ESTIMATING THE DEPTH OF PAVEMENT FROST AND THAW PENETRATIONS

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The design of foundations and pavements is affected by the depth to which frost penetrates during the winter or, in the case of permafrost areas, the depth reached by summer thaw. This report contains information on the depth of these penetrations as recorded at a number of Canadian airports. Correlations are developed between site air freezing index and the maximum depth of frost penetration beneath both asphalt and portland cement concrete pavements kept clear of snow during the winter. The standard error of these correlations is approximately 16 and 12 in. (41 and 30 cm) respectively. The maximum frost penetration that might be expected in undisturbed snow-covered areas is related also to site air freezing index. Similarily, for permafrost areas, relationships are developed between thaw penetration and site thawing index. More accurate estimates of frost penetration may be calculated if detailed soils information is available. Air freezing indices normally available for a site must be corrected to a pavement surface freezing index when making these calculations. The measurements recorded in the frost depth study indicate that the ratio of pavement surface/air freezing index decreases as site air freezing index decreases.

•THE design of many structures is influenced by ground frost conditions. The depth of seasonal frost penetration dictates thickness requirements for frost-protected pavements and is also an important factor to be considered when deciding on burial depths for building foundations and facilities such as water and sewer lines. Similarly, in permafrost regions, the depth of the active layer has a major influence on pavement thickness requirements and on the depth of pile embedment for building foundations.

Both types of ground frost conditions are encountered in Canada. In the southern part of the country the ground is normally unfrozen, and subfreezing temperatures penetrate the surface layers only during the winter months. In Arctic regions the ground is permanently frozen, with surface thaw occurring in the summer. The depth of these seasonal frost and thaw penetrations varies extensively throughout the country due to a wide range of climatic factors and soil conditions.

From 1964 to 1971, seasonal frost and thaw penetrations were recorded at a number of Canadian airports by the Construction Engineering and Architectural Branch of the Ministry of Transport. The information resulting from this survey is useful in estimating the maximum depth of frost and thaw penetrations at sites where actual measurements are not available.

THE FROST AND THAW DEPTH SURVEY

Frost Depth Indicator

The depths of frost and thaw penetrations were recorded at airports instrumented with frost depth indicators of the type devised by Gandahl (1). This instrument, with slight modifications incorporated by the Ministry of Transport, is shown in Figure 1.

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The instrument consists of a transparent acrylic plastic tube inside a heavier plastic casing. The tube and casing are inserted into a vertically bored hole to a depth exceeding the expected frost or thaw penetration. The inner acrylic tube contains a 0.05 percent solution of xylene cyanol. Normally a blue color, this solution turns colorless upon freezing. The depth of frost penetration is measured by simply extracting the inner acrylic tube from its casing and recording the depth of colorless solution. In the case of thaw, the depth of blue solution is measured.

Unlike thermocouple installations, which record actual soil temperatures, the frost depth indicator identifies only frozen and unfrozen zones. The frost depth indicator has certain advantages compared to thermocouples, provided that the only point of interest is the location of the ground frost line. The device is inexpensive, and a large number of installations for a comprehensive survey can be made without the necessity of complex recording devices at each site. Moreover, the simplicity of the instrument is such that it can be readily understood and used by inexperienced personnel. Instrument malfunctions can usually be easily identified.

In general, the Gandahl frost depth indicator performed satisfactorily during the frost survey program. Occasional difficulties arose when the indicator was frozen in and extraction of the instrument was either damaging or impossible.

Sites Instrumented

In 1964 frost depth indicators were installed at 30 airports in Canada. An additional 25 airports were instrumented in 1967, and some of the previous installations were then deleted from the program. The location of the instrumented airports is shown in Figure 2 in relation to the approximate boundaries of the continuous and discontinuous permafrost zones in Canada. Forty-two of these airports are situated in the southern part of the country, which experiences seasonal frost, and the depth of frost penetration during the winter was recorded at these sites. The eight airports located in the discontinuous permafrost zone have mean annual temperatures below 32 F (0 C), but the frost depth indicators recorded a seasonal frost penetration at these airports rather than permafrost. Thaw penetrations during the summer were recorded at five sites founded on permafrost (Cambridge Bay, Churchill, Frobisher, Inuvik, and Resolute).

Two or three frost depth indicators were usually installed at each airport. One indicator was located in a paved area surfaced with either asphaltic concrete or portland cement concrete kept relatively free of snow during the winter. Another indicator was located in an unpaved area with typical organic cover where snow was allowed to accumulate undisturbed.

Frost and Thaw Penetration Records

Frost and thaw penetration depths were recorded at weekly intervals throughout the season of interest by maintenance personnel or meteorological observers stationed at each airport. Table 1 gives the average maximum depth of frost penetration measured at each airport under pavement surfaces only. Table 2 gives the average maximum depth of thaw penetration recorded at permafrost sites. Site freezing or thawing indices are also given in these tables.

The freezing index is a measure of the severity of subfreezing temperatures experienced at a site, and it is the most influential climatic factor in predicting the depth of frost penetration. The freezing index is recorded in degree-days and is computed by accumulating from day to day during the freezing season the differences between 32 F (0 C), and the mean daily temperature. The freezing index begins to accumulate in the fall when the mean daily temperature falls below 32 F (0 C) and it reaches a maximum in the spring prior to thaw. The thawing index, which is of use in predicting the depth of summer thaw in permafrost regions, is similar to the freezing index except that it measures the above-freezing temperatures experienced during the summer.

