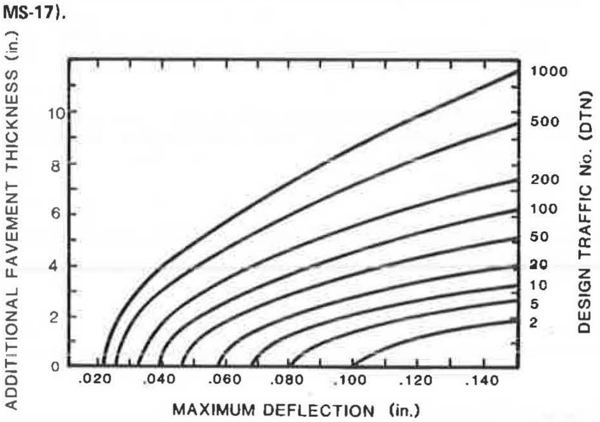
Figure 9. Design chart for required increases in pavement thickness based on maximum deflection levels and traffic factors (Asphalt Institute Manual MS-17).



formance predictions as compared to the U.S. Army Corps of Engineers Reduced Subgrade Strength design method and frost susceptibility soil classifications, and it is also superior to the use of Hveem R-value test data as a basis for predicting performance under conditions of seasonal freezing and thawing. The Alaska Department of Transportation and Public Facilities has recently adopted this approach for pavement design purposes, and a design guide has been prepared. This new design method was based on soils and performance data from 120 roadway sections. The maximum or critical fines content at various depths that can be allowed without causing significant thaw weakening of the pavement structure were established for all roadway study sections. Soil layers that have a fines content greater than this critical fines relationship contribute to thaw weakening and are used to predict the extent of weakening and the pavement thickness required. This approach has been termed the excess fines design method.

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The Val Gagne Pavement Insulation Experiment

T.M. LOUIE, W.A. PHANG, AND R.A. CHISHOLM

Since the first successful treatment of a frost heave problem in 1966 using Styrofoam HI brand (trademark of Dow Chemical, now called Dow Chemical Canada, Inc.) extruded polystyrene foam insulation, Ontario has used substantial quantities of insulation. However, knowledge of the performance of the insulation has been limited to sparsely documented observations of some sites where different types and amounts of insulation were used. In 1972 a joint experiment was launched by the Ministry and the Dow Chemical Inc. to construct, instrument, and observe the performance of pavement insulation at Val Gagne in Ontario. Three thicknesses of insulation and four different taper designs were used in the experiment. Winter temperature profiles, frost penetration depths, and frost heave measurements were observed during the winters of 1973-1977. The results of these observations were used to verify a two-dimensional finite element heat flow computer program intended for use in the design of insulation for controlling frost penetration. Although the program accurately predicts ground temperature for uninsulated situations and thinly insulated sections, changes in the program are needed to correct inaccuracies in predictions of ground temperatures when thick insulation is used. The results were also used to develop a set of frost penetration prediction curves for various thicknesses of insulation and for locations with different degree-days of freezing temperatures. These curves may be used to select the appropriate insulation thickness for any acceptable depth of frost penetration. Styrofoam insulation recovered from the test site after 5 years shows virtually no structural changes or changes in thermal properties.

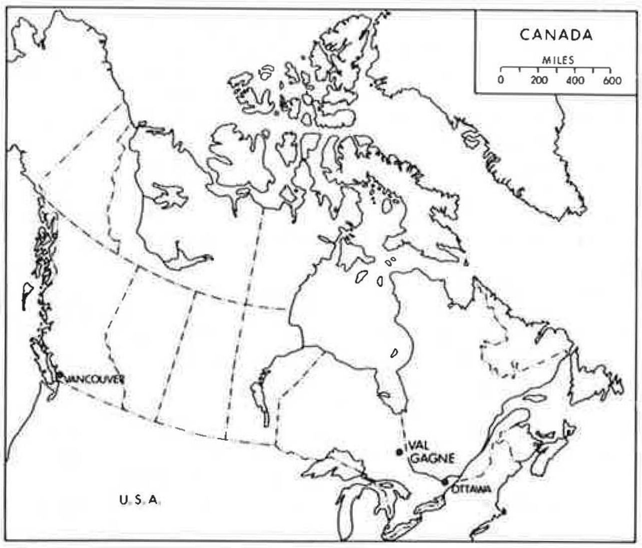
Differential frost heaving poses serious potential safety hazards and has perennial aftereffects on highways in Canada and the northern areas of the United States. Before 1966 all treatments of frost-heaves in Ontario involved removal of the frost-susceptible soil to great depths and/or ditching and drainage to remove entrapped water and to lower the water table. These treatments were not always successful.

Research into the use of Styrofoam for highway insulation began in the United States in the early 1960s, and by 1965 several full-scale experimental projects had been constructed (1-4). These early research sites were instrumented with thermocouples and frost depth indicators to measure the insulating properties of various thicknesses of Styrofoam insulation. The first major research sites in Canada were constructed near Winnipeg on the Trans-Canada Highway in 1962 and near Sudbury in 1966 (5). The findings of these early studies have resulted in the present widespread use of Styrofoam in areas where frost penetration makes differential frost heaving a significant problem.

