Field Study of Two Road Sections During a Freeze-Thaw Cycle

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The behavior of roadways depends on many parameters generally not well known, particularly in areas in which climatic conditions are severe in winter. Two road sections have been instrumented to understand how frost and thaw actions are related to climate and the availability of water. Field data monitored by a dedicated data acquisition system were used to measure air temperature, thermal soil conditions, frost heave, total stress, and bearing capacity by the Benkelman beam test. The results show that automatic monitoring improves the ability to detect short thaw events during freezing. Furthermore, accurate knowledge of air temperatures and the thermal conditions of the soil are useful in the interpretation of bearing capacity measurements with the Benkelman beam test.

The behavior of roadways depends mainly on parameters such as material soil properties, drainage, climate, traffic, and foundation types. In the province of Quebec, Canada, the severity of the climate is responsible for a large part of the damage caused by frost action in roadways. Particularly in fine-grained soils, it is well known that under freezing conditions, frost heave is affected by properties such as grain size, rate of freezing, availability of water, and applied load (*1*).

Although freezing produces an increase in moisture content in wet frost-susceptible soils, the thaw-weakening is what is costly to the Canadian economy. The road degradation associated with these thaw-weakening phenomena directly affects the cost of goods transported by truck vehicles in the spring. Once soil under the pavement thaws, the soil loses its bearing capacity for a time known as the spring breakup. As segregated ice melts, there is a possibility of both excess water being caught in the soil and surface water infiltration, which could lead to a loss of bearing capacity of the road foundations. Once the drainage becomes effective in the thawed zone, the excess water can dissipate, leading to a progressive increase in the bearing capacity of the roadways over time. The increase in bearing capacity depends on the type of foundation, geological conditions (i.e., bedrock inclination and stratigraphy of the soil), drainage, orientation of the road, snow conditions on the shoulders, and so forth.

In order to consider the most important parameters mentioned, a field study of two instrumented road sections in Quebec was initiated jointly by Laval University and the Ministry of Transportation of Quebec (MTQ).

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These field investigations focused on the measurement of the temperature conditions of the air, and soil of frost layers, and stress distribution while the roads were occupied with trucks of known weight. Furthermore, the bearing capacity was also measured using the Benkelman beam test. A description of the instrumented sites and the preliminary results obtained from the investigations during a freeze-thaw cycle starting in January are presented.

SITE DESCRIPTION AND CLIMATE

The two road sections used for the field investigation are on the south shore of the St. Lawrence River in the Bois-Francs region of Quebec. The instrumented section of Road 122 is near Victoriaville, in the township of Arthabaska, and the instrumented section of Road 265 is located just north of Plessisville, in the township of Mégantic. The two sites are located approximately 40 km southeast of Trois-Rivières, Quebec, Canada.

Geology

The Bois-Francs deposit belongs to the St. Lawrence Lowlands, which was formed 8,000 to 11,000 years ago with the withdrawal of the late glaciation; it is located between Laurentien Highlands to the north and the Appalachian Highlands to the south (*2*).

The two sites are on the fringe of the sand terraces close to the Appalachian Highlands. The surface of the sand terraces is slightly inclined toward the northeast with a mean elevation of about 100 to 125 m (*3*). The marine sediments are fine to medium sands and have few pebbles. Silt is present in varying amounts and is generally disseminated in minor amounts. The water table is generally located between 1 to 2 m below the surface.

Climate

The general climatic conditions of the Bois-Francs region can be assessed from the data given by Boyd et al. (*4*). These climatic data are based on the 29 years between 1931 and 1960. The mean annual air temperature is about 5°C with a maximum peak value of 34°C in summer and a minimum value of −35°C in the winter. Additional data on air temperature,

prepared by De Montigny and Légaré (*5*) and reported by Roy et al. (*6*), present the mean monthly air temperature for cold seasons during 1941 to 1970. The following results were obtained: 0°C for November, −8.7°C for December, −11.8°C for January, −10.7°C for February, −4.8°C for March, and +3.1°C for April.

The mean annual precipitation is about 1016 mm and is two-thirds rainfall and one-third snow. In an average winter, snow will be on the ground for approximately 5 months.

