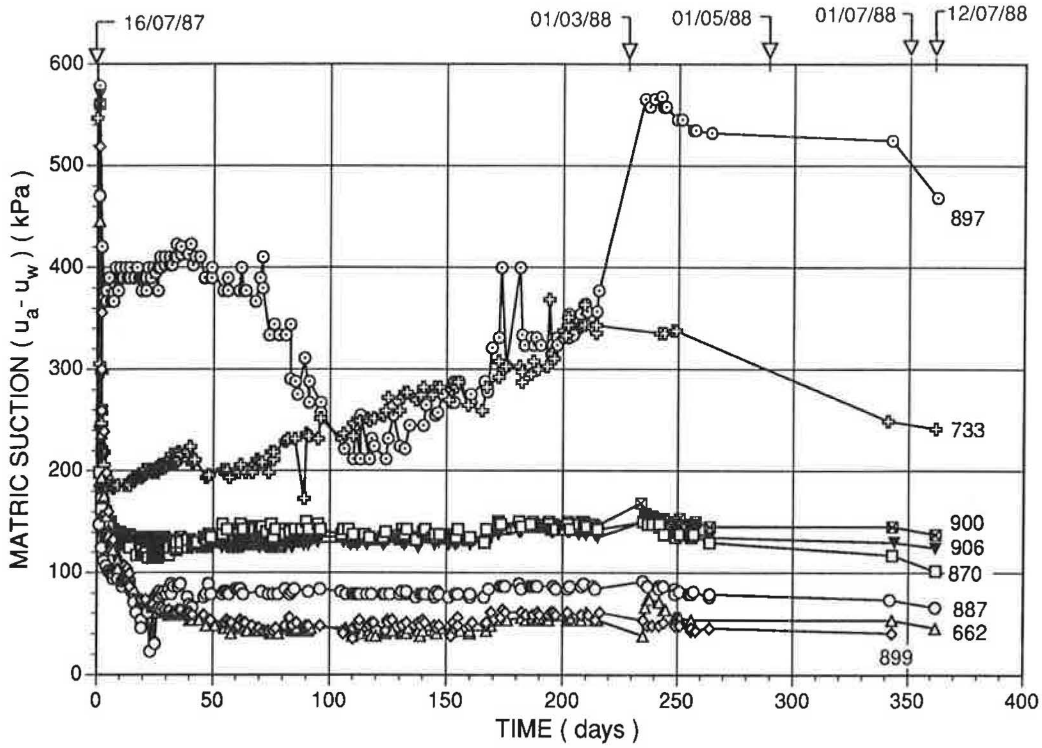

FIGURE 5 Long-term matric suction readings in till subgrade of Section 1B.

below the upper sand layer and was close to the surface. The reduction in matric suction may have been due to the accidental spillage of water on the pavement and the eventual seepage of the water to the sensor location. This suggests the possible existence of cracks in the pavement structure.

Data from sensors that were installed with prior wetting of the bottom of the drillholes are presented in Figure 8. The matric suction values were observed to decrease rapidly to values of less than 30 kPa and remained low over the entire monitoring period. The prewetting of the hole was an unfortunate innovation to the installation procedure inasmuch as the added water appeared to redistribute slowly throughout the soils.

The responses of the thermal conductivity sensors during the filtration test are presented in Figures 9 and 10. Data