Since the 1970s Ontario has been using increasing amounts of Styrofoam HI brand extruded polystyrene foam insulation for frost heave treatments in the northern part of the province. The reasons for this are two-fold:

1. Experience has shown that correctly designed Styrofoam always prevents recurrence of the frost heave, whereas other more conventional treatments may or may not be successful.
2. Cost comparisons of the various alternatives tend to show that Styrofoam is the most economical treatment.

Figure 1. Val Gagne test site.



In Ontario highway insulation has been adopted by the Ministry as an economical treatment for differential frost heaving. By 1972 the province was using approximately 3500 m^3 of Styrofoam per year (6) to treat frost heaves.

Thicknesses of Styrofoam in early installations depended on the number of degree-days of frost at the heave location. The rule of thumb used in the design to prevent frost penetration was 25 mm of Styrofoam for each 555 degree-days Celsius of frost. Through a trial and observation approach, some of the variables based on the best performing installations, such as minimum depth of granular over the Styrofoam and desired taper lengths, were determined and incorporated in a set of design standards. Studies of the use of Styrofoam for highway insulation have been continued in recent years by regional staff, primarily by observing closely the performance of numerous installations.

In 1971 the Ministry and Dow Chemical Canada Inc. jointly constructed a full-scale insulation research project to investigate the most effective methods for using the insulation. This experiment was constructed during the summer of 1972 at Val Gagne, which is located 65 km south of Cochrane. The basic experiment used three thicknesses of Styrofoam HI-35 covered with 460 mm of granular and 75 mm of asphaltic concrete. Full instrumentation was installed to measure ambient and ground temperatures, pavement elevations (frost heave), and frost penetrations. This report details the construction, instrumentation, and results of this 5-year study (1972 to 1977).

LAYOUT OF THE EXPERIMENT

The test site is located on Highway 11 in the Cochrane District (Figure 1) approximately 3.2 km north of the junction of Highway 101. The site was selected for several reasons:

1. The Val Gagne area regularly experiences severe winter weather with freezing indices of 1833 degree-days Celsius or greater. Frost indicator measurements have shown that penetration to a depth of 2.4 to 3.0 m is common (7).
2. The roadway was constructed as a 1.2 to 1.5 m cut through a heavy, clay soil. This cut is uniform

Figure 2. Val Gagne test site layout.

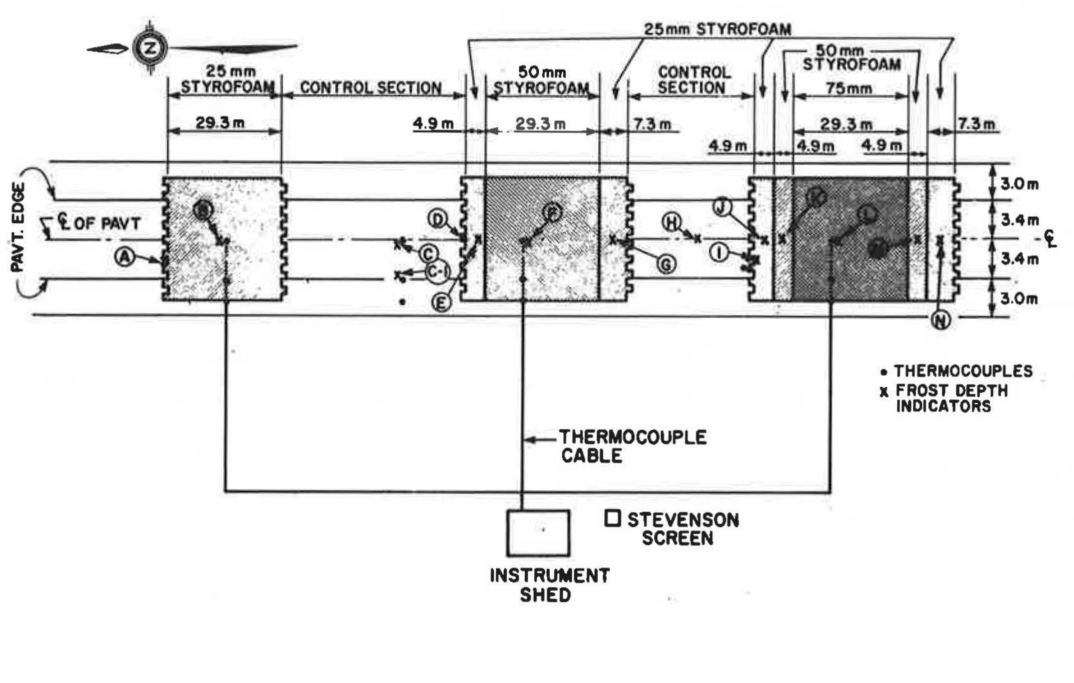
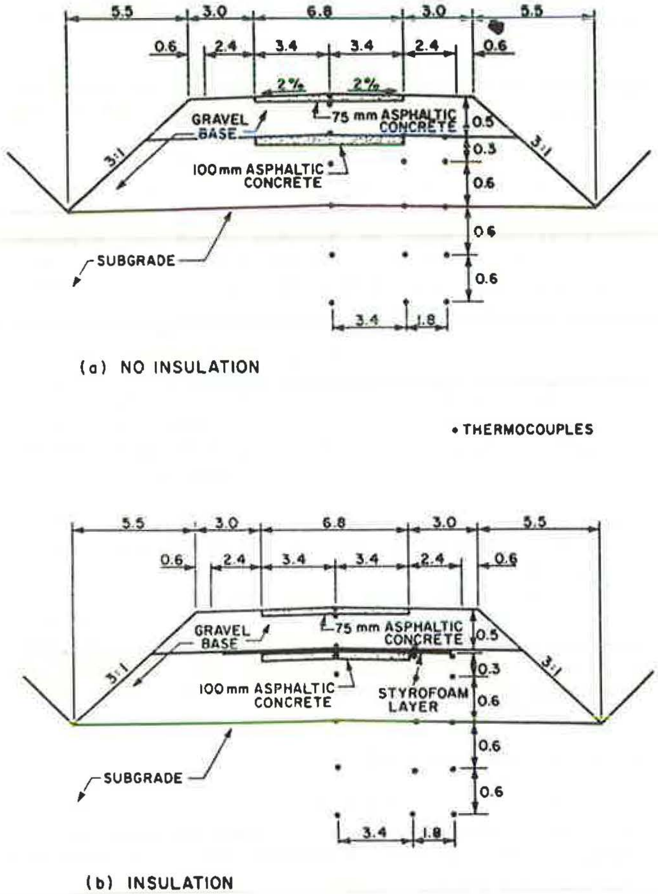