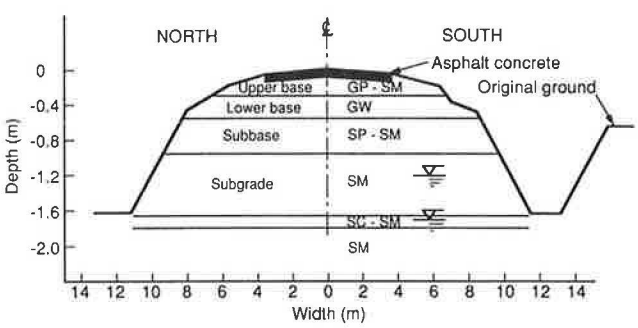
ROAD CHARACTERISTICS

Road 122 Section

This main road links Victoriaville to Drummonville and was constructed in 1979–1980. The instrumented section of the road is principally oriented in the east-west direction. The daily traffic evaluated in 1988 was 2,080 vehicles and 2,240 vehicles in 1990. This traffic comprised about 17.5 percent of heavy truck loads.

In order to get the road surface to 0.6 m over the original terrain elevation, the natural soil was excavated to 0.4 m. As shown in Figure 1, the road is composed of a 100-mm-thick asphalt concrete (AC) pavement, an upper base of 20-0 mm crushed rock (GP-GM) with a thickness of 200 mm, a 250-mm-thick lower base of 56-0 of crushed materials (GW) underlaid by a 400-mm-thick sand subbase (SP-SM). Grain-size characteristics of each layer show that the percentage passing the 80 μm is relatively low in the base layer, less than 6 percent, a little higher in the subbase, less than 10 percent, and highest in the subgrade, more than 14 percent.

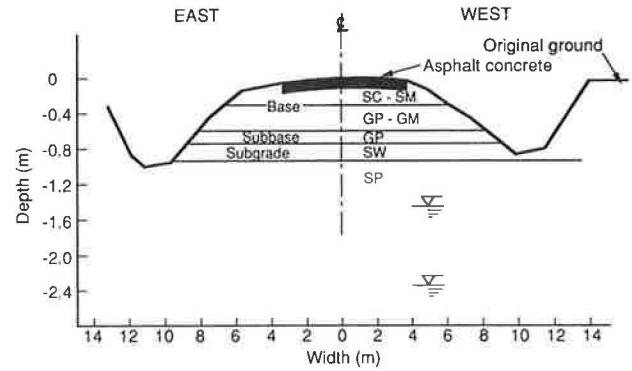
The road foundation is 1 m thick and consists of the low terrace sands previously described. More than 10 years after its construction the performance of Road 122 is excellent, with very little damage to the AC pavement.



Characteristics of the layers

Layers	Unified classification	Grain size distribution: Percent passing 5 mm	80 μm
Upper base	GP - GM	38	5.6
Lower base	GW	18	2.7
Subbase	SP - SM	96	9.4
Subgrade	SM	90	22.4
	SC - SM	97	14.6
	SM	82	49.0

FIGURE 1 Typical cross section of Road 122.



Characteristics of the layers

Layers	Unified classification	Grain size distribution: Percent passing 5 mm	80 μm
Base	SC - SM	62	13.3
	GP - GM	42	8.7
Subbase	GP	26	4.6
Subgrade	SW	89	16.6
	SP	100	4.7

FIGURE 2 Typical cross section of Road 265.

Road 265 Section

The old Road 265 is a secondary road that links the Thetford Mines region to the Trans-Canada Highway 20 and is oriented in the north-south direction. Constructed in 1964, the initial AC pavement received an overlay in 1973. The daily traffic recorded is approximately of 2,747 vehicles with 14.7 percent of heavy truck loads.

Field investigations in the instrumented section have shown that the road is composed of a 120-mm-thick AC pavement overlying a 480-mm-thick base of 20-0 mm of sand and gravel (SC-SM and GP-GM) with a 150-mm-thick gravel subbase (GP) of 56-0 mm (see Figure 2). The road was erected on low terrace sands (SW-SP) that belonged to the post-glacial deposits. Percentages passing 5 mm and 80 μm for each layer are shown in Figure 2. Fine particles in the base are higher than 9 percent, approximately 5 percent in the subbase and more than 16 percent in the subgrade.

Visual observations show that the road is in very poor condition; the asphalt pavement displays ruts and transversal, longitudinal, and alligator cracks.

INSTRUMENTATION AND DATA ACQUISITION

The two sites have been instrumented identically in order to measure the same parameters. The following description of instrumentation is general with reference to the road cross section.

As shown in the plan view, the instrumentation is composed of thermistors, frost probes, extensometers, total stress cells, and piezometers (see Figure 3).

