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IMPROVED DRAINAGE AND FROST ACTION CRITERIA FOR NEW JERSEY PAVE--ETC(U)
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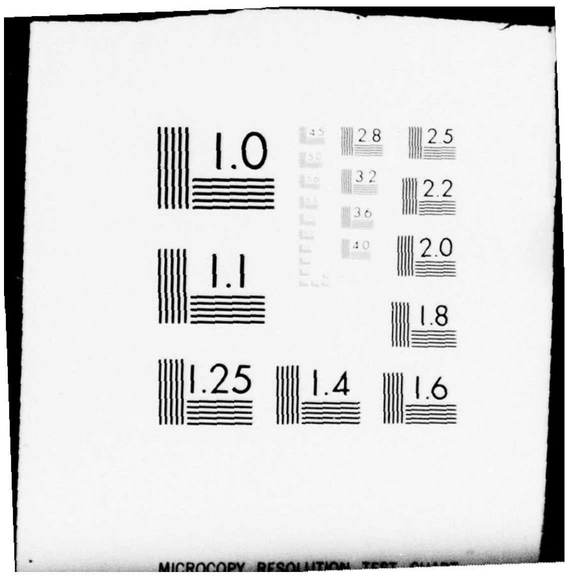
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Special Report 79-15

May 1979

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IMPROVED DRAINAGE AND FROST ACTION CRITERIA FOR NEW JERSEY PAVEMENT DESIGN

PHASE II (DATA ANALYSIS)

Richard L. Berg

Prepared for
NEW JERSEY DEPARTMENT OF TRANSPORTATION
DIRECTORATE OF RESEARCH AND DEVELOPMENT
By
UNITED STATES ARMY
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With the assistance of the Federal Highway Administration, the New Jersey Department of Transportation is studying the feasibility of including open-graded drainage layers in their highway pavements. Before constructing actual pavements with open-graded drainage layers, they chose to measure frost penetration depths and moisture content profiles beneath several pavements in New Jersey. Air and surface freezing indexes were measured at three locations during the 1975-1976 and 1976-1977 winters. Air freezing indexes ranged from

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20. Abstract (cont'd)

95°F-days to 783°F days. Surface freezing indexes in asphaltic concrete pavements ranged from 59°F-days to 400°F-days, and for Portland cement concrete pavements ranged from 57°F-days to 388°F-days. All freezing indexes were considerably greater during the 1976-1977 winter. Measured maximum frost penetration depths were compared with computed maximum depths for each of 30 test sites. The modified Berggren equation was used to compute the maximum frost depth at each site. Measured maximum frost depths ranged from 20.5 in. to 52.0 in., while computed maximum values ranged from 14.0 in. to 61.0 in. The mean difference between observed and computed maximum frost penetration depths was 3.8 in. Maximum frost penetration depths were computed for hypothetical pavements with open-graded drainage at four of the test sites. It was concluded that open-graded drainage layers would not significantly change the frost penetration beneath highway pavements in New Jersey. It was recommended that test pavements be installed to verify the computations.

PREFACE

This report was prepared by Dr. Richard L. Berg, Research Civil Engineer, of the Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

Primary funding for this study was provided by the New Jersey Department of Transportation, Directorate of Research and Development, Trenton, New Jersey, under New Jersey State Agreement No. 7740, December 1976, Improved Drainage and Frost Action Criteria for New Jersey Pavement Design, Phase II - Frost Action (Data Analysis). This is the final report submitted by CRREL on this study.

Secondary funding was provided by the Federal Highway Administration, Fairbanks Highway Research Station, Washington, D.C. (A.F. De Millio), under Order No. 5-3-0202, May 1978, Development of Mathematical Model in Correlating Observed Frost Heave of Highway and Airport Pavements with Laboratory Predictions.

The technical content of this report was reviewed by W.F. Quinn of CRREL and by G. Koslov of the New Jersey Department of Transportation.

Special recognition is given to SP4 C. Espiritu, and R. Godfrey, who accomplished most of the computer solutions to the modified Berggren equation.