For each set of frost or thaw penetration records, the corresponding freezing or thawing indices were computed from air temperatures recorded approximately 4 ft (1.2 m) above ground level by the Meteorological Branch of the Ministry of Transport. Show depth data were obtained during the winter months for those indicators located

Figure 1. Gandahl-type frost depth indicator (DOT pattern).

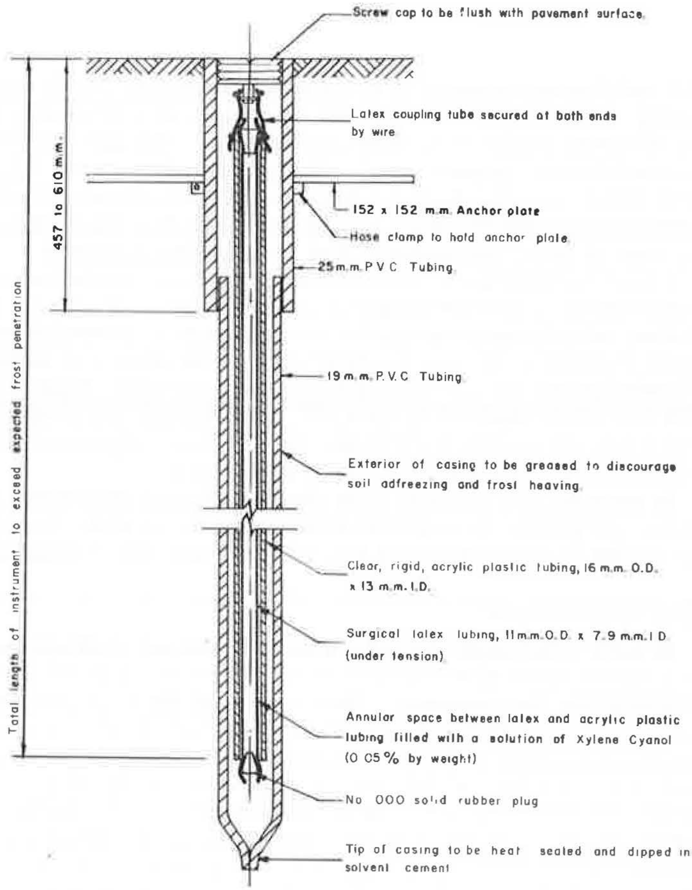


Figure 2. Airports instrumented in frost depth survey.

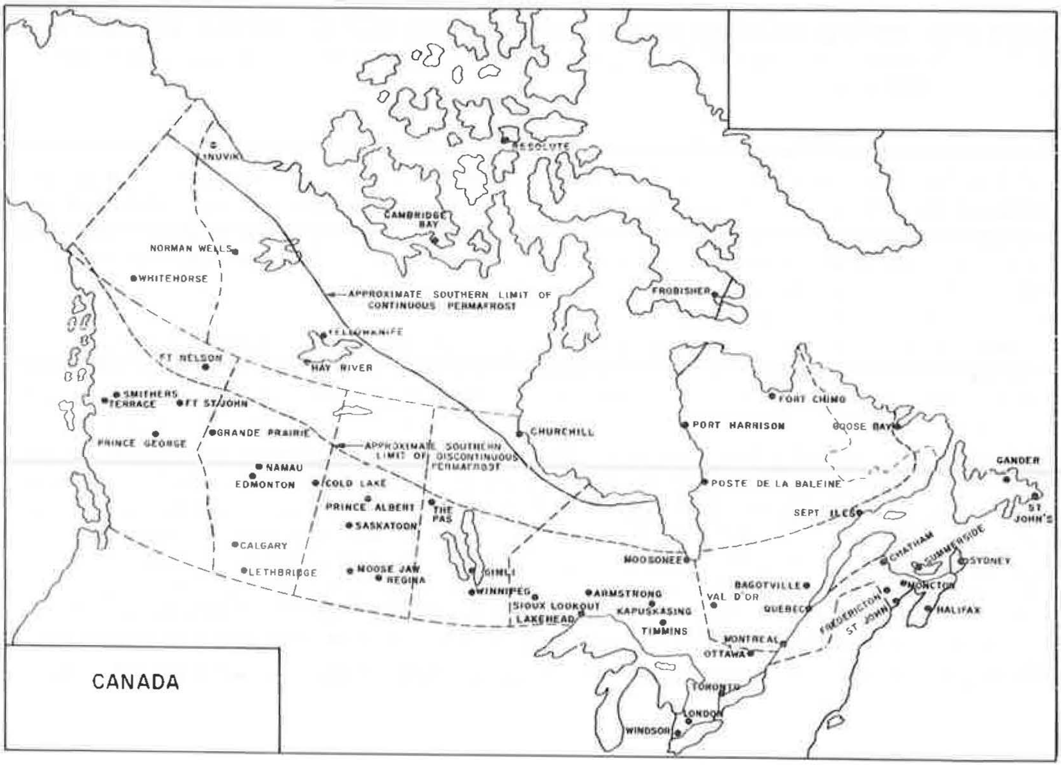


Table 1. Average frost penetrations, 1964-1971.