Thermistors

In each road section, 40 NTC thermistors of Fenwal Electronics, unicurve type 3,000 Ω ±0.02°C tolerance, were in-

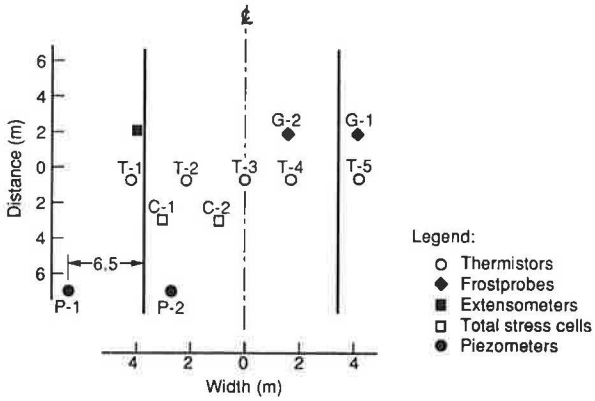


FIGURE 3 Plan view of an instrumented section.

stalled in the five boreholes shown in Figure 4: one borehole in the centerline, one under each halfway, and one under each shoulder. Each thermistor was prepared to withstand the harsh field conditions and calibrated individually in calibration bath.

Frost Probes

Two homemade frost probes were installed in the boreholes on one side of the centerline and on the shoulder, respectively, as shown in Figure 3. The frost probe is basically a long column of indicator solution (0.5 percent methylene blue in distilled water) encased in a clear plastic pipe.

Extensometers

Five extensometers of the electromechanical type were installed in a vertical position in the shoulder of the road, near the AC as shown in Figures 3 and 5. The extensometer column was mounted and calibrated in the laboratory and installed in a narrow trench dug through the road shoulder. Crispin (7) describes more details of the setup.

Total Load Cells

After calibration tests in the laboratory, two load cells, 23 cm in diameter, IRAD type with oil cushion, and connected to

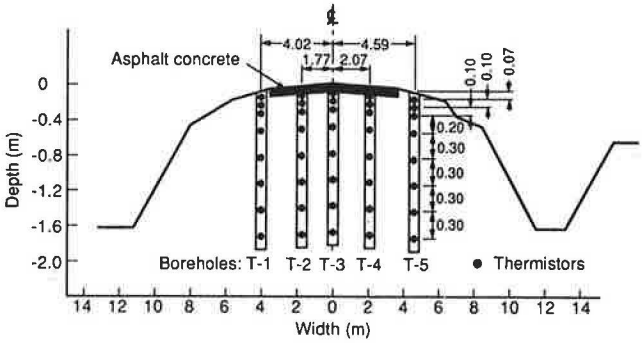


FIGURE 4 Cross section showing thermistors localization.

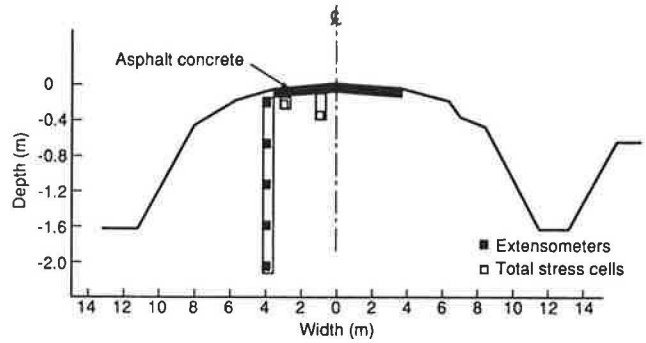


FIGURE 5 Cross section showing localization of extensometers and total stress cells.

a pressure transducer were installed in a large borehole carried through the AC pavement. One cell was located at a depth of 20 cm and the other one at 40 cm, under the wheel paths on one side of the road (Figures 3 and 5).

Piezometers

Two Casagrande open standpipe piezometers, made of 3.5 m of PVC pipe perforated on the bottom with a polyethylene high-density filter of 60 μm, were installed to depth 3.5 m on the shoulder and quarter side of the road as shown in Figure 3.

Data Acquisition

A PC-based integrated system for data acquisition, analysis, and control monitored each instrumented section of Roads 122 and 265. The main system components are a personal computer; data acquisition hardware, which included 64 analog and 16 digital input channels; a COPILOT software package; and a watchdog timer. The field system sustained by an electrical power line is controlled by a PC at the MTQ office via a modem and phone line.

RESULTS

The automatic data collection began on an hourly basis in mid-January. Therefore, as climatic conditions changed, all other manual readings were sporadic.

Water Table

The water tables observed by piezometers during the first 5 months of 1991 are shown in Figure 6. The elevation of the water table at Road 122 (Figure 6*a*) was constant from January to March and showed a slight increase of about 0.45 m because of the spring thaw. At the Road 265 section (Figure 6*b*), the free surface recorded by the piezometers moves down during the winter and rapidly moves up in mid-March because of the spring thaw. At the end of May both water tables reached the elevation observed in early January.