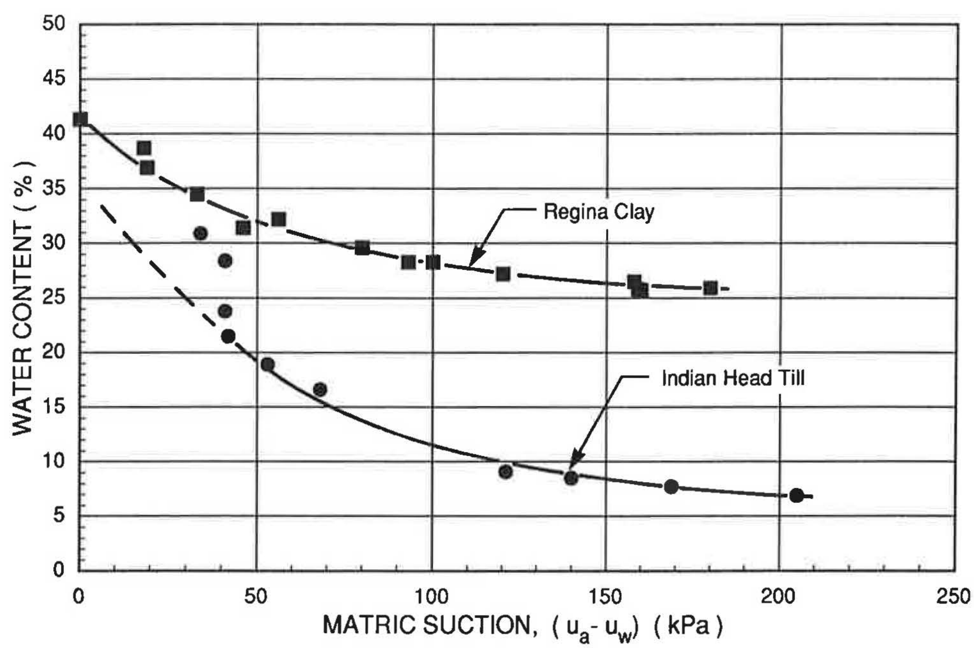

FIGURE 6 Water content-versus-matric suction relationships of slurried samples of Regina clay and Indian Head till.

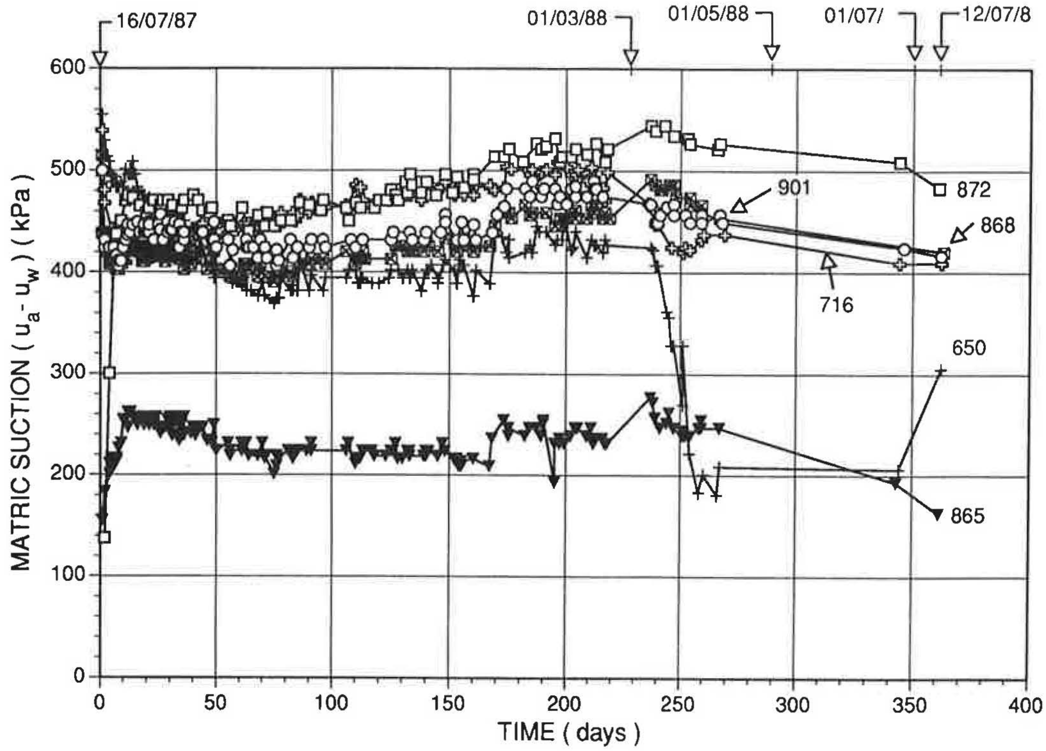

FIGURE 7 Long-term matric suction readings in Regina clay subgrade of Section 1A.