The contents of this report are not be used for advertising or promotional purposes. The citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To Obtain
inch	0.0254	meter
°F	0.556 (F-32)	°C
Btu/pound	2326.	joule/kilogram
pound/cu ft	16.018	kilogram/cu meter
Btu/sq ft	11356.53	joule/sq meter
foot	0.3048	meter
cubic foot	0.02832	cubic meter
mile (statute)	1.6093	kilometer

IMPROVED DRAINAGE AND FROST ACTION CRITERIA FOR NEW JERSEY PAVEMENT DESIGN PHASE II (DATA ANALYSIS)

Richard L. Berg

INTRODUCTION

In early 1975, engineers from the New Jersey Department of Transportation (NJDOT) visited CRREL to discuss a program they were embarking upon with assistance from the Federal Highway Administration. NJDOT was interested in including open-graded drainage layers in their pavement, but before doing so chose to determine analytically the effect of frost penetration beneath pavements when using an open-graded drainage layer. In early July 1975 NJDOT issued a contract to CRREL to conduct the study, the principal goal of which was to analytically determine the impact of an open-graded drainage layer on the depth of frost penetration beneath pavements in New Jersey.

The final report on that study (Berg and McGaw 1978) was submitted to NJDOT in June 1978. In the previous study, the modified Berggren equation was used to estimate the maximum seasonal frost penetration depths beneath several pavement profiles in New Jersey. Mean and design freezing indexes were developed for Newton, Trenton and Altantic City, New Jersey, and used in the calculations. Surface transfer coefficients, i.e., n-factors, were determined from air and surface temperature data supplied by NJDOT. They also furnished aggregates for thermal conductivity tests on base and subbase course materials and paving materials. Aggregates for the proposed stabilized and unstabilized drainage layers were also included for thermal conductivity tests.

The current study was initiated in December 1976 and was to extend through September 1977. In October 1977 the contract was extended to 30 March 1978.

The study had the following objectives:

a. To determine the probable magnitude of frost penetration depths at specific sites in New Jersey.

b. To compare calculated frost penetration depths with measured depths to verify the prediction capability of the modified Berggren equation in New Jersey, and

c. To determine whether there may be special or unanticipated adverse affects due to application of open-graded drainage layers.

THERMAL ANALYSIS

In the previous study (Berg and McGaw 1978), pages 23-34, the modified Berggren equation was used to calculate maximum frost penetration depths in selected New Jersey pavement profiles. At the suggestion of CRREL engineers, NJDOT engineers and technicians installed frost tubes for monitoring frost penetration depths and access tubes for monitoring subsurface moisture conditions with a nuclear probe. CRREL's NJDOT colleagues collected and tabulated data from the test sites and sent the data to CRREL. The remainder of this report describes information from the field test sites and gives calculations of frost penetrations at the sites.

Field Test Sites

During the 1976 summer and fall NJDOT installed frost tubes and access tubes for a nuclear moisture sensor at 30 locations in the northern, central and southern portions of New Jersey. Figure 1a shows the locations of the test sites. During the 1976-1977 winter, NJDOT personnel measured frost penetration depths and moisture contents at these sites two to three times per week. The frost penetration and moisture content data were tabulated by NJDOT personnel and mailed to CRREL. At CRREL the data were analyzed and used in the computations of frost penetration depth. All of the frost penetration data were plotted as were measured moisture contents at selected depths; these are presented in Appendix A.

Figure 1b shows three locations in the state (Rockaway, Bedminster and Bordentown) where air and pavement surface temperatures were measured simultaneously. Air and surface temperatures were measured at the same three sites during the 1975-1976 winter and their respective freezing indexes were reported previously (Berg and McGaw 1978), pages 5-6. Daily maximum and minimum air and pavement surface temperatures were tabulated by NJDOT personnel and sent to CRREL where freezing indexes and n-factors were determined. At each of the three sites, surface temperatures were measured on both asphaltic concrete and Portland cement concrete pavements.