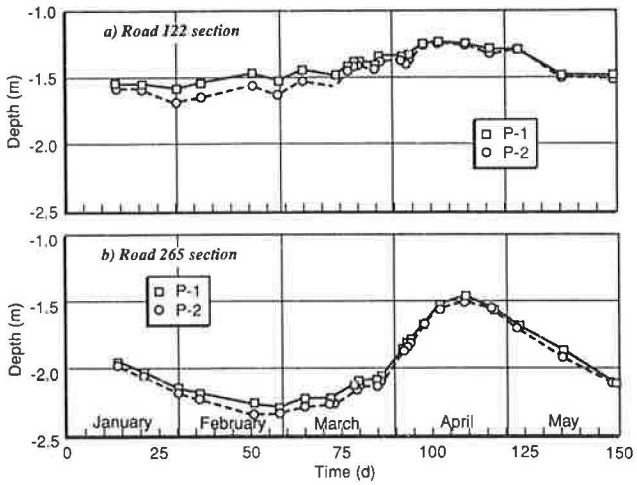


FIGURE 6 Variation of water tables in early 1991: *a*, Road 122 section; *b*, Road 265 section.

Climate

Air temperature and precipitations were measured on both sites to achieve a daily record of the climatic conditions for each site. The air temperatures measured during the first 5 months of 1991 are shown in Figure 7. The results are similar for Road 122 (Figure 7*a*) and Road 265 (Figure 7*b*). Except for some very short periods, the air temperature is below 0°C during January, February, and March. In April and May, the air temperature is generally over 0°C with smaller variations in the minimum and maximum values.

The precipitations recorded at the nearest stations are shown in Figure 8. The section on Road 122 is about 10 km southwest of the Arthabaska station, and the section on Road 265 is about 8 km northeast of the Princeville station.

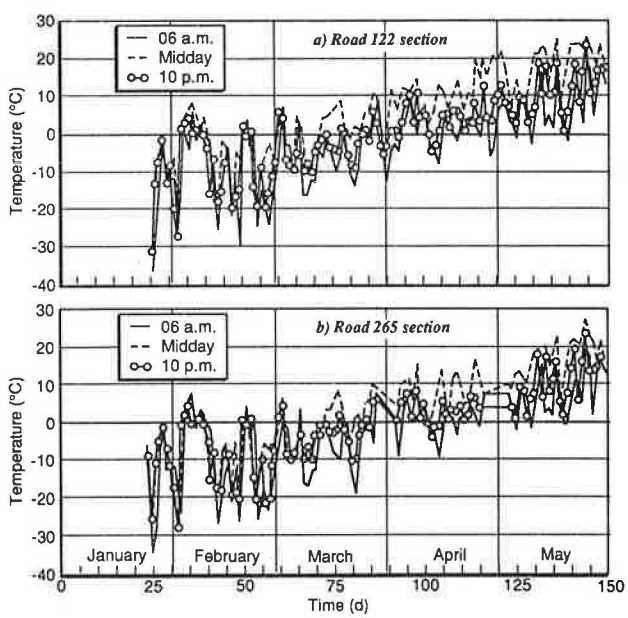


FIGURE 7 Variation of air temperature in early 1991: *a*, Road 122 section; *b*, Road 265 section.

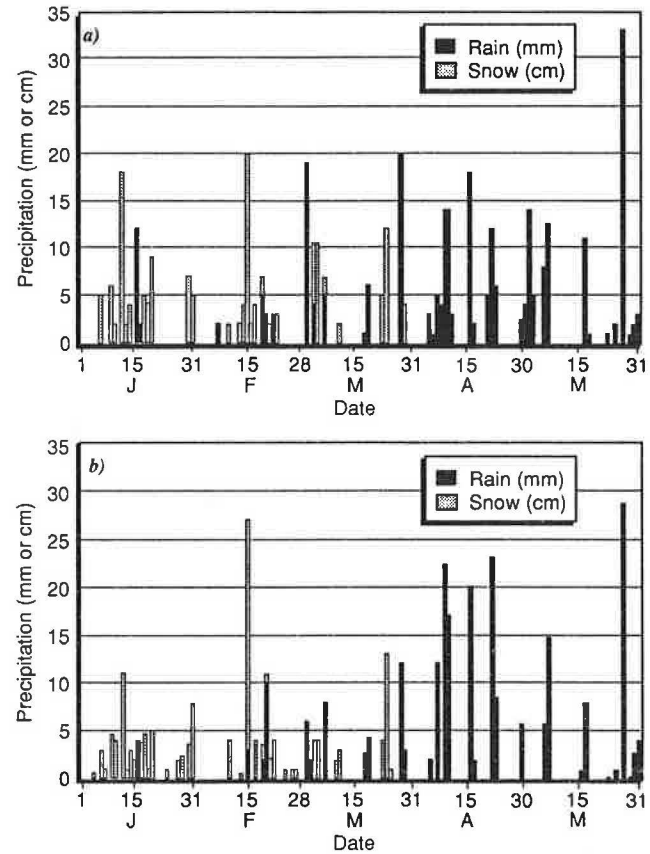


FIGURE 8 Daily precipitations recorded in early 1991: *a*, Road 122, Arthabaska station; *b*, Road 265, Princeville station.