Figure 3. Typical cross section: uninsulated and Styrofoam insulated sections showing thermocouple locations.



Note: All dimensions are in metres unless otherwise specified.

Figure 4. Construction of the Styrofoam insulated sections.

in depth throughout the site because the original ground profile has the same slope as the pavement.

3. The experiment was designed to evaluate three different thicknesses of Styrofoam: 25, 50, and 75 mm. Each of the three sections is 29.2 m in length plus transition areas, and they are separated from each other by noninsulated control sections. Figure 2 shows the site layout.

SOILS

The subgrade soils at the site are mainly fat and gumbo clays. This soil is classified by the Unified Soil Classification System as CH and as A-7-6-type soil by the AASHTO Soil System. It has a very high plasticity index and a liquid limit greater than 50 percent. The water content of the silty clay soil ranged from 22 to 67 percent. The water table was 1.2 m below the pavement surface in three boreholes. CH (silty clay) soil is considered to be a frost-susceptible soil because more than half of the fine-grained aggregate contained in the clay passes the No. 200 sieve.

DESIGN AND CONSTRUCTION

Design of the test sections was in accordance with Ministry standards SD-4-86, 87, and 91 (8) except for the transition taper lengths on the southern end of both the 50 mm and 75 mm Styrofoam insulated sections. The width of the Styrofoam layer was extended 1.8 m beyond the pavement edge (Figure 3). The 50 mm Styrofoam insulated section had the normal 4.9 m transition of 25 mm insulating foam on the northern or uphill end and a longer 7.3 m length of 25 mm insulation on the other end (Figure 2). The normal 9.8 m transition was used at the northern end of the 75 mm section, and a longer, 12.2 m transition consisting of 4.9 m of 50 mm foam and 7.3 m of 25 mm foam was placed at the southern end.

The 2.40- by 0.60-m Styrofoam boards of the required thickness were laid directly on the old pavement surface after a light tack coat of emulsion had been applied to the surface by hand spraying. Shovels filled with granular base material were placed on the Styrofoam boards to prevent movement during the subsequent operation (Figure 4). The granular base material was end dumped at the beginning of the Styrofoam layer and spread in a thick layer by a small bulldozer over the length of the section. With this construction method there is minimal displacement of the Styrofoam sheets. A minimum layer thickness of 310 mm of granular material is placed on top of the Styrofoam to prevent its damage by subsequent compaction and other operations by construction equipment. The completed sections were brought up to profile grade with a total lift of 460 mm of granular cover and then paved with 75 mm of HL-4 asphaltic concrete. A more detailed description of the construction is given by Adamson (9).

INSTRUMENTATION

Full site instrumentation was installed to measure ambient ground temperatures, frost penetration, and pavement heaving. Ground temperatures were taken by 21 copper constantan thermocouples installed in each insulated section and control section. The thermocouples were arranged in three vertical strings with one set placed at the centerline, one at the edge of the pavement, and one at the edge of the Styrofoam layer. The strings have thermocouples at the following depths: top and bottom of the pavement, just above and just below the Styrofoam, 0.3 m below the Styrofoam, and three at 0.61 m intervals below that. A total of 84 thermocouples were installed in this way (Figures 3 and 5). In addition three thermocouples were placed in the 25 mm Styrofoam-insulated transition area of the 75 mm insulated section; one thermocouple was located under a "finger," one between the fingers, and one off the end of the finger. (In transitions, every other sheet is extended beyond the body of the insulation and is called a finger.)

Fifteen frost-depth indicators of the modified Swedish type were located throughout the site (Figures 2 and 6). They were installed in the middle of each section, and some were placed in the tapers to measure frost penetration depth in this critical area. These frost depth indicators have been used by the Ministry for several years and are an inexpensive, efficient way to measure frost depth.