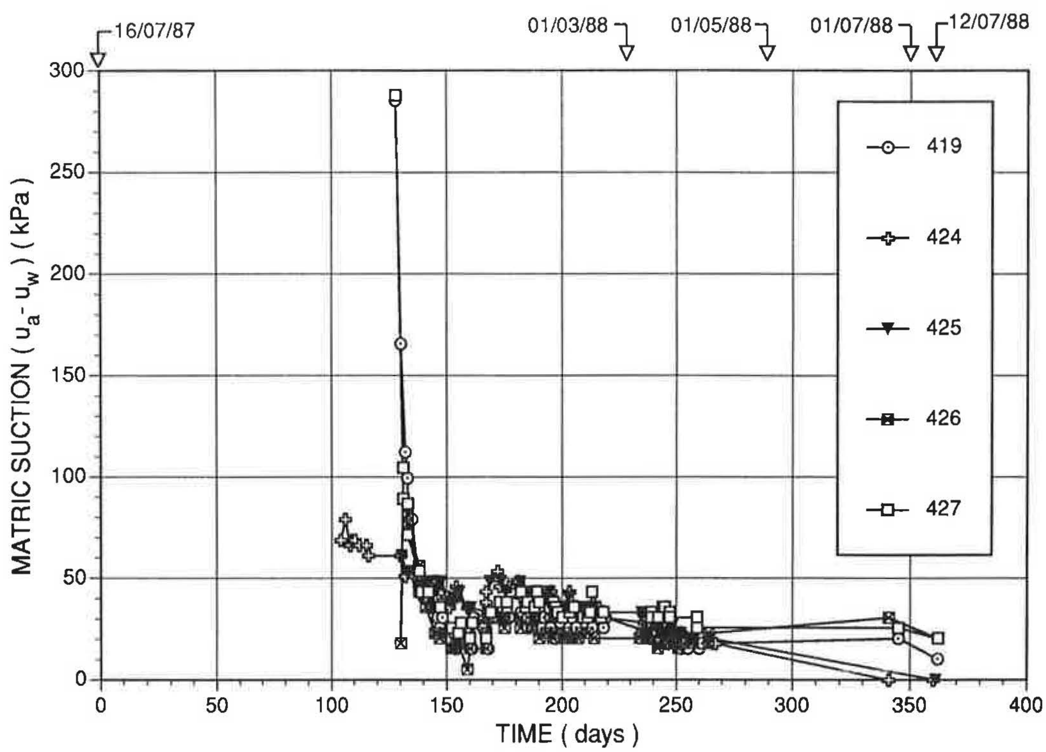

FIGURE 8 Long-term matric suction readings from thermal conductivity sensors installed in prewetted holes.

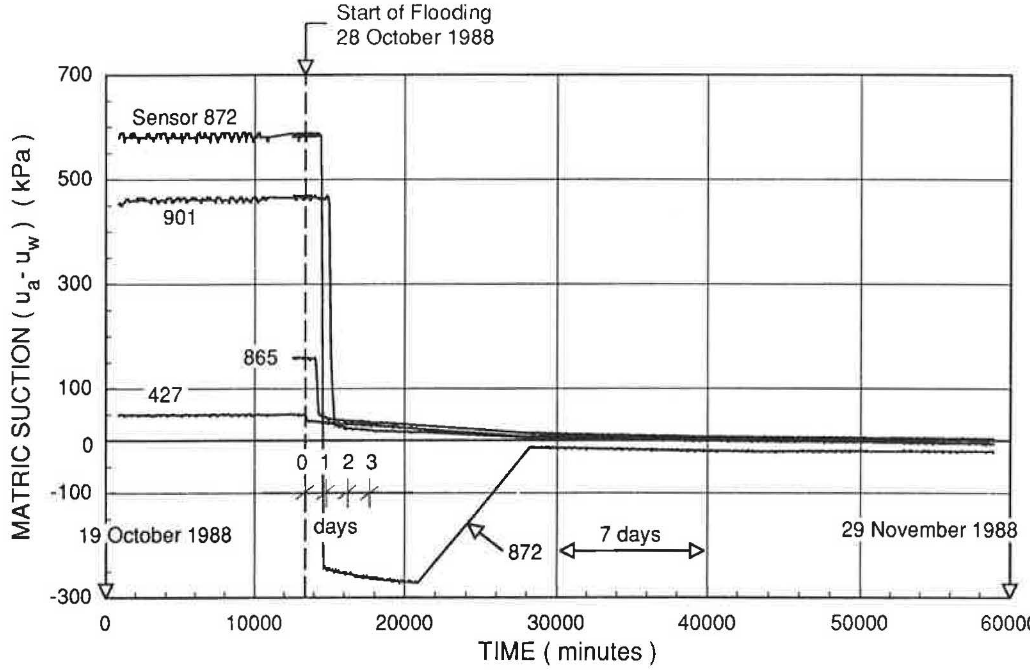

FIGURE 9 Responses of thermal conductivity sensors in Section 1A to infiltration test.