Six sites were choosen by NJDOT (1977) for detailed thermal analysis using the modified Berggren equation. At these sites, different parameters in the modified Berggren equation were varied to evaluate their influence on computed frost depths. After completion of these calculations, frost penetration depths were computed and compared to measured values for the remaining 24 sites. The six sites chosen for detailed analysis were Site Numbers 6, 9, 11, 18, 22 and 29 (Figure 1a). The thickness and properties of various materials in the pavement profiles are discussed subsequently.

Surface Transfer Coefficients

Berg and McGaw (1978) discussed surface transfer coefficients, n-factors, which have been observed in various geographical locations in the United States, Canada and Norway. As previously stated the New

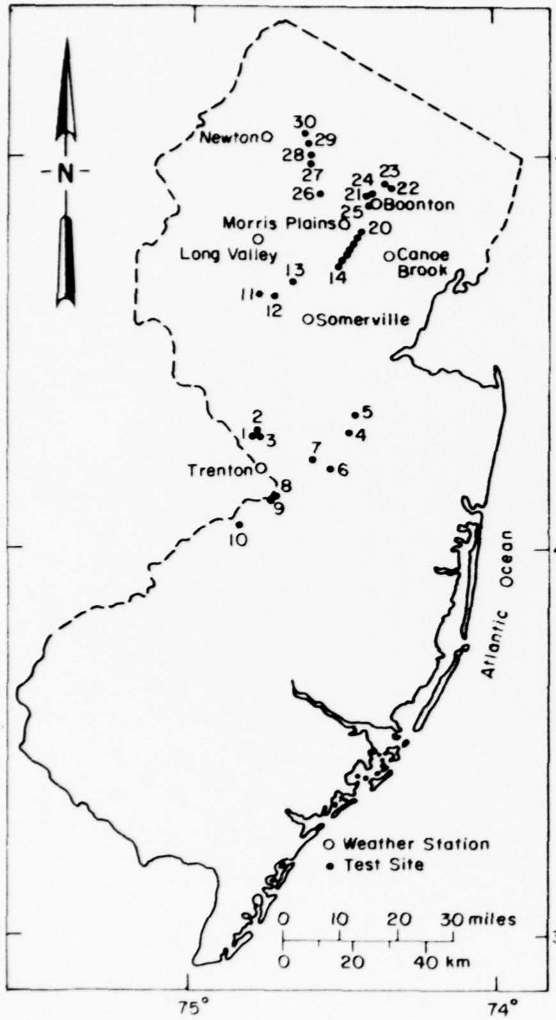

Figure 1a. Location of test sites where frost depths and subsurface moisture contents were measured.