Seasonal Frost Sites	Number of Years Observed	Average Freezing Index (F degree-days)	Average Frost Penetration (in.)	
			Asphalt-Surfaced Pavements	PCC-Surfaced Pavements
Bagotville, Que.	4	2,840		84
Calgary, Alta.	5	2,067	76	
Chatham, N.B.	1	1,892		78
Cold Lake, Alta.	3	3,549		108
Edmonton, Alta.	6	3,301		87
Fort Nelson, B.C.	7	4,852	129	
Fort St. John, B.C.	1	2,603	112	
Fredericton, N.B.	3	1,573		68
Gander, Nfld.	4	1,092		55
Gimli, Man.	3	3,438	118	
Grande Prairie, Alta.	4	3,545	80	
Halifax, N.S.	4	941		45
Hay River, N.W.T.	2	5,641	140	
Lakehead, Ont.	4	2,833	59	
Lethbridge, Alta.	3	1,511	46	
London, Ont.	1	988	34	
Moncton, N.B.	3	1,366	49	
Montreal, Que.	3	1,730	56	
Moose Jaw, Sask.	4	2,820	102	
Namao, Alta.	3	3,097		106
Ottawa, Ont.	3	1,662	62	
Prince Albert, Sask.	4	4,328	99	
	3	4,139		119
Prince George, B.C.	4	1,757	64	
Quebec, Que.	3	2,290	51	
Regina, Sask.	7	3,488	80	
St. John, N.B.	4	1,401		62
St. John's, Nfld.	4	611	28	
Saskatoon, Sask.	2	3,372	69	
Sept-Iles, Que.	2	2,270	70	
Smithers, B.C.	3	1,780	60	
Summerside, P.E.I.	4	1,209		49
Sydney, N.S.	4	875	36	
Terrace, B.C.	1	1,002	60	
The Pas, Man.	5	4,620	119	
Toronto, Ont.	3	1,022	36	
Val d'Or, Que.	3	3,127	84	
Whitehorse, N.W.T.	7	4,022		127
Winnipeg, Man.	3	3,596	73	
	4	3,762		84
Yellowknife, N.W.T.	2	7,559	169	

Table 2. Average thaw penetrations, 1965-1971.

Permafrost Sites	Number of Years Observed	Average Thawing Index (F degree-days)	Average Thaw Penetrations (in.)		
			Asphalt-Surfaced Pavements	Gravel Surfaces	Undisturbed Natural Surfaces
Cambridge Bay, N.W.T.	3	1,087		57	
Frobisher, N.W.T.	2	1,292	78		
Inuvik, N.W.T.	4	2,053		89	
	5	2,181			53
Resolute, N.W.T.	2	473		26	

in areas with undisturbed snow cover. At the time of installation, bore holes were drilled for soil-sampling purposes. The thicknesses of distinct soil layers were measured and samples were taken for mechanical analysis and determination of moisture content. No density measurements were made.

MAXIMUM PENETRATIONS RELATED TO CLIMATIC INDICES

Frost Penetration in Snow-Cleared Pavements

The depth of frost penetration depends on both climatic factors and soil conditions. However, rough estimates of maximum frost penetration, which are sufficient for some purposes, can be predicted with a knowledge of the air freezing index only. From the data collected at Canadian airports, Figures 3 and 4 show the relationship between these variables for snow-cleared pavements surfaced with asphaltic concrete and portland cement concrete respectively. If the maximum frost penetration in inches is denoted by X and the maximum air freezing index by F (F degree-days), the regression relationships are approximately

Pavement Surface	Equation	Standard Error
Asphalt	$X = -24 + 2.0\sqrt{F}$	15.8 in. (40.1 cm)
Concrete	$X = -10 + 1.9\sqrt{F}$	12.2 in. (31.0 cm)

The negative values at low freezing indices indicate that the air freezing index must reach certain minimum values before frost penetration is experienced. This effect occurs because average pavement surface temperatures are slightly higher than the corresponding air temperatures measured approximately 4 ft (1.2 m) above the ground surface and the freezing index at the pavement surface will lag behind the air freezing index. Due to the black color of asphalt, slight differences also occur in the average temperature of asphalt and portland cement concrete surfaces, which leads to a lesser depth of frost penetration in asphalt pavements than in portland cement concrete pavements for the same air freezing index.

In Figures 3 and 4, a distinction is made between observations in pavements having cohesive subgrades and those having predominantly granular subgrades. Normally, with other factors equal, one would expect deeper penetrations in granular subgrades, but this trend is not noticeable in Figures 3 and 4. Most likely, the influence of subgrade type is not noticeable in Figures 3 and 4 because dense pavement layers are generally thicker on cohesive subgrades than on granular subgrades and because the substantial thicknesses of airport pavements in general tend to attenuate the effects of subgrade type.

Frost Penetration in Undisturbed Snow-Covered Areas

Figure 5 shows the maximum frost penetrations observed in undisturbed snow-covered areas plotted against the maximum air freezing index. Because of differences in the depth of snow cover, these observations are much more variable than those for snow-cleared pavements. However, for design purposes, an upper limit representing the maximum frost penetration that might be expected can be established from Figure 5. The equation, $X = 1.7\sqrt{F}$, describes this upper boundary. The maximum expected penetration occurs when little or no snow cover is present during the freezing season. A comparison of Figure 5 with Figures 3 and 4 shows that the average depth of frost penetration in undisturbed snow-covered areas amounts to approximately one-half the penetration that occurs under snow-cleared paved areas.