presented in Figure 9 were obtained from sensors located in the Regina clay subgrade of Section 1A. The responses of these sensors showed that the water traveled to the sensor locations in a matter of a few hours to a day after flooding. The matric suction values decreased to zero rapidly (less than one hr, in some cases). The high flow of water suggests an extensive network of secondary desiccation cracks in the clay. Extensive cracks will lead water into the sand layer at the base, conveying water rapidly to the interioı section of the subgrade. In addition, observations made during the excavation to retrieve the sensors at the end of the program showed that there were preferential flows along the wires leading to the sensors. This was probably due to a poor backfilling procedure for the sensors.

In Section 1B, the responses of the sensors were more varied; some sensors showed a considerably slower and more

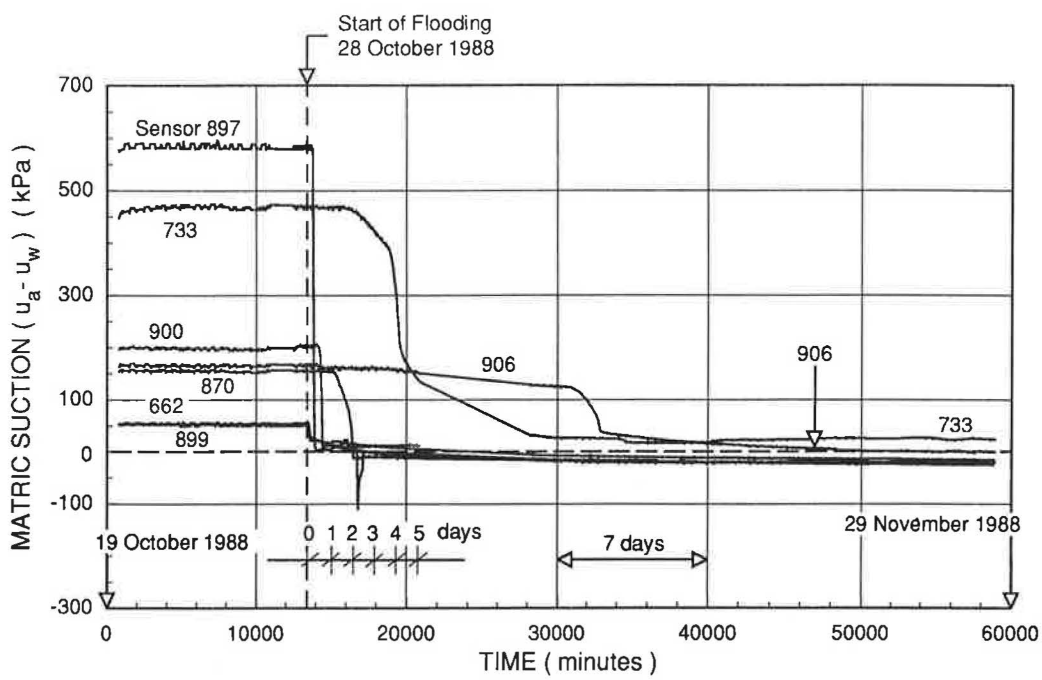

FIGURE 10 Responses of thermal conductivity sensors in Section 1B to infiltration test.

gradual infiltration of water to the sensor locations (Figure 10). The rapid reduction in matric suction recorded by Sensors 899 and 662 suggests that there was preferential flow along the till-clay interface. Sensors 899 and 662 were in the till, close to the till-clay interface. Sensors 897 and 900 also registered a rapid response. Sensor 897 was located near the sideslope, and Sensor 900 was about 500 mm above the till-clay interface near the edge of the pavement structure. Sensors 733, 870, and 906 showed a gradual wetting, taking from 2 days to about 2 weeks to reduce to zero suctions. These sensors were located farthest from the sideslope and from the sand base. It may thus be concluded that secondary desiccation cracking is less widespread in the till than in the clay.

Heave measurements were conducted throughout the ponding period. The results are presented in Figure 11. Results show that the swelling potential of Regina clay is substantially greater than that of Indian Head till. Cracks were observed on the pavement. Cracking was found to be more severe in Section 1A, which was constructed over the Regina clay subgrade. Cracks were as wide as 5 mm.

Neutron probe water content measurements obtained for the period of November 20, 1989, to February 16, 1990, confirmed that the soils were saturated as a result of the infiltration test.