Precipitations are recorded as snow during winter and as rain and snow during spring. The maximum snowfall has been recorded in February with a mean value of 24 cm.

Soil Temperatures

Typical results of soil temperature profiles are shown in Figure 9 for Road 122 and Figure 10 for Road 265. These profiles show the soil temperature evolution as a function of elevation and time. Early in March, the frost front has reached a depth of approximately 1.25 m (Figure 9) in Road 122 and approximately 1.74 m in Road 265 (Figure 10).

Figures 9 and 10 show the temperature distribution during the thaw period for both roads. Thaw starts under the AC pavement and progresses to the base, the subbase, and the subgrade. Thaw penetration is usually faster in the central part of the roads than near the shoulders. The profiles corresponding to April 7 and 8 are still showing a frozen zone in the shoulder of the two roads and especially at a greater depth on Road 265.

The results shown in Figure 10 clearly indicate the poor quality of the AC pavement, which allows deicing salt and rain to reach the base and the subbase course and could result in the rapid penetration of the thawed zone developing in the centerline of the Road 265 section.

The variation of the frost and the thaw front are shown in Figure 11 as a function of depth and width of the road. At

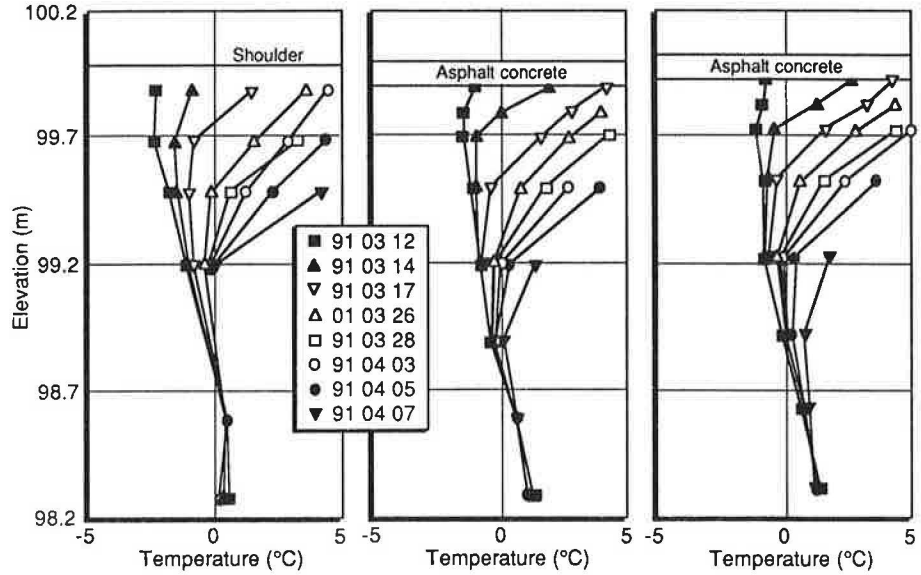


FIGURE 9 Soil temperature profiles, Road 122: *left*, Borehole T-1; *middle*, Borehole T-2; *right*, Borehole T-3.