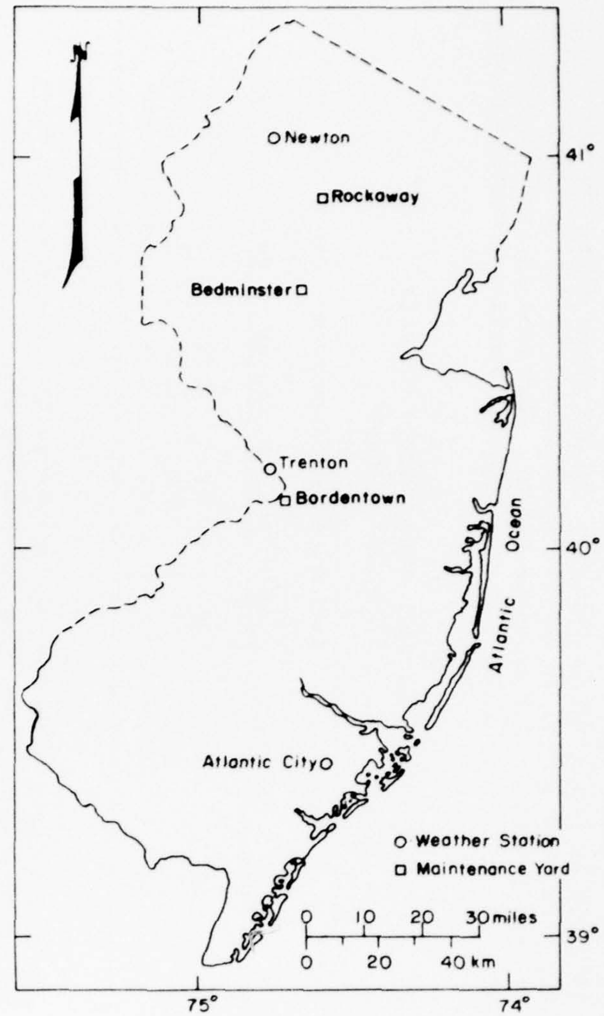

Figure 1b. Map of New Jersey showing the test site locations for measuring air and surface temperatures.

Jersey Department of Transportation measured surface and air temperatures during the 1975-1976 and 1976-1977 winters.

Data for the 1975-1976 winter were reported previously (Berg and McGaw 1978), and freezing indexes and n-factors measured during the 1976-1977 winter are shown in Table 1. At all three sites the air freezing index and length of the air freezing season were greater in the 1976-77 winter than in the previous winter. The same is true for the Portland cement and asphaltic concrete pavement surface freezing indexes.

Table 1. Freezing indexes and n-factors 1976-1977 winter.

Site	Air		Portland cement concrete			Asphaltic concrete		
	Season days	Index °F-days	Season days	Index °F-days	n-factor	Season days	Index °F-days	n-factor
Bordentown	46	316	41	93	0.29	44	181	0.57
Bedminster	51	446	52	388	0.87	52	400	0.90
Rockaway	84	783	72	295	0.38	70	304	0.39

Table 2 summarizes n-factors for the asphalt concrete and Portland Cement concrete pavements during 1975-76 and 1976-77 winters. For Bordentown and Rockaway the n-factors were generally slightly lower during the 1976-1977 winter than observed in the 1975-1976 winter. The exception was the n-factor for the Portland cement concrete test section at Bordentown which was considerably less during the 1976-1977 winter than observed during the 1975-1976 winter. Data from Bedminster exhibited a different behavior. During both winters the n-factor for asphaltic concrete was considerably higher at Bedminster than observed at the other two sites. Data from the Bedminster site also indicated that the n-factor for the asphaltic concrete pavement was slightly higher during the 1976-1977 winter than measured during the 1975-1976 winter. Although the n-factor over the Portland cement concrete pavement at Bedminster agreed quite well with the observations at the other two sites during the 1975-1976 winter, it was considerably higher during the 1976-1977 winter.

Table 2. n-Factors from New Jersey sites.

Site	Asphaltic concrete 1975-1976	Asphaltic concrete 1976-1977	Portland cement concrete 1975-1976	Portland cement concrete 1976-1977
Bordentown	0.62	0.57	0.60	0.29
Bedminster	0.84	0.90	0.54	0.87
Rockaway	0.46	0.39	0.40	0.38
	Use* 0.55		Use* 0.45	

*Value used in computation of maximum frost depth using the modified Berggren equation if the surface freezing index was not measured at a nearby location.

Air and surface temperature data information from Bedminster show no anomalous behavior during either the 1975-1976 or 1976-1977 winters. As part of the current study, however, air freezing indexes during the 1976-1977 freezing season were computed for several other locations in New Jersey (Table 3). These data indicate that air temperatures measured at Bedminster were significantly higher than those measured in nearby communities, thereby causing a lower freezing index at Bedminster. Air freezing indexes at Long Valley and Somerville averaged 795 degree days for the 1976-1977 winter, whereas the air freezing index measured at Bedminster was only 446 degree days.

The lengths of the freezing seasons were significantly different at the three sites also.

Table 3. Weather stations, air freezing indexes and lengths of freezing season used in the thermal analysis.

Site No	Weather station*	Location**	Air freezing index, °F-days	Length of freezing season, days
6	Trenton	12 mi W	446	51
9	Bordentown	at site	316	46
11	Long Valley	9 mi N	800	85
11	Somerville	9 mi SE	790	85
18	Canoe Brook	5 mi SE	771	86
18	Morris Plains	4 mi NW	764	86
22	Boonton	1 mi S	822	86
29	Newton	7 mi W	1075	86

* National Oceanic and Atmospheric Adminstration stations except Bordentown where temperatures were obtained by NJDOT.

