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RÉSUMÉ

On a étudié pendant cinq ans le comportement thermique d'un remblai de route construit sur le pergélisol dans la zone discontinue de la vallée du Mackenzie. Ce remblai de faible hauteur (1,2 m) était formé de matériau de remblai propre, déversé sur une partie d'emprise préalablement débarrassée de ses arbres. La route n'ayant jamais été ouverte à la grande circulation, les activités de déneigement étaient réduites au minimum.

Les mesures prises comportaient l'enregistrement horaire des températures du sol à l'aide d'un appareil enregistreur autonome. Les tassements ont été contrôlés et des sondes de conductivité thermique installées pour obtenir des données sur les tendances saisonnières dans le remblai même et dans les divers matériaux composant la couche active.

Les données obtenues indiquent que la dégradation du pergélisol est en cours et fournissent des renseignements sur le rapport entre les températures de surface de la route et les facteurs climatiques de la région.

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THERMAL PERFORMANCE OF A SECTION OF THE MACKENZIE HIGHWAY

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The thermal performance of a shallow road embankment constructed on permafrost in the discontinuous zone of the Mackenzie Valley was monitored over a 5-year period. The shallow (1.2 m) embankment consisted of clean borrow material end dumped on a right-of-way which had previously been cleared of trees. The road was never opened to general traffic; consequently snow removal was minimal. Measurements included hourly ground temperatures recorded with a data logger operating unattended. Settlements were monitored and thermal conductivity probes were installed to yield information on seasonal trends within the embankment and in the various natural materials comprising the active layer. The data indicate that degradation of the permafrost is under way and provide information on the relation between road surface temperatures and climatic factors for this region.

INTRODUCTION

In 1972 the Mackenzie Highway Environmental Working Group was established by the Department of Indian Affairs and Northern Development to monitor the environmental impact of the proposed Mackenzie Highway joining Fort Simpson to Inuvik and the Arctic coast. The Division of Building Research of the National Research Council of Canada was invited to carry out a limited study of the thermal aspects. At that time no case studies of shallow embankments constructed on permafrost had been carried out in the Fort Wrigley region. It was expected that although degradation would not pose serious problems in the zone south of Fort Wrigley, the data collected could be used to anticipate problems in the more difficult soils to the north. Although, as originally planned, the road was to be a graveled, all-weather road, construction was halted and during the final two winters of this study there was only minimal snow removal.

OBJECTIVES

The specific objectives of this study were:

1. to observe the changes in temperature regime in the ground underlying the road embankment as well as in the surrounding right-of-way in order to assess the thermal disturbance caused by the embankment;
2. to collect data on temperatures within the embankment for design purposes;
3. to assess the settlements of the embankment;
4. to obtain basic soil information for the site, including profiles of ice content, soil density, and composition; and
5. to measure thermal conductivities both in the natural ground and in the embankment and to assess seasonal and year-to-year variations.

FIELD INSTRUMENTATION

Field work was begun in March 1976 at mile 419.5, near the northern end of the proposed new construction on the Mackenzie Highway (Figure 1). Earlier reconnaissance had indicated the presence of permafrost. This location also offered important logistic advantages. The Hire North camp at River-Between-Two-Mountains could serve as base of operations, and in addition, a winter road facilitated access to Fort Simpson, the nearest point with land connections to the south. For these reasons this site was selected, even though more sensitive terrain could be found to the north.

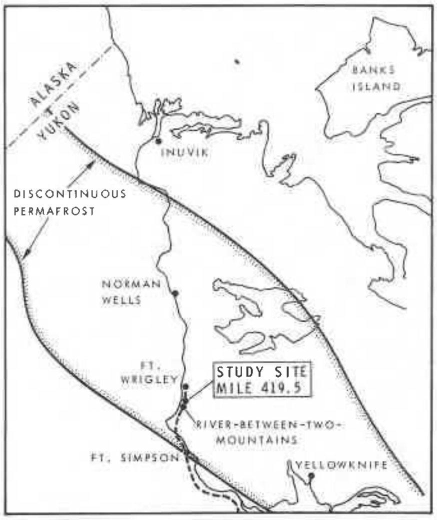

FIGURE 1 Location map.