The insulating effects of snow cover are shown in Figure 6, where the ratio $X/\sqrt{F}$ is plotted against average depth of snow cover. The points are dispersed because the insulation effect depends not only on the average depth of snow but also on the time of season it is in place and on the snow density. A trend, however, is quite noticeable in Figure 6. Beginning at approximately 1.2, for no snow cover, the proportionality constant between depth of frost penetration and square root of the freezing index decreases with increasing depth of cover to a value of about 0.4 for 2 ft (61 cm) of snow.

Figure 3. Maximum frost penetrations in asphalt-surfaced pavements.

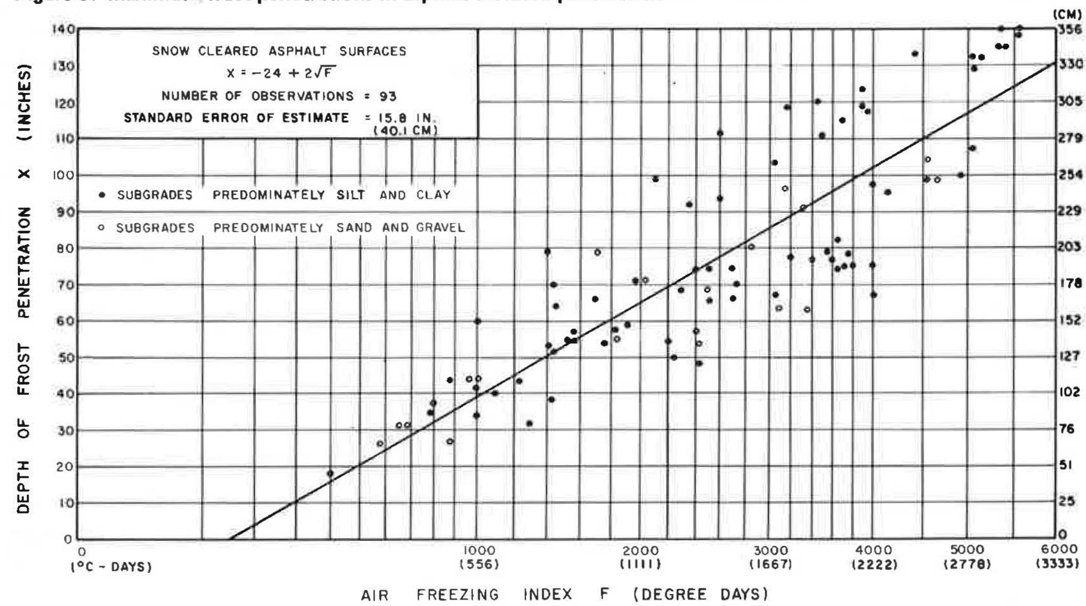


Figure 4. Maximum frost penetrations in PCC-surfaced pavements.

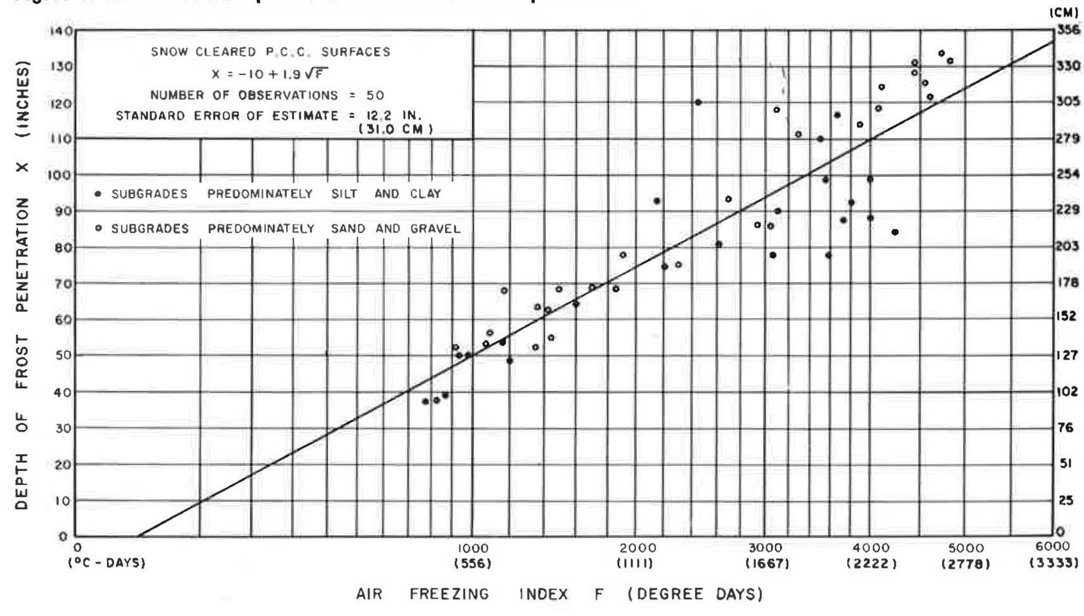


Figure 5. Maximum frost penetrations in undisturbed snow-covered areas.