** Approximate distance and direction from test site.

At both Long Valley and Somerville the freezing season was 85 days, but the season observed at Bedminster was only 51 days. Using the average air freezing index (795°F-days) from Long Valley and Somerville with the surface freezing indexes (388 and 400°F-days) measured at Bedminster, the calculated n-factors of 0.49 and 0.5°F for the Bedminster site agree much more closely with values observed at the other two sites. The effect of variations in the n-factors and the influence of these variations were discussed previously (Berg and McGaw 1978).

Conditions used in the computations for each of the sites are summarized subsequently, and the n-factor used when the surface temperature was not measured near the field test site is shown in Table 2.

Thermal Properties

For the calculations in this report, thermal properties were determined by methods discussed by Berg and McGaw (1978). Moisture contents for each of the field test sites were estimated from measurements made by NJDOT personnel and furnished to CRREL in tabulated form. The moisture content and the estimated density influence all of the thermal properties, i.e., thermal conductivity, volumetric heat capacity and volumetric latent heat of fusion.

The volumetric heat capacity, in Btu/cu ft °F, is determined from the following equation:

$$C = \gamma_d \left[c + (0.75)\ (w/100)\right] \tag{1}$$

where γ_d = the dry unit weight, lb/cu ft

c = the specific heat of dry soil, Btu/lb °F

w = the moisture content, % dry weight

The volumetric latent heat of fusion, in Btu/cu ft, is determined from equation (2):

$$L = 144\ \gamma_d\ (w/100) \tag{2}$$

The thermal conductivity was determined by the procedure outlined by Berg and McGaw (1978):

a. For the unknown soil, determine or estimate the dry density and moisture content by dry weight.

b. Using the equations below or Figures 2 and 3 find Kersten's value of thermal conductivity, K_s, for a soil having the same density and moisture content.

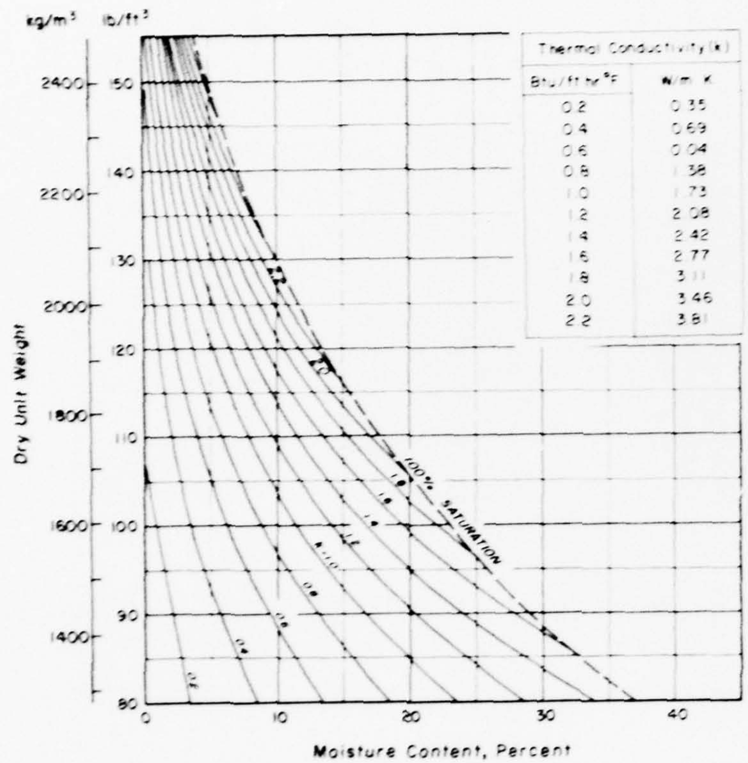

Figure 2. Kersten's thermal conductivity values for sandy soils, frozen (in Btu/ft hr °F).