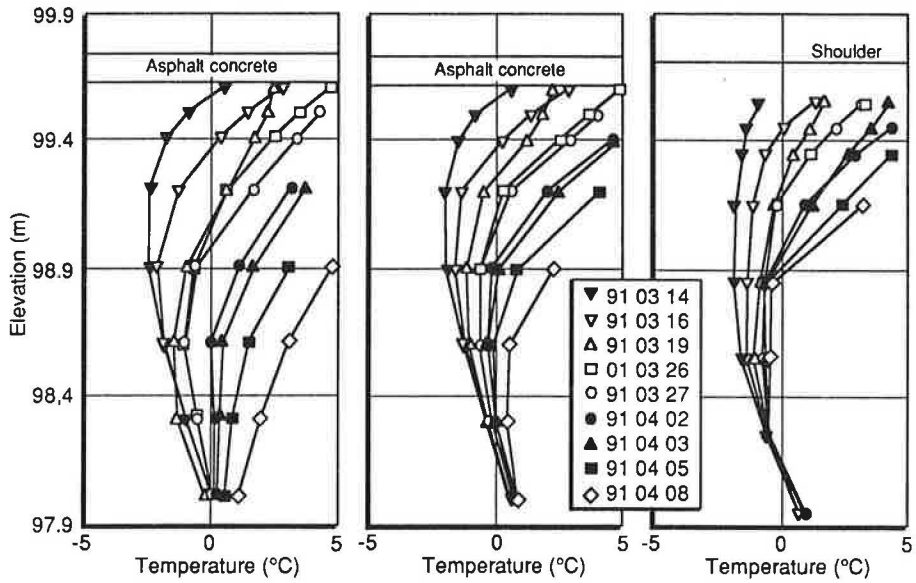


FIGURE 10 Soil temperature profiles, Road 265: *left*, Borehole T-1; *middle*, Borehole T-2; *right*, Borehole T-3.

the end of January the frost front was approximately 1.2 m deep in Road 122 [Figure 11 (*top*)]. Later, in the warmer period that occurs in early February, a thaw front appeared under the AC pavement. However, at the end of February and throughout March, the frost front was stable at an approximate depth of 1.45 m (i.e., in the subgrade). The thaw period was well initiated at mid-March, and the thaw front progressively moved down and the frost front stayed relatively stable.

For Road 265 [Figure 11 (*bottom*)] the frost front stabilized at approximately 1.74 m deep. The thaw front progressively moved down after mid-March, but at a much higher rate near the centerline of the road. Early in April, the thaw front moved under the shoulders while the soil under the centerline totally thawed.

Frost Heave

Frost heave was measured by regularly surveying the road sections. The results for the first winter are shown in Figure 12. About 4 and 3 cm of surface heave were measured at Roads 122 and 265, respectively. Figure 12*a* shows the initial survey performed in early November 1990 and indicates the

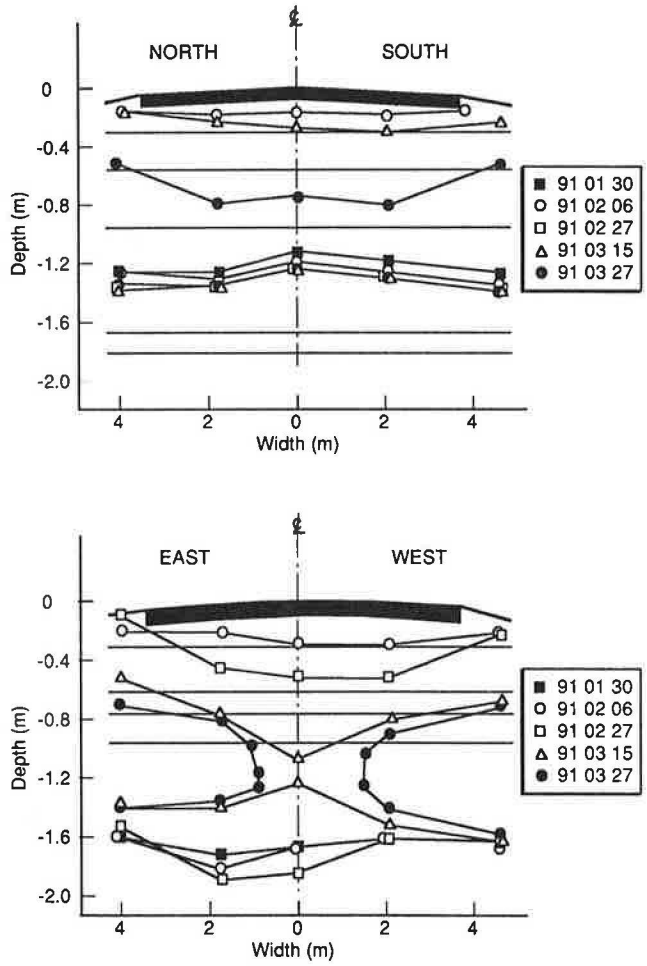


FIGURE 11 Inferred frost and thaw fronts: *top*, Road 122 section; *bottom*, Road 265 section.

elevation of Road 122. The frost was uniform and principally occurred in January and February 1991. It reached its maximum value in mid-March. The surface road moved down rapidly at the early stage of thawing and it was near its original elevation in early April.

Road 265 (Figure 12*b*) did not heave uniformly. This is consistent with earlier observations that indicate more complex freezing and thawing conditions at this site with poor pavement conditions. Unfortunately, the extensometer results are not available because 50 percent of the extensometers broke during the winter, and because this type of homemade electromechanical extensometer did not perform satisfactorily.