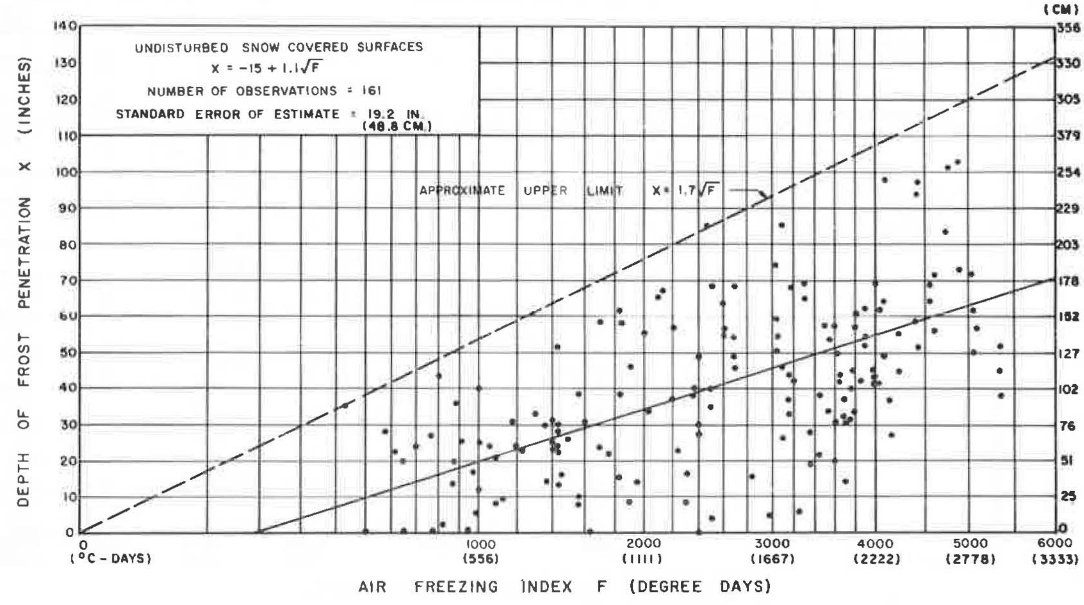
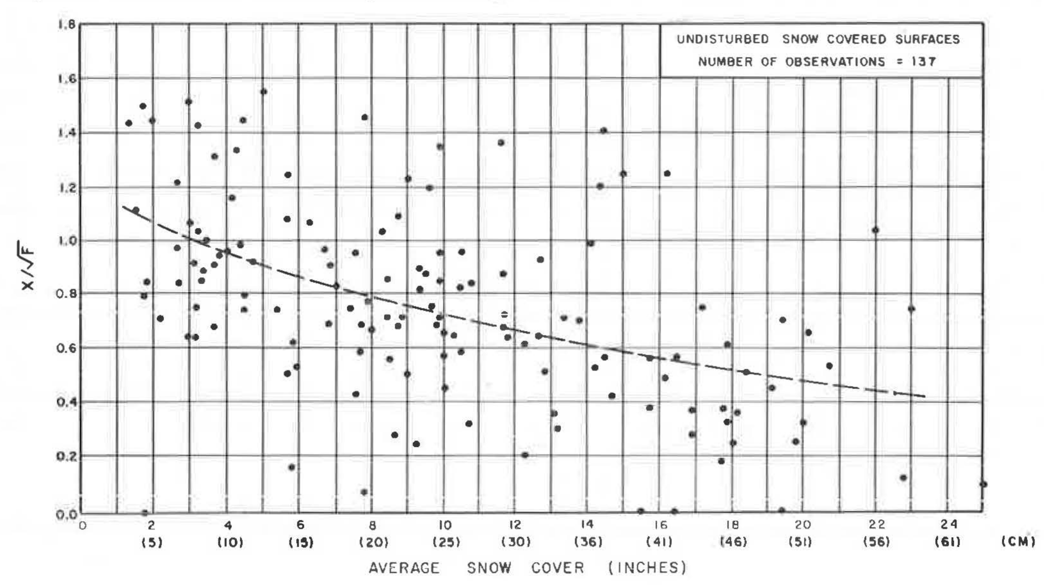


Figure 6. Ratio of X/√F versus average snow cover.



Thaw Penetration in Permafrost

The data obtained from the study on the maximum depth of summer thaw in both asphalt and gravel-surfaced pavements founded on permafrost are limited by the few sites instrumented. The observations recorded for gravel surfaces are plotted in Figure 7 against maximum thawing index on a square-root scale. Figure 7 provides a very approximate indication only of the maximum thaw penetration that might be expected; more measurements are needed to adequately define the relationship.

Figure 8 shows some measurements of maximum thaw depths recorded in undisturbed natural ground areas. Most of these measurements were obtained during a previously conducted program in which maximum thaw depths at a number of northern permafrost sites were established by soundings. Although the thaw depths are quite variable because of variations in soil condition and depth of organic cover, an upper boundary can be established from Figure 8. If the site thawing index is denoted by I, the maximum active layer depth in inches that might be expected at the site is in the order of $1.85\sqrt{I}$.

CALCULATION OF FROST PENETRATION IN PAVEMENTS

Modified Berggren Equation

The theoretical calculation of frost penetration depths is commonly based on the modified Berggren equation (2, 3, 4, 5). The equation may be written in the following form for layered soil systems such as pavements (6, 7):

$$\Delta F_n = \frac{L_n \Delta X_n}{24\,\lambda^2} \left\{ \sum_{i=1}^{(n-1)} R_i + \frac{R_n}{2} \right\}$$

where

ΔF_n = the partial pavement surface freezing index required to freeze the nth layer (F degree-days);
ΔX_n = thickness of the nth layer (ft);
L_n = latent heat of fusion of the nth layer (Btu/ft^3);
λ = correction coefficient based on site soil and climatic factors;
R_i = thermal resistance of the ith layer = $\Delta X_i/K_i$; and
K_i = thermal conductivity of the ith layer (Btu/ft/hour/deg F).