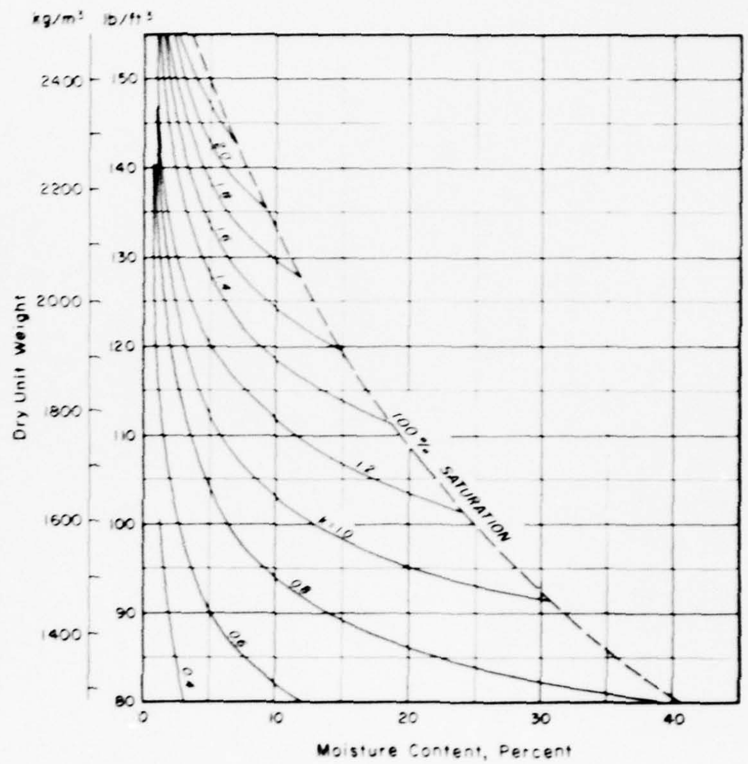

Figure 3. Kersten's thermal conductivity values for sandy soils, unfrozen (in Btu/ft hr °F).

For unfrozen sandy soils

$$K_s = [0.7 \log (w) + 0.4] \, 10^{0.01\gamma_d} \qquad (3)$$

and for frozen sandy soils

$$K_s = 0.076 \, (10)^{0.013\gamma_d} + 0.032 \, (10)^{0.0146\gamma_d} \, (w) \qquad (4)$$

where K_s = thermal conductivity, Btu/sq ft hr °F/in

γ_d = dry density of the soil, lb/cu ft

w = moisture content, % dry weight

c. Enter the appropriate curve for Figure 4 or 5 with the percentage passing the 200 sieve for the New Jersey soil and find the corresponding ratio of K/K_s.

d. Multiply the Kersten value, K_s, by the ratio determined in step c and the resulting value should be within $\pm 10\%$ of the thermal conductivity for the New Jersey soil.

For the pavement material and the stabilized and unstabilized drainage layers, thermal conductivity values used in the calculations were those determined from thermal conductivity tests conducted during the previous study (Berg and McGaw 1978).

Frost Depth Calculations

Thicknesses and representative values for the moisture contents of the various paving materials were obtained from data provided by the NJDOT. Densities for each of the materials were obtained from data used in the previous study (Berg and McGaw 1978), and from NJDOT (1978).

Densities and moisture contents were used with the methods described above to estimate the thermal properties for each soil layer; results are shown in Table 4.

As previously stated a detailed analysis of the influence of various parameters was performed at six of the selected test sites. Table 5 contains initial and upper boundary conditions used at these six sites. Also shown in Table 5 are the frost penetration depths computed using each set of initial and boundary conditions in conjunction with the soil and pavement properties shown in Table 4. The frost depth was calculated using the modified Berggren equation, a complete explanation of which is