To compare thermal conditions under the future embankment centerline, the shoulder, the previously cleared right-of-way, and the original undisturbed terrain, four holes were drilled approximately 8 m deep (the maximum achievable with equipment at hand). These locations correspond to profiles A, B, C, and D in Figure 2. Nearly continuous core was recovered from hole A (centerline), and grab samples were collected from holes B and D. The soil type, moisture content, and density were determined on site. In addition, representative core samples were shipped to the laboratory for further evaluation, including thermal conductivity measurements. The holes were instrumented with Yellow Springs #44033 thermistors mounted on multiconductor cable to a depth of 7 m. The cables were cased in PVC plastic tubing for protection from mechanical damage, and the boreholes were backfilled with dry sand. A prefabricated instrument hut made of fiberglas-styrofoam sandwich panels was erected at the site.

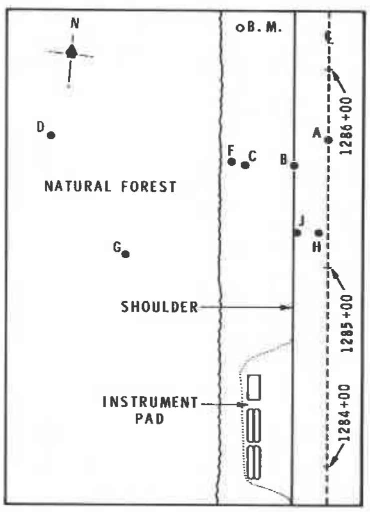

FIGURE 2 Site layout.

A Monitor Systems 9400 data logger using a lower power Digi-Data tape drive was installed in September 1976. Power was provided by a 3M propane-driven thermoelectric generator which simultaneously charged a bank of Gel-Cell batteries serving as a backup power supply. A propane furnace was installed to maintain ambient temperatures within the hut at levels adequate for the data-logging equipment. At this time also, three small pits (E, F, and G in Figure 2) were dug to a depth of approximately 1 m. The pits were instrumented with thermistors potted into metal tubes mounted horizontally on vertical wooden stakes. These installations were intended to provide more reliable information on near-surface temperature conditions than that available from the deep cables A-D. The pits were also instrumented with thermal conductivity probes (Goodrich 1979) to measure the seasonal variation of conductivity for the different materials comprising the active layer.

In June 1977 the final grade was completed past the instrumented section. A trench was dug across the road and stake-mounted thermistor probes, similar to those used in the shallow pits, were installed in the trench wall (Cables H and J in Figure 2). The addition of four thermal conductivity probes completed the thermal instrumentation. Finally, settlement plates were installed on the centerline and near the shoulder to monitor total settlement of the embankment.

The test site was operated, with some interruptions, from September 1976 until March 1981. During this time the data-logging equipment and thermoelectric power supply were left to function unattended for periods of 3-4 months. Approximately 80 channels, including 3 used to verify the equipment, were recorded every hour. Thermal conductivity measurements and level surveys were made whenever possible during site visits.

RESULTS

Figure 3 shows the soil profile for the centerline borehole (profile A). Conditions at the three remaining boreholes were similar, as inferred from split spoon sampling. The profiles consist primarily of silts and sands with some layers of gravel. Fine-grained materials are prevalent in the upper part of the profile, while the gravel layers are found only below 4 m. Correspondingly, the total volumetric moisture content varies from nearly 80% in the upper levels to less than 40% at depth. While some small ice lenses (<5 mm) are present in the silt layers, most of the ice is dispersed, and the soil is well bonded with ice throughout.