Figure 5. Thermocouples being installed.

Figure 6. Frost depth indicators being installed.

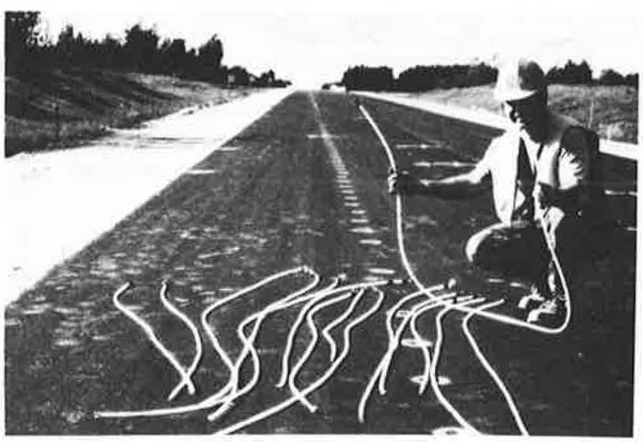


Figure 7. Overall view of the tests site showing leveling nails and instrument shed.

To facilitate accurate monitoring of the heaving movements occurring throughout the test site, approximately 700 nails were placed in the pavement surface (Figure 7). The nails were set in epoxy in pre-drilled holes. The nails were spaced at longitudinal intervals of 1.2 m throughout the site. For transition areas, the nails were spaced longitudinally 0.61 m apart extending 6.1 m in each direction beyond the transition. Three rows were placed in this manner in the transition areas--along the centerline and in the center of each lane.

Also two benchmarks were placed in the pavement. The benchmarks are founded well below the maximum frost depth and consist of steel rods in outer telescoping casings to assure that the elevation will remain constant throughout the years. A geodetic benchmark located near the site provided an accurate datum for all measured elevations.

Measurement Frequency

A 5-year period of observation of the test site has been completed. During this time, the thermocouples were usually read weekly during the frost season and at monthly intervals during the summer months. Frost depth indicators were usually read weekly when any ground frost was present. Four sets of elevations on the nails were taken yearly: in the fall before any frost entered the ground, at mid-winter, during the spring thaw, and mid-summer.

TEMPERATURE AND PRECIPITATION

Ambient air temperatures and precipitation for the site were obtained from the Environment Canada Climatological Station at Iroquois Falls, located approximately 24 km to the northeast. Freezing indexes calculated by using the mean daily air temperatures as well as the coldest recorded air temperatures in each of the 5 years are tabulated in Table 1.

The weather during the 5-year test period ranged from a very severe winter experienced during 1973-1974 to the relatively mild winter of 1974-1975. This range provided a good test for the materials and their performance under varying climatic conditions.

GROUND TEMPERATURES

Temperatures were taken in each section at various depths (Figure 3) by the use of thermocouples. During the winter months temperatures above the insulation are usually considerably lower than those below the insulation. This temperature difference increases as the thickness of the insulation increases. A typical example of temperatures taken above and below the 50 mm insulation layer is illustrated in Figure 8. Complete results of temperature measurements are reported by Louie (10-12).

FROST PENETRATION TIME PROFILE

Frost penetration can be determined by interpolating the thermocouple readings or from direct readings of the frost indicators. Figure 9 shows typical time-depth patterns of frost penetrations determined from readings of the frost indicators at the pavement centerline in all sections. The insulating effect of the Styrofoam layer is clearly illustrated; i.e., increasing the thickness of the Styrofoam leads to reduced frost penetration. Frost penetration recorded by the indicators for all sections over the 5 years is summarized in Table 2. Increasing depths of frost were recorded for each succeeding year except for the mild winter of 1974-1975.

Table 1. Freezing indices and lowest recorded temperatures taken from the nearest climatological stations.

	Climatological Station			
	Iroquois Falls		Cochrane	
Year	Degree-Days °C	Lowest Temp.°C	Degree-Days °C	Lowest Temp.°C
1972-1973	1810	-41	1805	-44
1973-1974	2097	-40	2209	-45
1974-1975	1659	-40	1783	-42
1975-1976	2038	-42	2124	-46
1976-1977	1849	-38	2080	-39
5-year mean	1891	-	2000	-
30-year mean	1882[a]	-	1838[a]	-
Design freezing index	2097	-	2209	-

[a] T.M. Louie (10).

Transverse Cross Section of Frost Penetration

The depths of frost penetration measured transversely across each section are illustrated in Figure 10. In both the uninsulated and 25 mm insulated-pavement sections, the depths of the 0°C isotherm recorded by the thermocouples were much lower at the centerline than at the edges of the embankment. This heat gain can be attributed to the insulating effect of the snow accumulated on the shoulders and ditches of the highway embankment. In the 50 mm and 75 mm insulated sections, the 0°C isotherms recorded below the insulating layers were roughly parallel to the roadway surface.