The average initial water content of the upper clay layer in Section 1A before the infiltration test was about 15 percent. Neutron probe measurement after infiltration test showed that the water content had increased to about 40 percent (Figure 12) at elevations below the maximum ponding water level, which was at an elevation of 1600 mm. This corresponds closely to the saturation water content of the clay (a water content of 40 percent at saturation gives a void ratio of 1.1 assuming a specific gravity of 2.7 for the solids). Water content versus matric suction relationships presented in Figure 6 showed that Regina clay had zero matric suction when the water content reached about 40 percent. This relationship was obtained from slurried samples using thermal conductivity sensors for the matric suction measurements. The water contents obtained using the neutron probe device agreed well with the gravimetric water content measurements conducted on samples retrieved near the neutron tube locations on February 15, 1989, 1 day before the draining of the sideslopes. Sample C12 was taken from an elevation of approximately 1180 mm near Neutron Tube 1, and Sample C22 was taken from an elevation of about 1200 mm near Neutron Tube 2 (Figure 12). These samples showed water contents of 42.3 and 41.8 percent, respectively.

In the till section (i.e., Section 1B), the average initial water content before ponding was about 11 percent. Neutron probe measurements after the infiltration test showed that the water content had increased to values of 20 to 30 percent. Water content–versus–matric suction relationships presented in Figure 6 showed that the till had matric suction values of zero when the water content reached about 30 percent. At Neutron Tube 5, which is on the sideslope, water contents of about 30 percent were measured (Figure 13). Water content data at elevations 1612 and 1460 mm indicated that the soil near the surface was drying out. The wetting of the soil at these elevations, after drainage of the sideslope, might have been caused by the spraying of the pavement surface with water (for an unknown reason). Neutron Tube 6 was within the asphalt pavement section. Water content measurements from Tube 6 showed that the soils became progressively drier toward the surface, which is to be expected because of evaporation.

Matric suction values of less than zero were recorded for some of the sensors after ponding. Thermal conductivity sensors measure matric suction indirectly by correlating the temperature rise when a controlled heat pulse is applied for 1 min. In the integrated circuit–type thermal conductivity sensor, the temperature rise is converted into a voltage reading. The calibration curve of a sensor used in this program is

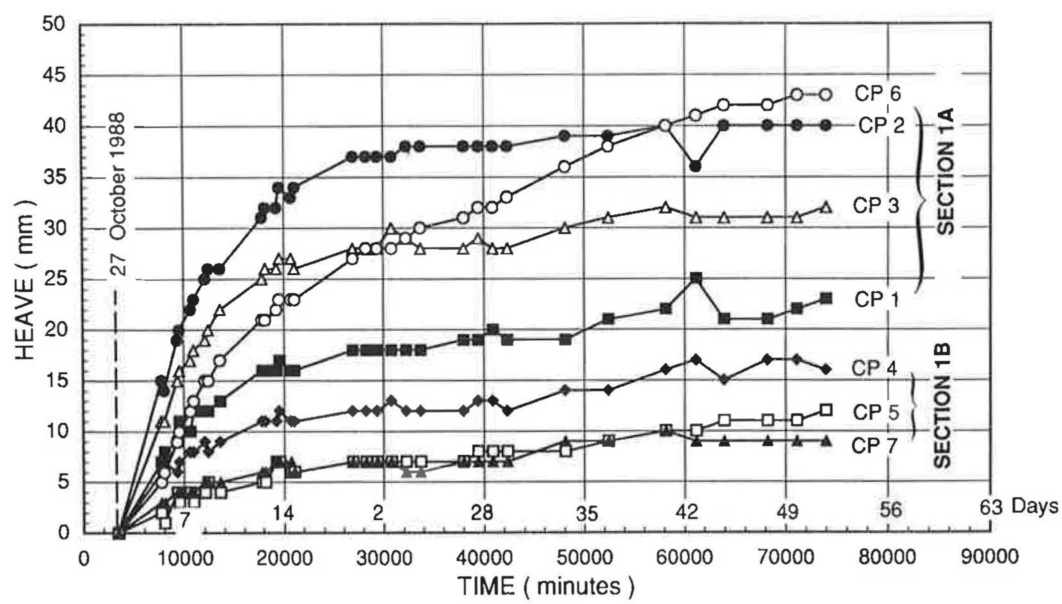

FIGURE 11 Heave measurements in Sections 1A and 1B.