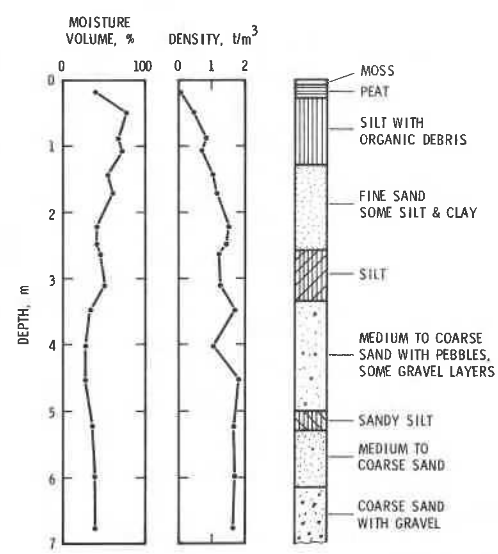

FIGURE 3 Soil conditions: mile 419.5.

Daily mean temperatures for all channels were computed from hourly data recorded on the original tapes. Data processing included a check of each scan for instrument drift, channel sequence, range and sign bit, and clock errors. If more than five unsatisfactory scans occurred in a daily period, the entire daily record was rejected. Since the manufacturer claimed an interchangeability error of less than ±0.1°C, thermistor linearization was done using the same formula for all channels. Examination of Figure 4 reveals, however, that overall errors may be considerably greater. The temperatures for channels 8-10, all of which are located at levels within the active layer (also channel 11 from 1979 onwards), should be near or at the freezing point during the autumn freezeback period (zero-curtain effect). Although this is well verified for channels 8 and 10, the error for channel 9 is rather more than 1°C, and that for channel 11 is nearly as great. It can also be seen that the errors increase with time. Errors of similar magnitude were found in other profiles for several channels in the active layer where a well-defined zero-curtain existed; nearly a third of these channels required corrections of more than 0.2°C. For channels below the active layer there is no certain reference temperature. In a few cases, corrections could be inferred from an examination of the annual mean profiles along with observation of the temporal behavior. In most instances, however, the data for these points were rejected. Typical corrected data are shown for the centerline profile in Figure 5.

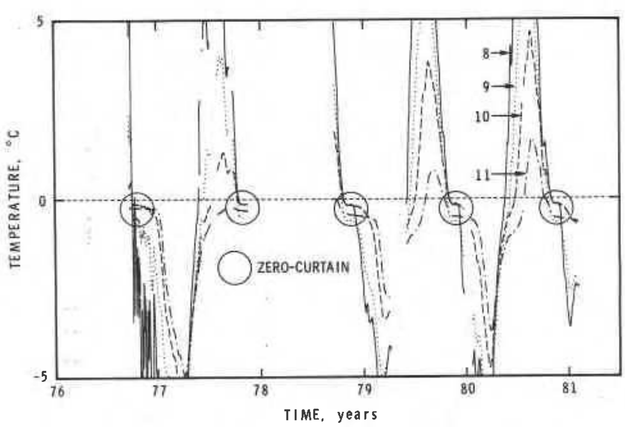

FIGURE 4 Errors in raw data of profile A C/L.

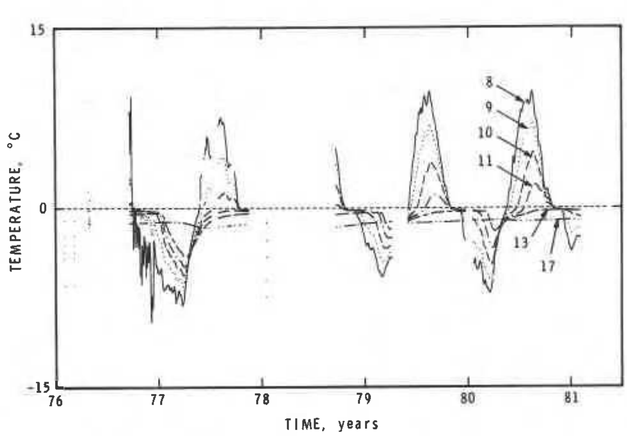

FIGURE 5 Corrected profile A C/L.