As Figure 9 shows, the total pavement surface freezing index required to freeze n layers in the pavement structure is determined by summing the partial freezing indices, ΔF_n, required to freeze each layer.

Soil Thermal Properties

For use in the modified Berggren equation, the coefficient of thermal conductivity K, latent heat of fusion L, and correction coefficient λ may be estimated from Figure 10. The thermal conductivity values given in Figure 10 were established by Kersten (8). Latent heat of fusion depends on the amount of water in the soil and may be calculated as $1.434\,\gamma d\,Wn$, where γd is the dry density of the soil in pounds per cubic foot and Wn is the moisture content in percent. As given by Aldrich (5), the correction coefficient λ is a function of the mean annual temperature experienced at a site, the average freezing temperature, and the soil moisture content. In Figure 10, which gives approximate values for λ, the variables of mean annual temperature and average freezing temperature have been replaced by the site air freezing index by using empirical correlations between these statistics.

Freezing Index Surface/Air Correction Factors

An additional factor entering frost depth calculations is the relationship between pavement surface freezing index and air freezing index. Calculations with the modified

Figure 7. Maximum thaw penetrations in gravel-surfaced runways on permafrost.

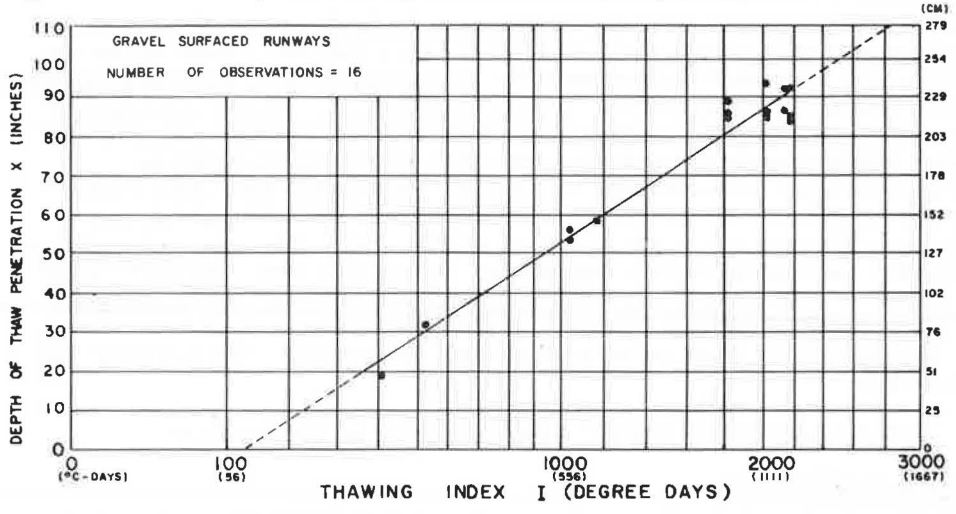


Figure 8. Maximum thaw penetrations in undisturbed permafrost areas.

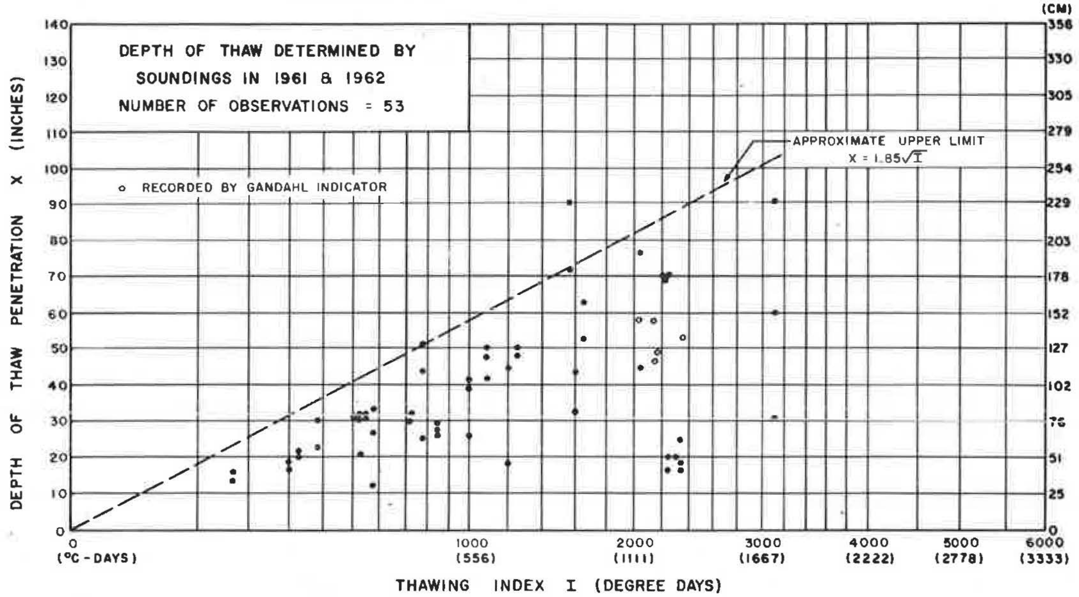


Figure 9. Layered soil system.