FROST HEAVING

Soil conditions at this site did not lead to unusual or severe differential frost heaving. In general, during the more severe winters, the uninsulated sections of roadway heaved approximately 24 to 40 mm. This compares with heaves ranging from 0.0 to 6 mm in the 75 mm insulated section, and 8 to 24 mm in the 25 mm insulated section. Table 3 lists the average heave for each section during the 5-year

Figure 8. Typical temperatures taken directly above and below the 50 mm layer of insulation at the centerline.

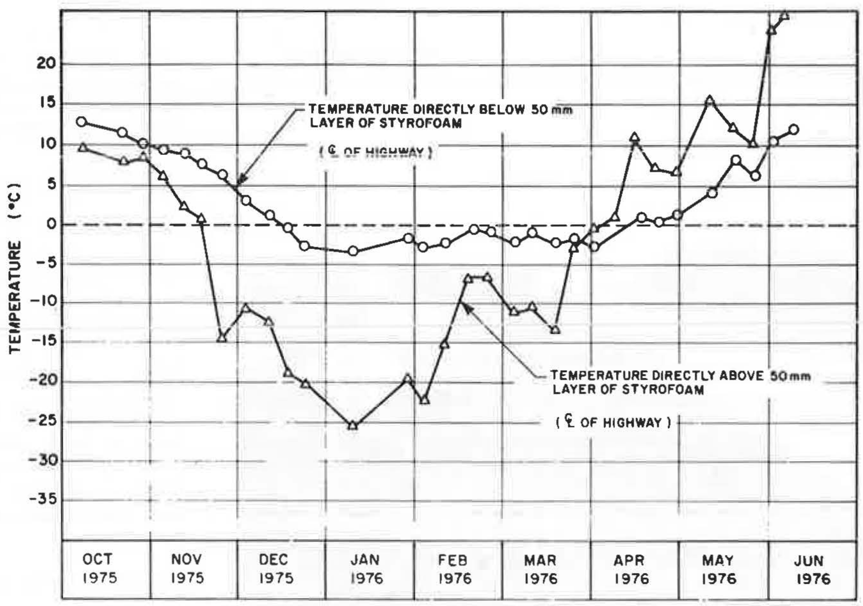


Figure 9. Comparison of frost penetration as recorded by the frost depth indicators for all sections.

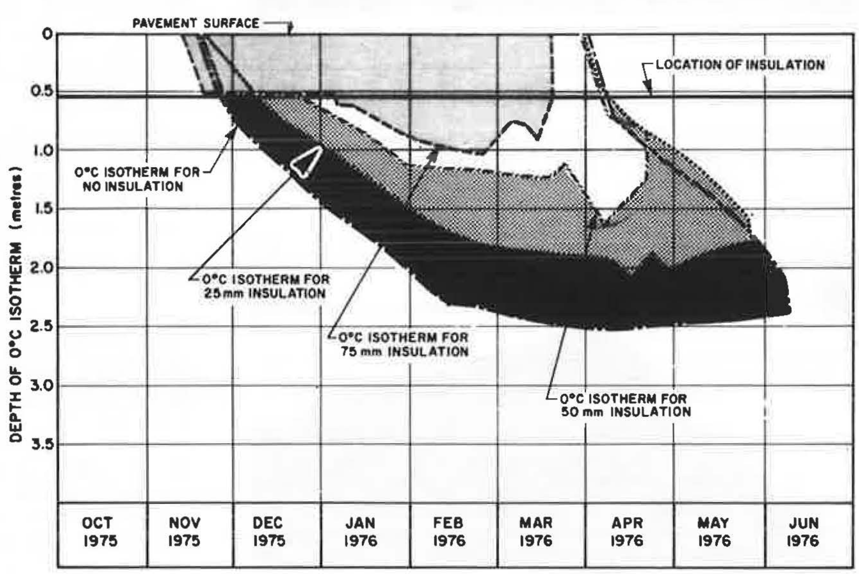
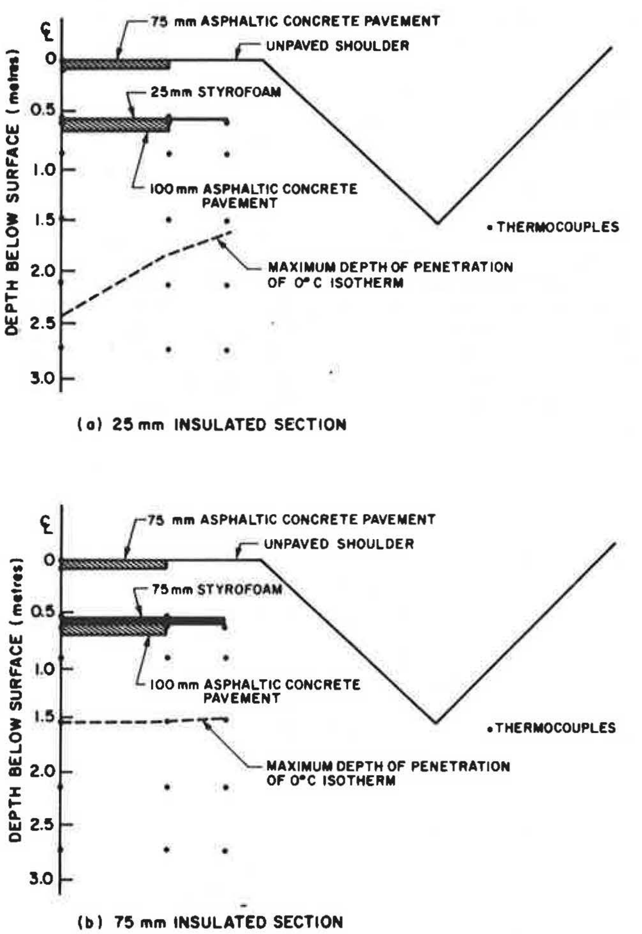


Table 2. Maximum frost penetration measured by the frost depth indicators.