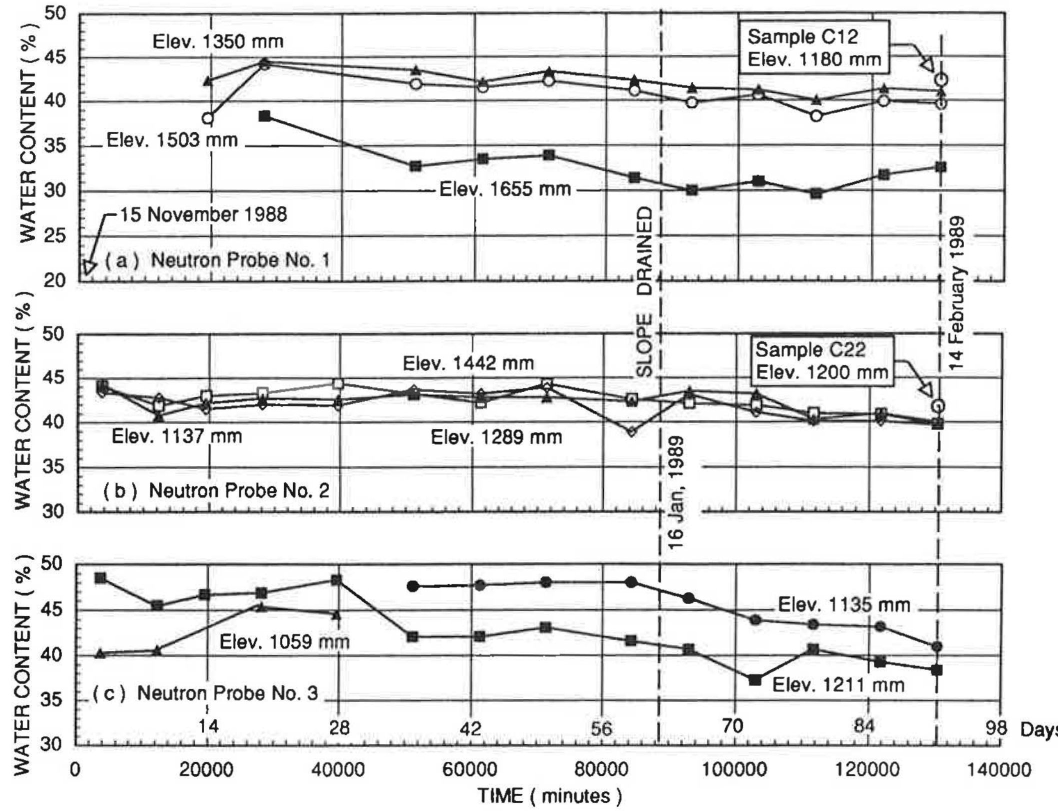

FIGURE 12 Neutron probe water content and gravimetric water content measurements in Section 1A.