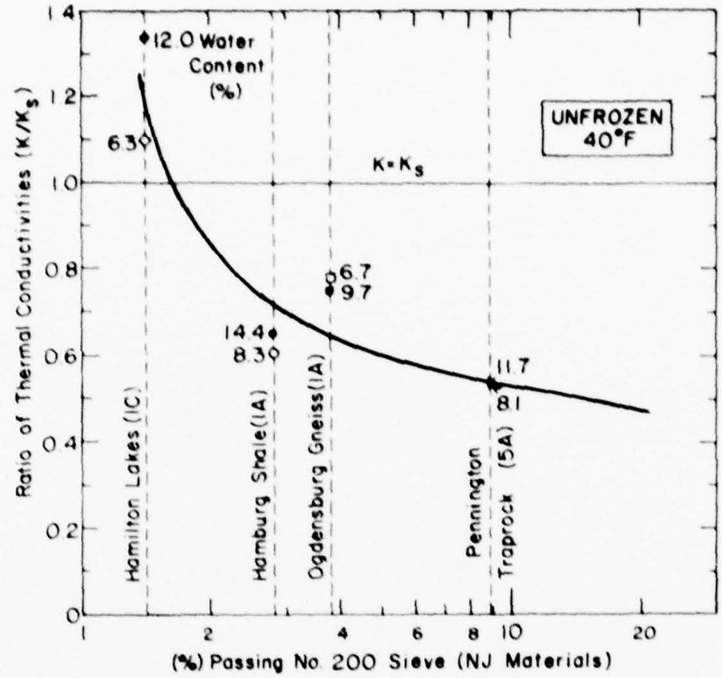

Figure 4. Comparison of thermal conductivity (K) of New Jersey soils with Kersten's values (K_s) for sandy soils, unfrozen.

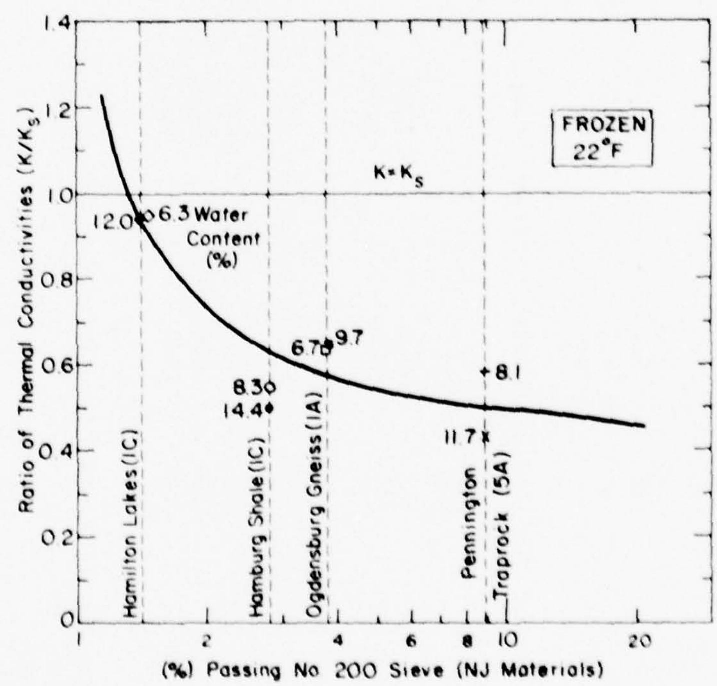

Figure 5. Comparison of thermal conductivity (K) of New Jersey soils with Kersten's values (K_s) for sandy soils, frozen.

Table 4. Properties of materials in pavement sections.