Benkelman Beam Tests

The Benkelman deflections measured during the 4 months covering the first winter-spring period are shown in Figure 13*a*. Each point corresponds to a measurement at the road sites. Very small deflections (i.e., about 0.1 mm) were measured when the road foundation was completely frozen, and this was the reason for conducting the tests again at the end of February. The deflections increased to approximately 0.3 mm once the air temperature approached or slightly exceeded 0°C. The deflections became greater during the thawing period of March and April with a peak value of 0.75 mm. During May the deflections progressively decreased, which indicates the road foundations regain strength over time.

Total stresses monitored by the load cells in the foundations, recorded at the same time as the Benkelman beam tests, follow the same trend as the surface deflections. Spring breakup does not appear to have a significant effect on the stresses measured at a depth of 40 cm. However, at 20 cm deep, the total stress increases drastically, passing from 200 to 300 kPa in a very short time during spring breakup at the beginning of April.

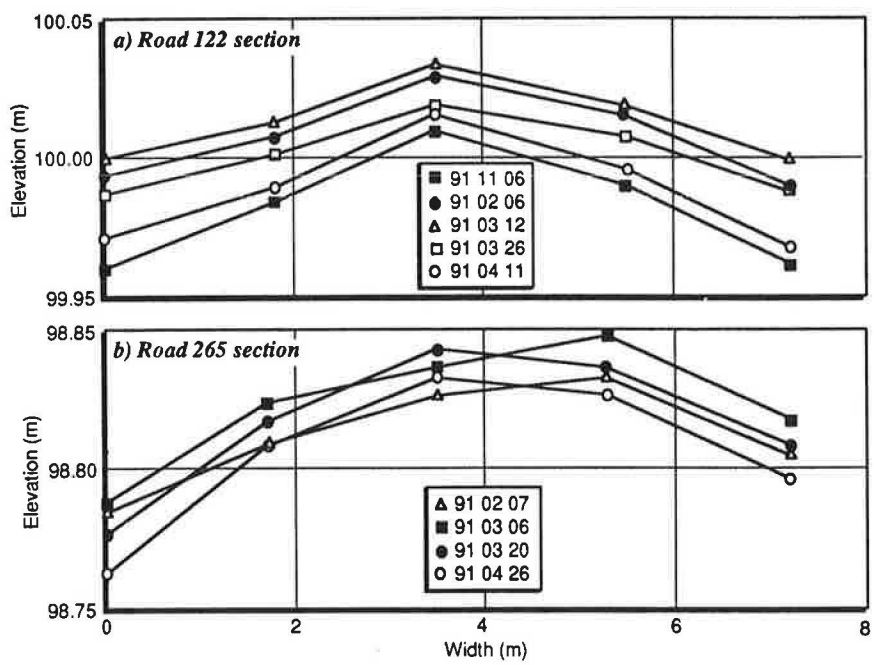


FIGURE 12 Frost heaves measured by survey: *a*, Road 122 section; *b*, Road 265 section.

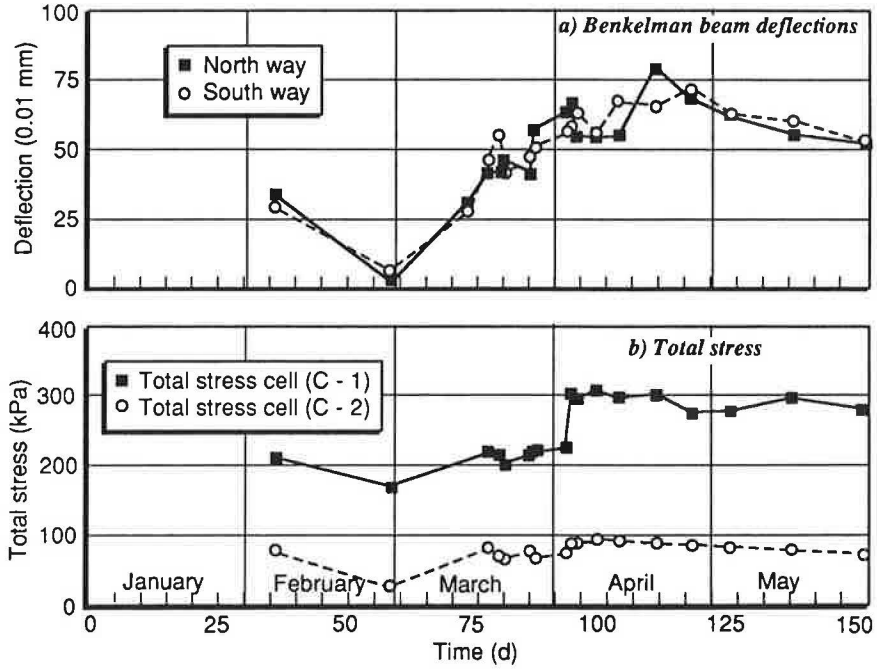


FIGURE 13 Road 265 behavior: *a*, Benkelman beam deflections; *b*, total stress.