As regards equipment reliability, Figures 4 and 5 indicate that a nearly complete record was obtained, with two major exceptions. The long gap from mid-November 1977 to mid-September 1978 was the result of three separate circumstances. The data logger had to be removed for repairs in November 1977. All the equipment, except the defective data logger, was lost when fire destroyed the site in March 1978. Further delay resulted when plans to abandon construction of the road were announced. The second major gap, during early 1979, was purely the result of human error and not of equipment malfunction.

Thermal conductivity measurements were made whenever possible during routine site visits. Fifteen probes were eventually emplaced in a variety of materials, including the natural lichen mat and the decomposed peat layer, as well as at several depths in the natural soil and in the embankment. Figure 6a shows results obtained both in natural peat and in the peat layer underlying the embankment. Data for all years have been plotted on the same axes. The data can, in both cases, be reasonably well represented by constant frozen or thawed values. The thermal conductivity of the compressed peat beneath the embankment is 2-3 times that of the natural peat. In addition, the ratio of frozen to thawed conductivity is reduced from approximately 4 for the natural peat to approximately 2 for the compressed peat. Figure 6b shows thermal conductivities measured near the surface and near the base of the embankment. The data suggest that for the level near the surface the thawed conductivity is remarkably similar from one year to the next. Frozen values are distinctly greater but also show more scatter. It is interesting to note that for the lower level no distinct seasonal pattern is evident. The greatest year-to-year variation is, however, again found in the winter values.

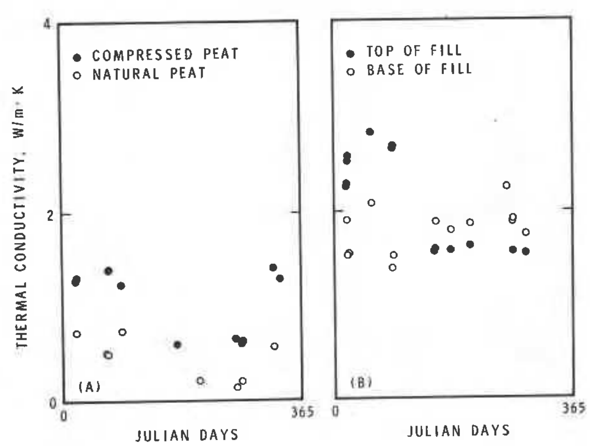

FIGURE 6 Thermal conductivity variation.

Some level survey results for the embankment centerline are summarized in Figure 7. The curves suggest similar trends at the embankment surface and base. (The increase in surface level in mid-1979 reflects road maintenance operations.) Total settlement from construction in mid-1977 to the final survey in mid-1980 was approximately 0.3 m. At many stations in the 200 ft (~60 m) section surveyed, there was considerably more settlement near the shoulders than on centerline. By mid-1980 the road surface had become a series of bumps and hollows with elevation differences of approximately 0.15 m over 10 m intervals.

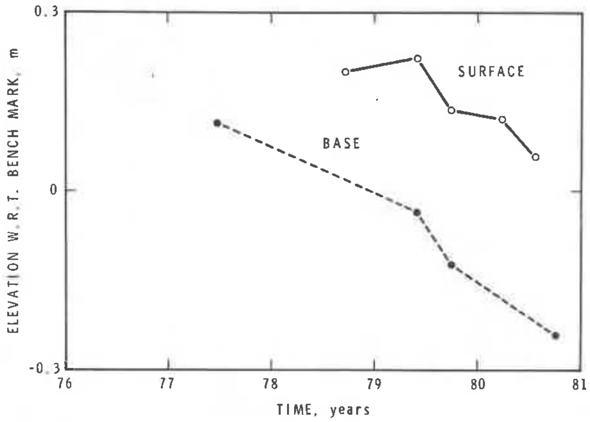

FIGURE 7 Settlement: C/L STN 1285 + 17.