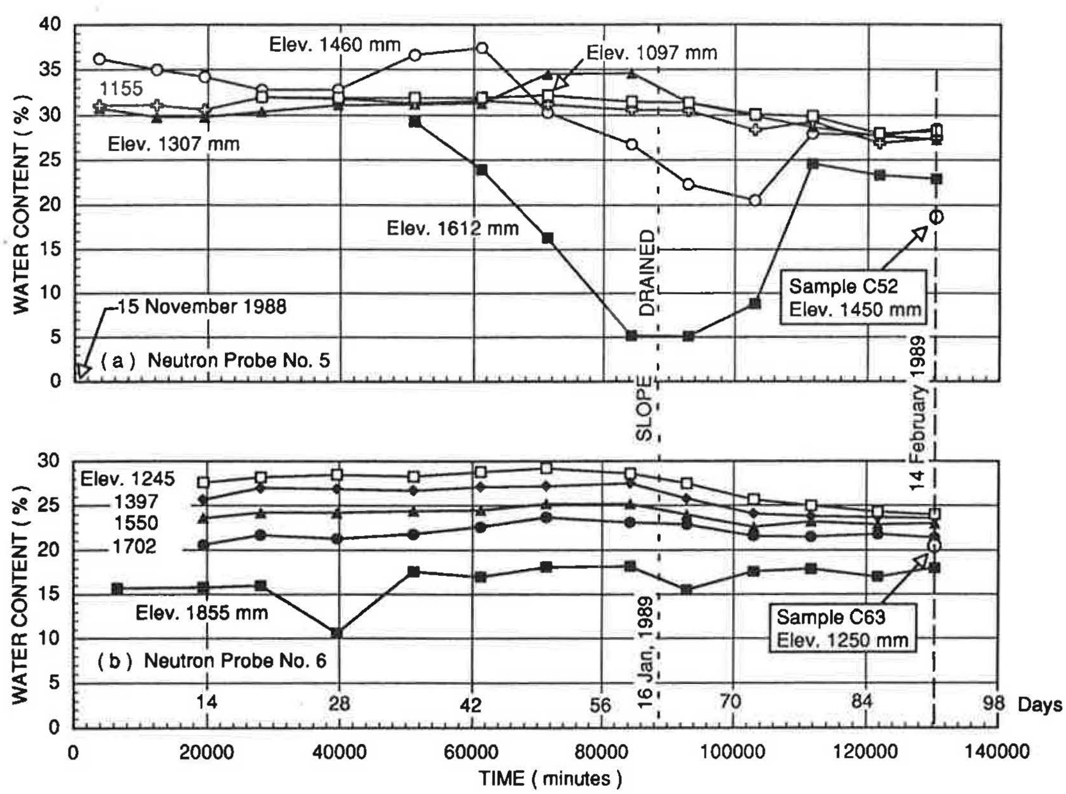

FIGURE 13 Neutron probe water content and gravimetric water content measurements in Section 1B.

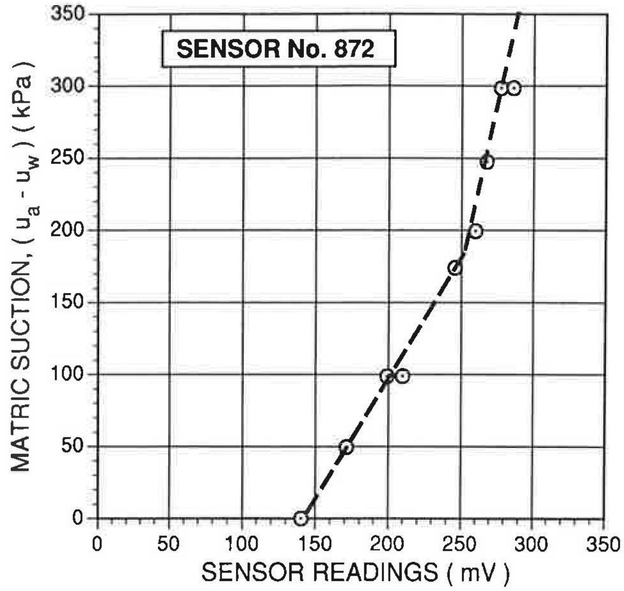

FIGURE 14 Typical thermal conductivity sensor calibration curve.

presented in Figure 14. Because of the higher thermal conductivity of water in comparison to air, a saturated tip at zero matric suction will register the lowest temperature rise because of the high heat loss from the water. The temperature rise is a function of the degree of saturation of the ceramic tip and not of the pressure of the water. The sensor, therefore, cannot measure positive pressures. Negative matric suction readings may be due to the following reasons:

1. The sensor tips were not large enough to contain the heat pulse completely within the porous ceramic. In this case, the heat loss will be affected by the surrounding soil medium. The calibration obtained will then be in error when installed in a different soil medium.
2. The sensor tips were broken in the process of installation, resulting in tips that were not large enough to contain completely the heat pulse.
3. With time, the ceramic deteriorated in the ground, particularly in a ponded condition under positive water pressures. The ceramic changes from a rigid structured medium to a structureless mass of soil-like material, altering the characteristics of the sensor tip.
4. The sensor tips were not fully saturated at zero matric suction during the calibration process. Positive water pressures will compress the air within the pores of the tip and force more air into water. Or, the tip simply got more saturated under prolonged submergence.
5. A gap existed between the sensor and the soil. A water-filled gap, particularly in conjunction with tips that were not large enough to contain the heat pulse, could result in higher heat loss.
6. Prolonged submergence caused a breakdown of the electronics.

Upon retrieval of the sensors at the end of the study, it was found that the sensor tips were quite soft and that most of them disintegrated upon handling.