DISCUSSION OF RESULTS

Frost Penetration

The results presented in Figures 9 and 10 have shown that the advancing frost boundaries reach a depth of 1.25 m on Road 122 and 1.74 m on Road 265, respectively. Considering that the road foundations have been set on the same subgrade, it is interesting to associate the advancing frost boundary to soil moisture and indirectly to the level of the water table. For the Road 122 section, the water table has been relatively stable at the depth of 1.5 m in January and February (see Figure 6*a*). The high water table and the saturated capillary fringe zone have probably limited the advancing frost boundary to a depth of approximately 1.25 m.

The water table in the Road 265 section was recorded at a level that varied from 2 to 2.3 m below the road surface for the months of January and February 1991 (Figure 6*b*). Therefore, the lowest frost boundary was observed at depth of 1.74 m in mid-March.

Climate

The recorded air temperatures near the two instrumented road sections (Figure 7) show that they are very similar and fairly representative of the Bois-Francs area. It is interesting to put the air temperature data in relation with the Benkelman beam tests and the total stress results obtained during winter and spring.

In the last part of February, the air temperature was near −20°C for 5 consecutive days (Figure 7), which caused the foundations to freeze completely. The results shown in Figure 8 suggest that when the road foundation is fully frozen, the corresponding deflections are very close to zero because the rigidity of the frozen foundation is high. This, in turn, leads to a small stress transfer to the embedded load cell during the load tests. Since the applied surface loads are redistributed through a rigid plate over the whole area of the road, the measured stress is only 170 kPa.

The Benkelman beam tests conducted during this period (Figure 13*a*) indicated a deflection of 0.3 mm with the measured total stress of 210 kPa at 20 cm depth in the base course (Figure 13*b*). These observations are consistent with the fact that the rigidity of the thawed base material is much smaller than in the frozen state and therefore leads to a larger deflection. The reduced rigidity of a small layer of soil will also affect the stress transfer mechanism, which is shown by the increased load cell reading.

As the thickness of this thawed zone increased during the spring breakup, the measured Benkelman beam deflections steadily increased from 0 to 0.65 mm and the total stress slowly increased from 170 to 220 kPa during March. Early in April the total stress rapidly increased for 220 to 300 kPa. This change in total stress corresponds to the time when the soil temperature, recorded in Borehole T-3 in the centerline section [Figures 10*a* (*left*) and 11], rose from below 0°C to above 0°C. The soil went from a frozen to a thawed condition even though a frozen zone still existed in neighboring Boreholes T-4 and T-5.

These results indicate that the stress distribution in the base and subbase courses is affected by the frozen zone and that the deflection depends on the moisture content of the thawed zone and the rigidity introduced by the frozen zone in the foundation.

Bearing Capacity

The loss of bearing capacity is difficult to correlate with the variation of the deflection measured by the Benkelman beam tests, especially if the results are known only for a very short

period that corresponds to the passage from winter to spring (Figure 13*a*). Nevertheless, the deflections measured at the end of October are about 0.5 mm, and it is assumed that the deflections measured at the end of May (0.52 mm) are approaching the conditions corresponding to initial refreezing moisture contents. In this case the deflection variations associated with thawing are approximately of 0.25 mm. These data show that the deflections increase rapidly with thawing; this is related to an increase in the moisture content of the thawed soil and causes a loss of road bearing capacity. On the other hand, the decrease in the deflections measured during the winter is caused by an increase in the rigidity of soil layers below the AC pavement due to their frozen state.

These data show that the road foundations are flexible in summer and fall seasons, very rigid during the cold season, and extra flexible during the spring breakup—particularly when the thaw zone reaches the unfrozen soil that was not affected by freezing. Detailed moisture content measurements will be carried out during the second freeze-thaw cycle.

CONCLUSION

The field investigations devoted to the observation of the behavior of two instrumented road sections in the Bois-Francs region in the province of Quebec led to the following observations:

1. The thermal conditions of soil can be measured easily by appropriate thermistors distributed in the ground—especially if daily or weekly data are required. Otherwise, a simple type of frost probe is adequate for a general survey on the progression of the freeze and thaw fronts.
2. Climatic conditions summarizing precipitation and air temperature are essential to interpreting and following up any road behavior, especially for analyzing the Benkelman beam deflection.
3. The PC-based integrated system for data acquisition has been a powerful tool for monitoring each instrumented section and for analyzing air temperature and thermal soil conditions every hour.
4. Observation of a second freeze-thaw cycle with improved monitoring is under way.

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