DISCUSSION

Hand probing carried out during the initial reconnaissance (autumn 1975) indicated that the active layer in adjacent undisturbed terrain at the site was typically about 50 cm thick. There was, however, evidence that significant thermal degradation was under way following removal of the black spruce cover some 2 years earlier. Near the eastern side of the cleared right-of-way, advanced degradation was evident along the route of the former Canadian National Telegraph line. Here the ground was thawed to depths of 2 m or more.

The annual progress of the zero isotherm within the embankment and in the underlying ground is shown for the centerline profile in Figure 8. Although the term "zero isotherm" is used here and elsewhere for convenience, the graph, in fact, shows the isotherm for -0.15°C, this value being consistent with the zero-curtain "calibration" of Figure 5. The isotherm histories were computed from the adjusted daily mean temperatures with no temporal or spatial smoothing. This explains some of the apparent scatter in the curves. Note also that the cuspoidal shapes, seen especially in the advancing thaw fronts, are merely artefacts of the method (linear interpolation) used to calculate the position of the isotherm. This procedure will necessarily overestimate isotherm depth, except when the isotherm traverses a measurement level.

It can be seen from Figure 8 that prior to embankment construction the subgrade thawed to a depth of less than 1 m. Since construction, the thaw has progressed to successively greater depths each year so that by 1980 the total thaw reached 1.4 m.

Annual mean temperatures computed from the 3 years of nearly continuous records are shown for the embankment and subgrade centerline profile in

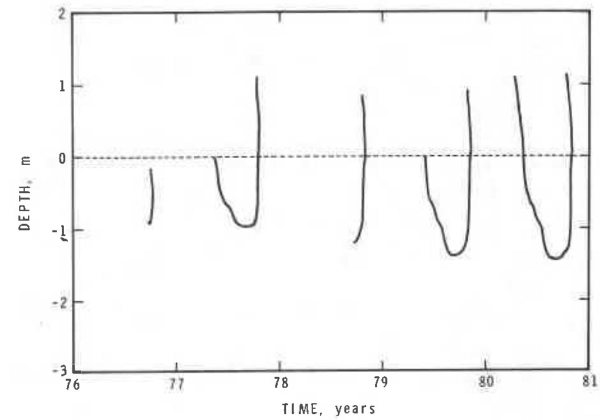

FIGURE 8 Centerline zero isotherm.

Figure 9 and shoulder profile in Figure 10. In 1979 and 1980, annual mean temperatures at the embankment surface were approximately +1.5°C on centerline and +3°C at the shoulder. A substantial increase (about 1°C) has occurred in the upper 1-2 m of the subgrade since the embankment was built. A similar trend is seen in the embankment shoulder profile (Figure 10). While shallow subgrade temperatures under the shoulder are not more than 0.3°C warmer than those at the centerline, near the surface the difference is substantially greater. The reversed curve in the upper levels of the 1977 profiles seen in both Figures 9 and 10 reflects the fact that construction activities took place during the first half of that year.

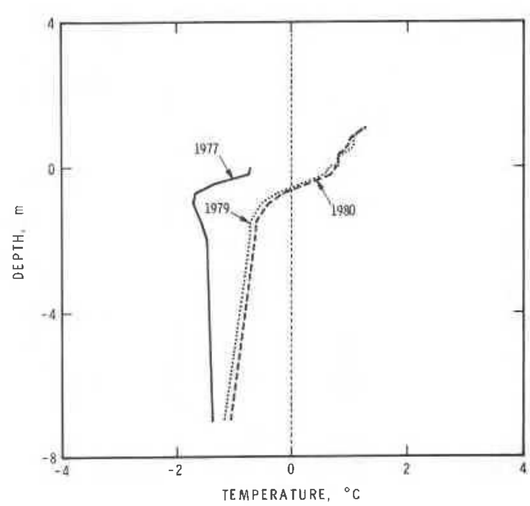

FIGURE 9 Annual means: centerline.