There were no noticeable immediate or long-term effects on the matric suction readings due to wheel loadings, even though the loading tests resulted in severe deformations. The surface profiles before and after the wheel loading test of February 15, 1989, are presented in Figures 15 and 16, respectively. The initial track surface was rougher over the Regina clay subgrade section. The deformations, however, were more severe over the till section. The till was compacted slightly wetter than optimum and had low matric suctions. The till section, in comparison, was inferior to the clay section, which had much higher matric suctions.

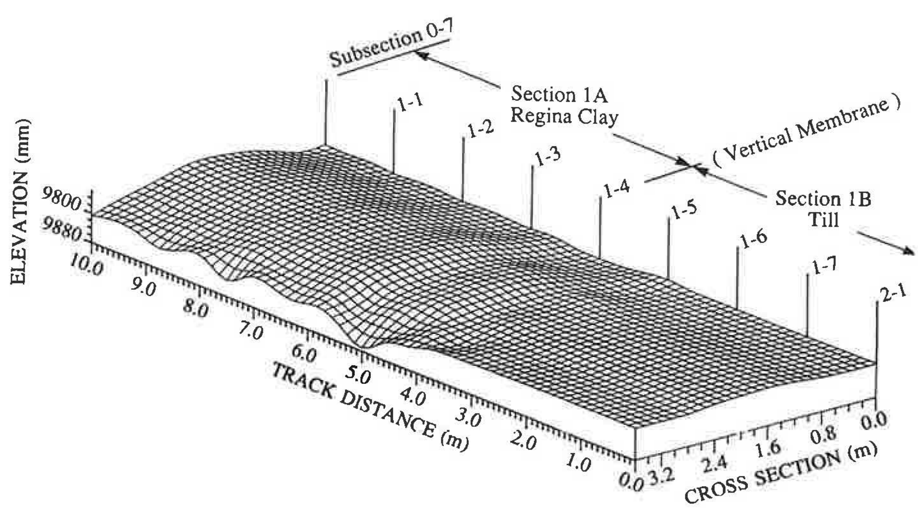

FIGURE 15 Track surface elevation just before wheel load test of February 15, 1989.

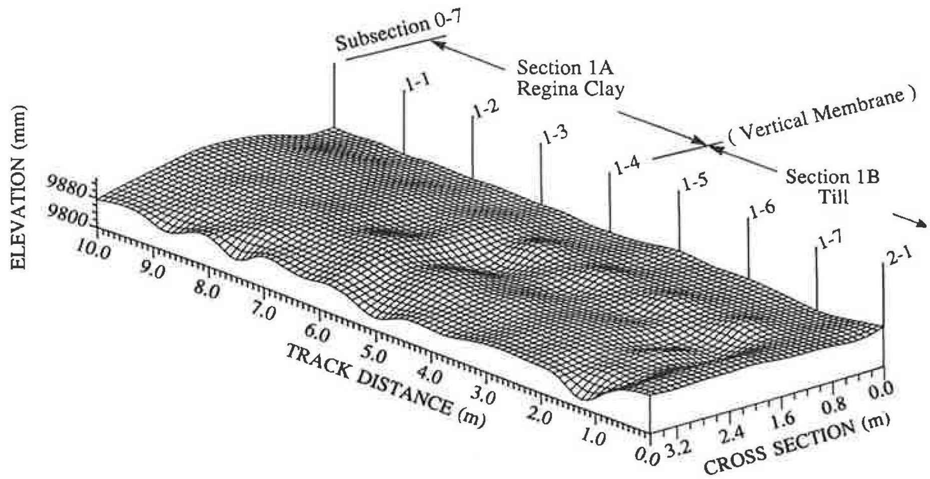

FIGURE 16 Track surface elevation after wheel load test of February 15, 1989.

CONCLUSIONS

The conclusions from this research program can be summarized as follows:

1. Long-term stable and reliable matric suction readings in highway subgrades can be obtained using thermal conductivity sensors, as long as the sensor is not subjected to prolonged positive pore-water pressures.
2. Poor backfilling procedures can result in preferential flow along the leads to the sensors. This problem is augmented by the vertical position of the installation boreholes. Secondary, dessication cracking also appeared to provide pathways for the rapid inflow of water to the subgrade.
3. Water introduced into the soil during installation of the sensors does not redistribute easily. It is easy to put water into a hole. Once this water gets into the soil, it is difficult to remove.
4. Further investigations are required to ascertain the reasons for negative suction readings.
5. The deterioration of the sensor tips shows that there is an urgent need for the development of a more durable ceramic for the sensor tip.

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