Section	Frost Penetration (m) 1972-73	1973-74	1974-75	1975-76	1976-77
Control no insulation	2.36	2.49	2.39	2.59	2.62
25 mm insulation	1.60 (1.07)	1.73 (1.20)	1.60 (1.07)	1.90 (1.37)	2.03 (1.50)
50 mm insulation	1.02 (0.49)	1.14 (0.61)	1.12 (0.59)	1.22 (0.69)	1.42 (0.89)
75 mm insulation	0.58 (0.05)	0.94 (0.41)	0.68 (0.15)	1.02 (0.49)	1.09 (0.56)

Note: Numbers in parenthesis are measurements taken below the Styrofoam layer.

Figure 10. Transverse cross section of maximum frost penetration (1975-1976).



test period. The slight bumps that did occur over the transition areas were never great enough to adversely affect riding comfort over the test sections. Further information such as heave profiles is shown for centerline and midlanes by Louie (10-12).

Transverse Heaves

Heave measurements taken transversely across the pavement show the difference in heaving between the insulated and uninsulated sections. The pavement edge tends to heave more than the center of the pavement, possibly because water penetrates under the pavement edge. Typical results of the transverse heave measurements are shown in Figure 11.

Table 3. Average heave measured at the centerline (mm).

Section	1972-73	1973-74	1974-75	1975-76	1976-77
Control no insulation	30	37	0	34	18
25 mm insulation	9	24	3	9	2
50 mm insulation	0	6	3	3	0
75 mm insulation	0	6	0	3	0

The heave is negligible over the 50 mm and 75 mm layers of Styrofoam.

Transition Heaves

The transition tapers on the southern end of the 50 mm and 75 mm Styrofoam-insulated sections were lengthened to try to provide a more gradual transition from the insulated sections (which move relatively less) to the noninsulated portion of the highway (which moves relatively more). Differential heaving was not a problem at this site because gradual changes instead of abrupt heaves occurred at all transitions.

It appears from the slope of the frost-heave curve in the transition areas (Figure 12) that the 7.3 m transition for the southern end of the 50 mm insulated section is better than the 4.9 m transition used on the north end. On the 75 mm insulated section, no improvement was observed with the 12.2 m transition taper used on the south end over the standard 9.8 m transition taper on the north side. Figure 12 illustrates the 1973-1974 heaves in the transition areas.

DURABILITY OF STYROFOAM INSULATION

Three different thicknesses of Styrofoam samples (25, 50, and 75 mm), approximately 0.45 m square, were recovered near the wheel path of the driving lanes after being buried under the roadway for 5 years. The recovery procedure involved removing 75 mm of asphaltic concrete pavement and 460 mm of granular base course. Two samples of Styrofoam (25 and 75 mm) were removed from the northbound driving lane, and the remaining sample (50 mm) was recovered from the southbound lane. All recovered samples were immediately sealed in polyethylene bags for transporting to the laboratory. Before laboratory testing, dirt on the surface of the samples was carefully removed by washing.

Table 4 summarizes the laboratory results of tests on the three Styrofoam samples removed from the pavement. Only in the 25 mm sample was there an observed loss in measured thermal conductivity in the wet state. There was negligible moisture pickup in the 50 mm and 75 mm samples and hence no significant change in thermal conductivity after the 5 years. Furthermore, all three test samples exhibited no decrease in thickness and no reduction in the minimum vertical compressive strength of 240 kPa.

COMPUTER ANALYSIS

The ability to predict accurately the depth of frost penetration beneath highways with or without insulation can be a valuable tool for the designer. A part of this project consisted of testing the accuracy of a computer prediction program developed by Wang of Dow Chemical Canada Inc. (13). The program provides detailed predictions of frost depths and ground temperatures. It can be used to design for the worst possible conditions and to determine the optimum designs for new pavement structures using experimental materials.

The model is a two-dimensional finite element program for transient heat flow conduction and is capable of handling a multilayered soil profile, i.e., soil layers of varying thicknesses and thermal properties. Computer simulations were run for all of the Val Gagne sections based on 1975-1976 recorded weather data. Complete details regarding these simulation runs are given by Louie (13).

The 1975-1976 climatological data required for the simulation were obtained from the Climatological Station at Iroquois Falls. Soils information from the Soils Report (14) was sufficient to characterize the thermal properties of the embankment and foundation soils.