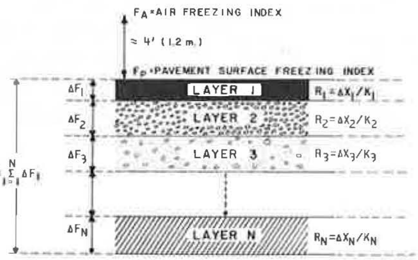
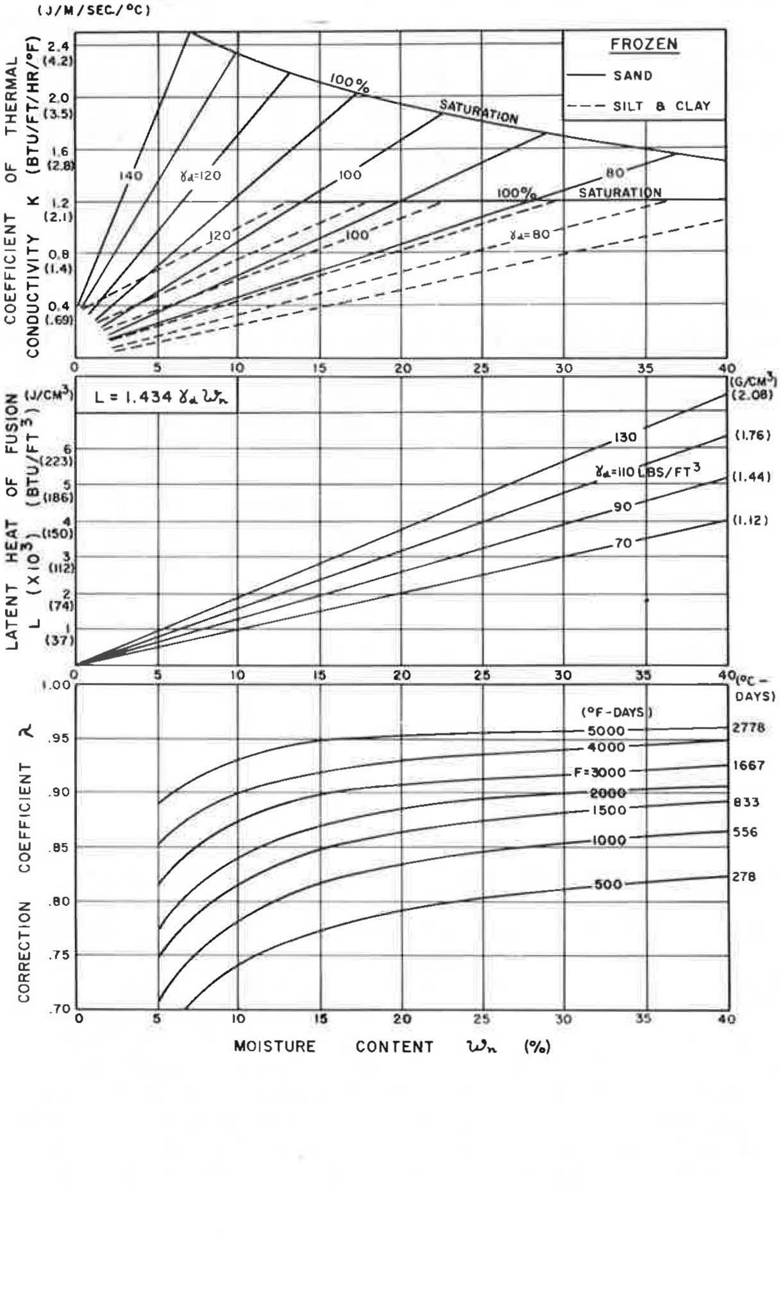


Figure 10. Soil parameters versus moisture content.



Berggren equation require the use of the pavement surface freezing index whereas the site data available usually consist of freezing indices computed with air temperatures measured 4 ft (1.2 m) above ground surface. Since average pavement surface temperatures are higher than their corresponding air temperatures, it follows that the freezing index of the pavement surface is lower than the air freezing index. As an engineering approximation, the surface freezing index may be estimated by applying a percentage correction factor N to the air freezing index:

$$F \text{ (pavement surface)} = N \times F \text{ (air)}$$

Information concerning surface/air correction factors is quite limited. Sanger (7) reports a value of 0.9 for bare pavements in the northern United States. Carlson (9), based on studies at Fairbanks, Alaska, reports values of 0.77 for portland cement concrete surfaces and 0.72 for asphaltic concrete surfaces.

Surface/air correction factors resulting from the Ministry of Transport's frost depth measurements are shown in Figure 11. The correction factors for each site were calculated by first computing the surface freezing index required to give the measured depth of frost penetration and then dividing this surface freezing index by the recorded air freezing index. For both asphalt and portland cement concrete surfaces, the freezing index surface/air correction factors determined show a tendency to decrease with decreasing site freezing index. Again, due to the black surface of asphalt pavements, the correction is greater for asphalt-surfaced pavements than for portland cement concrete pavements. The correction factor to use for a particular site may be estimated from the curves of Figure 11.