Figure 11 shows the annual mean temperatures for the deep datum cable located in the nearby partially cleared bush. It should be noted that the

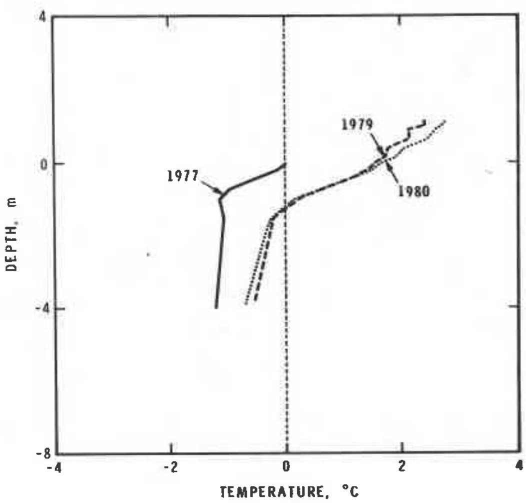

FIGURE 10 Annual means: shoulder.

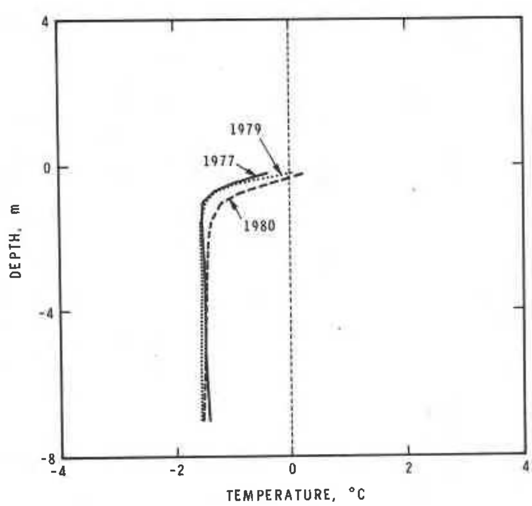

FIGURE 11 Annual means: deep datum.

results for 1979 are nearly identical to those for 1977. This may be interpreted as evidence that the large differences between the temperatures for these years in the embankment profiles are indeed caused by the presence of the embankment and are not merely a reflection of different weather conditions. Note, too, in Figure 11 that in successive years the near surface temperatures are a fraction of a degree warmer. In addition, there is some tendency for the active layer to deepen, as seen in Figure 12.

At all three sites, annual mean temperatures exhibit a strong tendency to decrease sharply through the active layer. This may be, at least in part, a manifestation of the thermal rectification effect resulting from temperature-dependent thermal

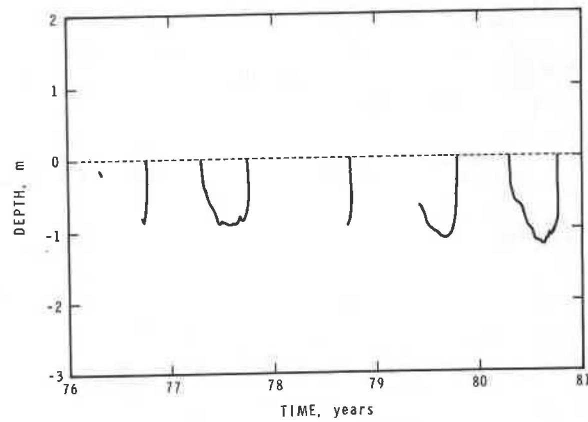

FIGURE 12 Deep datum zero isotherm.

conductivity. When the frozen conductivity is greater than the thawed conductivity, as it is here, annual mean temperatures will decrease with depth. The fact that profile distortion is confined primarily to the active layer suggests that thermal rectification is indeed the principal mechanism at these sites.