Frost Penetration Predictions

The comparison between the predicted and the measured maximum penetration of the 0°C isotherm is shown in Figure 13 for the 25 mm and 75 mm insulated sections, and the results for all sections are given in Table 5. An examination of the data shows that the computer prediction agrees well with the measured penetration in both the noninsulated control sections and the 25 mm Styrofoam-insulated sections. However, the program predicts almost identical frost penetration for both the 25 mm and 50 mm insulated sections. This is not in agreement with measurements from the frost depth indicators which show that frost penetration is substantially less for the 50 mm insulated sections than for the 25 mm sections.

In summary the computer program now available closely predicts the frost penetration beneath the 25 mm Styrofoam-insulated and uninsulated sections. The program overpredicts the frost penetration in the thicker 50 mm to 75 mm Styrofoam-insulated sections.

DESIGN OF STYROFOAM TREATMENTS

On the basis of the measurement of frost penetration at Val Gagne and other sites with Styrofoam insulation, a diagram of frost penetration versus thickness of Styrofoam insulation for different temperature environments was created. (See the chart in Figure 14.) Frost penetration with no insulation was calculated from the prediction formula

$$P = -0.328 + 0.0578 \sqrt{F}$$

and represents a 5-year average value (7). This chart allows the designer to determine the insulation thickness needed to control the penetration of frost to any desired depth, such as would be needed to control frost heaving. For example in an environment of 2000 degree-days Celsius, if frost may penetrate 1.5 m without excessive heave, 40 mm is the standard thickness of insulation needed for the treatment.

Figure 11. Typical heave recorded in the transverse direction (1973-1974).

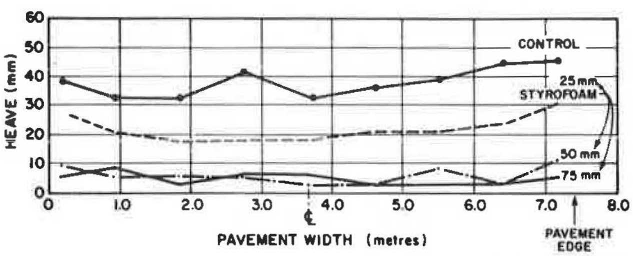


Figure 12. Longitudinal heaving through the transition areas (1973-1974).

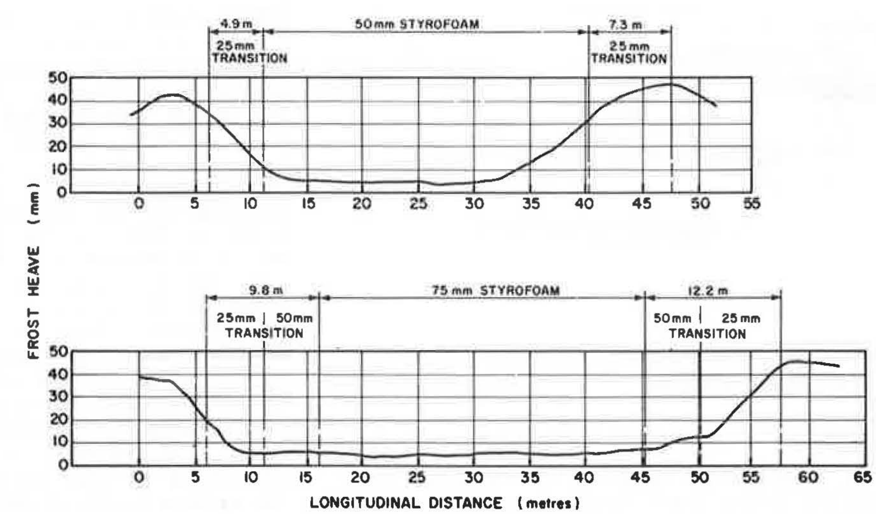


Table 4. Laboratory test results of Styrofoam samples recovered from the road after 5 years.

Sample	'K' Factor,[a] W/(m² · °C) Wet	'K' Factor,[a] W/(m² · °C) Dry	Water Content by Volume (%)	Dry Density (kg/M³)	Vertical Compressive Strength (kPa) 5% Deflection	Vertical Compressive Strength (kPa) 10% Deflection	Vertical Compressive Modulus (kPa)
25 mm Styrofoam HI-35	1.329	1.203	3.95	37.49	291.7[b]	337.9[b]	8,964[b]
50 mm Styrofoam HI-35	1.260	1.203	1.29	40.05	519.2	577.8	12,742
75 mm Styrofoam HI-35	1.243	1.197	0.93	33.00	344.1	344.1	13,204

[a] Thermal conductivity of samples was derived by using ASTM C-518.
[b] Irregularity in surfaces were removed.

Figure 13. Maximum depths of measured and predicted frost penetration for the 25 mm and 75 mm insulated sections.