Accuracy of Computed Penetrations

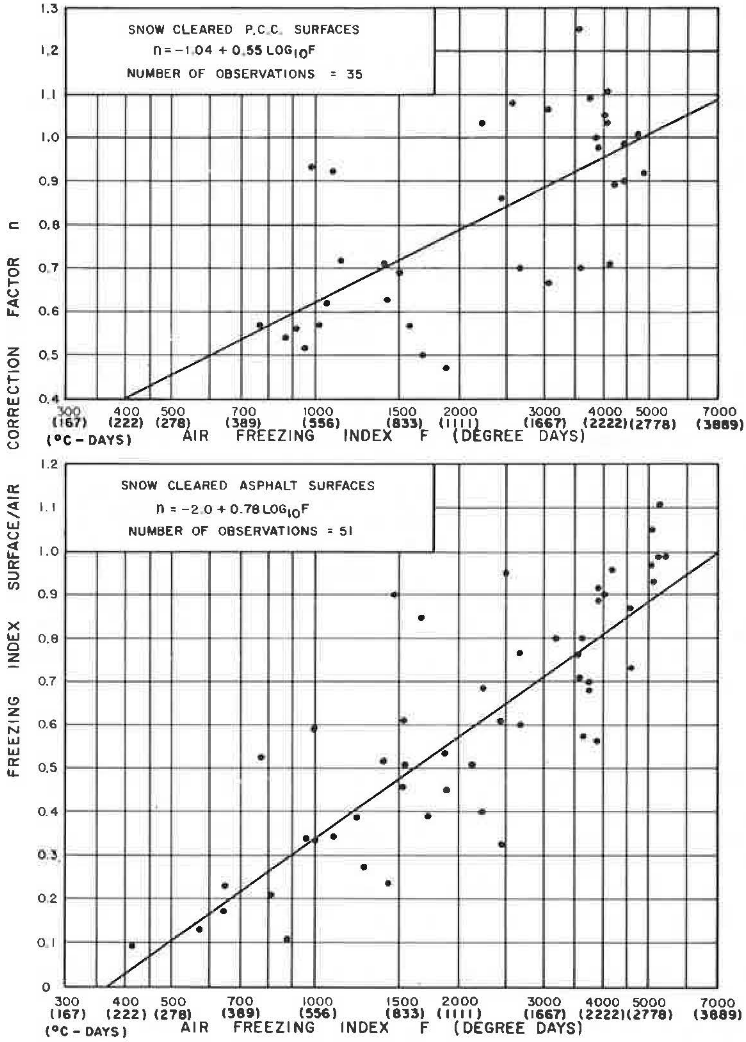
In performing the frost depth calculations, layer thickness and moisture content data were available from bore holes drilled during installation of the frost depth indicators. Soil densities were not known in most cases and had to be estimated. Typical values of densities and thermal characteristics adopted for the calculations were as follows:

Layer	Density, lb/ft^3 (g/cm^3)	W_n, Percent	K, Btu/ft/hour/deg F (J/m/s/deg C)	L, Btu/ft^3 (J/cm^3)
Asphalt	150 (2.40)	1	0.83 (1.4)	Fig. 10
PC	150 (2.40)	1	0.54 (0.93)	Fig. 10
Base courses	140 (2.24)	Measured	Fig. 10	Fig. 10
Sand subgrades	110 (1.76)	Measured	Fig. 10	Fig. 10
Silt + clay subgrades	90 (1.44)	Measured	Fig. 10	Fig. 10

Maximum frost depths calculated were compared with measured values and the standard error of the computed values was of the order of 7 in. (18 cm) for asphalt surfaces and 6 in. (15 cm) for portland cement concrete surfaces. The error would likely have been less if actual soil densities had been available and used in the calculations.

Because the effect of variable soil properties is included, estimates of frost penetration in pavements are more accurate when based on the modified Berggren equation rather than on Figures 3 and 4. The empirical relationships of Figures 3 and 4 are useful, however, because only a knowledge of site air freezing index is required and these indices can usually be estimated for most sites from readily available freezing index contour maps. Subgrade soil conditions, and hence the depth of frost penetration, will vary throughout any stretch of pavement. In addition, the depth of frost penetration at any given location will vary from year to year, depending on the freezing tem-

Figure 11. Freezing index surface/air correction factor.



peratures experienced. Because of these variations, the accuracy of estimates obtained from Figures 3 and 4 is often sufficient.

SUMMARY AND CONCLUSIONS

The following conclusions were derived from the frost and thaw measurement program undertaken at Canadian airports from 1964 to 1971:

1. The Gandahl frost depth indicator is a simple, inexpensive device that enables comprehensive surveys to be undertaken in recording the depth of frost and thaw penetrations.
2. With a knowledge of site freezing index only, the maximum frost penetration in snow-cleared pavements can be estimated from the relationships established with a standard error in the order of 12 to 16 in. (30 to 41 cm). Estimates with a standard error of less than 6 in. (15 cm) can be calculated if the necessary soils information is available.
3. The depth of frost penetration in undisturbed snow-covered areas is quite variable due to variations in the depth of snow cover, snow density, and the time of season it is in place. An upper limit, representing the maximum penetration that can be expected, may be estimated from the site freezing index alone.
4. Because of limited data, only a general indication is presently available on the maximum depth of thaw to be expected in gravel-surfaced pavements established on permafrost. However, a limit has been established for the maximum depth of thaw that might be expected in undisturbed permafrost areas with organic cover.
5. The freezing index surface/air correction factor, which must be employed in frost penetration calculations, depends on the site air freezing index. The correction factor decreases with decreasing site air freezing index, and the correction is greater for asphalt-surfaced pavements than for concrete-surfaced pavements.

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