Profile curvature may, in addition, indicate that deep temperatures are not yet in equilibrium with long-term conditions at the surface. The 1980 profile at the deep datum site, Figure 11, suggests that mean temperatures will probably continue to rise somewhat and that, not unexpectedly, this datum site is far from being "undisturbed."

Figure 13 shows a comparison of temperatures at 1 m depth below the original ground surface for the embankment centerline, the shoulder, and the deep datum site. From the shape of the curves it can be inferred that thawing did not occur at the deep datum site during the first 2 years, but did occur in 1979 and was more intense in 1980. The data also indicate that some slight thawing occurred at the shoulder profile even before construction. There was no thawing prior to construction at the centerline 1 m level. Finally, it should be noted that the subgrade temperatures are warmer than the datum values not only in winter but also in summer; the shallow embankment enhances summer heating while reducing winter cooling.

Table 1 presents approximate values of "n-factors" for the site. The n-factors are computed as the ratio of the thawing or freezing index at the road surface (that is, beneath the snow cover) to that of the air. Surface temperatures were estimated by extrapolation from measurements starting at a level 20 cm below the surface. Since the air temperature records at the site were incomplete, data were extracted from the published records for Fort Simpson (200 km south of the site), the nearest regularly reporting standard meteorological station. The values in Table 1 should therefore be considered with caution. They can, however, be used for relative comparisons. Table 1 implies that the gravel surface had a thawing n-factor only 16%-19% greater than that of the original terrain. The difference is smaller than expected, and this may, in part, reflect disturbance at the datum site.

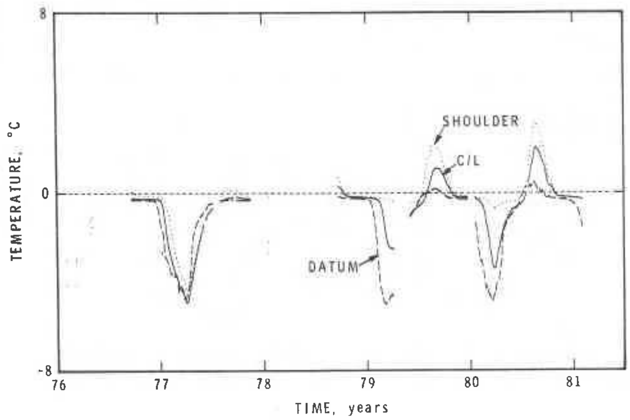

FIGURE 13 Comparison of temperatures at 1 m below original surface.

TABLE 1 Estimated "n-factors".

Year	Thawing Index (°C•day)	Freezing Index (°C•day)	C/L n_t	C/L n_f	Datum n_t	Datum n_f
1978–79	1970	3250	1.08	0.50	0.93	0.56
1979–80	2080	2920	1.02	0.56	0.86	0.64

CONCLUSION

The data suggest that for the climatic and soil conditions in the Fort Wrigley area, road construction results in degradation of the permafrost in spite of special precautions taken to minimize disturbance of the organic cover. For the present conditions of road operation (winter road) with infrequent traffic and limited snow removal, annual mean road surface temperatures are up to 3°C above the freezing point. Since there may, however, be a significant thermal rectification effect associated with temperature-dependent thermal properties at shallow levels, it is possible that mean temperatures at depth will remain negative.

The maximum thaw penetration is about 50% greater beneath the embankment than at the datum site. During the study period there was an evident tendency for the active layer to deepen with time. This tendency, however, in addition to implying a long-term increase in deep-ground temperatures, also mirrors the increase observed in summer air temperatures; consequently, it cannot be stated unequivocally that the active layer beneath the embankment will continue to deepen significantly. Further monitoring of the site would be required to establish the long-term trends with certainty.

Not all the data have been examined at this time. Further analysis, including numerical model simulation, may shed light on the ambiguities noted in this paper and provide useful guidance in designing future embankments in the Mackenzie Valley region.

ACKNOWLEDGMENTS

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