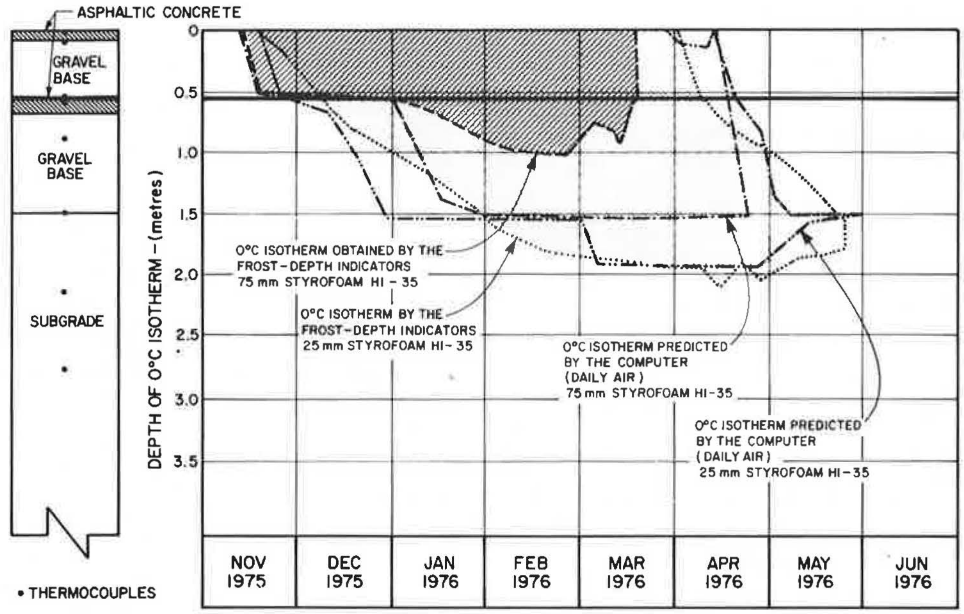
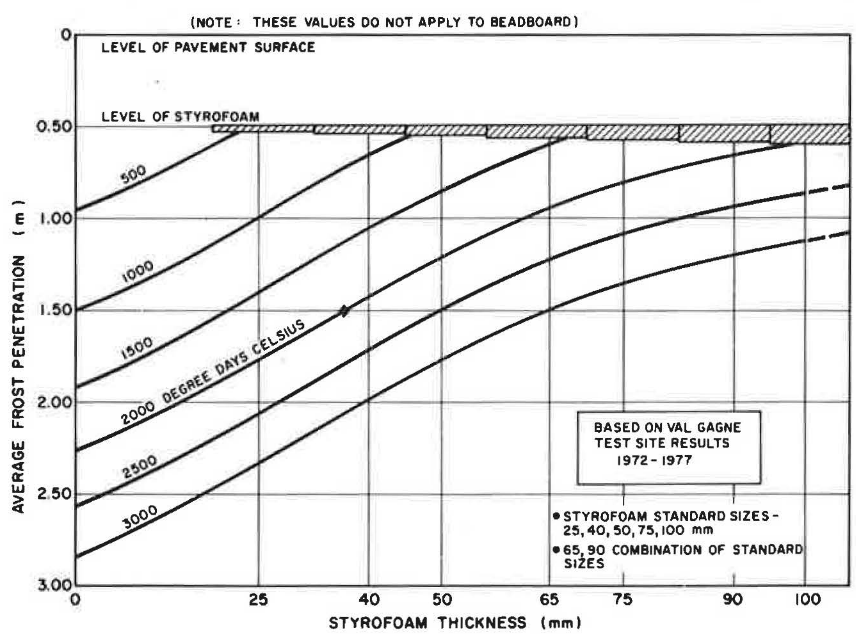


Table 5. Computer prediction of maximum frost penetration compared with measurements by frost indicators at the site.

Section	Predicted 0°C Isotherm Depth (m) Thermocouples	Frost Indicators	Computer (daily air)
Control no insulation	3.10	2.59	2.59
25 mm insulation	2.71 (2.18)	1.90 (1.37)	1.93 (1.40)
50 mm insulation	2.08 (1.55)	1.22 (0.69)	1.90 (1.37)
75 mm insulation	1.65 (1.12)	1.02 (0.49)	1.47 (0.94)

Note: Numbers in parenthesis represent measurements taken below the Styrofoam level.

Figure 14. Average penetration of frost beneath Styrofoam in paved highways.



CONCLUDING REMARKS

1. Experience has shown that frost depth probes are more reliable indicators of the location of the frost front than instantaneous thermocouple readings. Thermocouple readings taken on a continuous automatic basis will give reliable frost penetration results.

2. Longer lengths of transition tapers do result in a reduction in the abruptness of the bump at the end of the insulation caused by differential heave. In this experiment, however, the differential heave was not large and no recommendation is made to increase standard taper length.

3. Frost measurements made transversely indicate that reducing the standard width of the insulation beyond the pavement edge from 1.8 to 1.2 m would not substantially alter the frost penetration profile.

4. At this site, 460 mm of gravel base cover adequately protects the insulation from the effects of construction equipment and traffic so that there was no detectable change in the final insulation thickness. Moreover, over the 5 years of tests, only the 25 mm thick insulation showed any detectable change in thermal insulating value.

5. The insulation not only retards the escape of ground heat to the air during winter, it also retards the replenishment of ground heat storage during the summer months. However, the observations at this site are not adequate to show effects of reduced heat storage on frost penetration.

6. The computer simulation program accurately predicts the frost penetration of uninsulated pavements and thin (25 mm) insulated sections. The computer predicts deeper frost penetration than actual for the thicker (50 mm, 75 mm) insulated sections. The measurements at the site can be used to check future modifications to the computer program to predict frost penetration more accurately for thicker insulation.

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