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 1, I-295, Flower Hill ramp.									
AC	138.	0.	0.83	-	0.54	28.	0.	-	-
5A	138.	7.0	0.5	2.15	-	31.	1391.	-	-
1C	128.	8.0	0.5	1.75	-	29.	1475.	-	-
M-S-G	125.	13.4	1.0	1.31	-	34.	2412.	-	-
Site No. 2, I-295, incomplete entrance ramp.									
AC	138.	0.	0.88	-	0.54	28.	0.	-	-
5A	138.	8.0	0.5	2.33	-	32.	1590.	-	-
1C	128.	9.0	0.5	1.88	-	30.	1659.	-	-
M-S-G	125.	16.0	1.0	1.46	-	36.	2880.	-	-
Site No. 3, I-295, main line pavement.									
AC	138.	0.	0.83	-	0.54	28.	0.	-	-
5A	138.	9.0	0.5	2.51	-	33.	1788.	-	-
1C	128.	10.0	1.0	2.01	-	31.	1843.	-	-
Site No. 4, Route 130, north of Cranbury Circle.									
PCC	140.	0.	0.83	-	0.57	30.	0.	-	-
G	125.	12.8	1.0	2.14	-	33.	2304.	-	-
Site No. 5, Route 130, across from Cranbury Lake.									
PCC	140.	0.	0.88	-	0.57	30.	0.	-	-
S	125.	8.4	1.0	1.65	-	29.	1512.	-	-
S	125.	14.4	1.0	2.31	-	35.	2592.	-	-

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 6, I-195, ramp onto Route 526.									
AC	138.	0.	0.83	-	0.54	28.	0.	0.	0.
S-M	125.	7.9	1.42	1.60	0.96	29.	1422.	1062.	702.
S	125.	11.9	1.0	2.05	1.23	32.	2142.	1926.	1710.
S	125.	9.5	2.0	1.90	1.14	30.	1710.	1494.	1278.
Site No. 7, I-195, ramp onto Route 130, north.									
AC	138.	0.	0.71	-	0.54	28.	0.	-	-
5A	125.	6.5	0.5	1.43	-	27.	1170.	-	-
S-G	125.	13.6	1.0	2.23	-	34.	2448.	-	-
C-S	125.	13.3	1.0	2.00	-	33.	2394.	-	-
Site No. 8, I-295, Bordentown, incomplete exit ramp.									
AC	138.	0.	0.79	-	0.54	28.	0.	-	-
5A	138.	12.0	1.0	3.01	-	36.	2385.	-	-
G-S-M	130.	12.5	1.0	2.44	-	34.	2340.	-	-
Site No. 9, I-295, incomplete rest area ramp.									
PCC	140.	0.	0.75	-	0.57	30.	0.	0.	0.
S-M-G	130.	11.4	1.0	2.30	1.38	33.	2134.	1760.	1385.
M-C	130.	13.8	2.0	2.40	1.44	27.	2583.	1928.	1273.

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 10, I-295, main line pavement.									
PCC	140.	0.	0.79	-	0.57	30.	0.	-	-
S-M	130.	15.2	1.0	2.78	-	37.	2845.	-	-
Site No. 11, I-78, ramp onto Route 523.									
PCC	140.	0.	0.79	-	0.57	30.	0.	0.	0.
1A	130.	13.7	1.0	2.59	1.55	35.	2565.	2340.	2115.
RS	126.	10.0	1.0	1.89	1.13	31.	1814.	1597.	1379.
RS	126.	9.5	3.0	1.83	1.10	31.	1724.	1506.	1288.
Site No. 12, I-78, ramp to Lamington - north branch.									
PCC	140.	0.	0.88	-	0.57	30.	0.	-	-
1A	128.	11.0	1.0	2.13	-	32.	2028.	-	-
RS	130.	10.5	3.0	2.19	-	32.	1966.	-	-

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 13, I-287, ramp onto Route 206, south.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
5A	138.	12.5	0.5	3.09	-	36.	2484.	-	-
1C	128.	13.5	0.5	2.42	-	35.	2488.	-	-
RS	130.	10.7	1.0	2.21	-	33.	2003.	-	-
Site No. 14, I-287, ramp onto Mt. Airy Road.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
1A	128.	8.7	1.0	1.84	-	30.	1604.	-	-
M-C	125.	13.0	1.0	1.29	-	33.	2340.	-	-
Site No. 15, I-287, ramp onto North Maple.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
1A	128.	9.5	1.0	1.94	-	31.	1751.	-	-
M-S-G	128.	10.0	1.0	1.20	-	31.	1843.	-	-
M-C	125.	12.0	1.0	1.23	-	32.	2160.	-	-
Site No. 16, I-287, ramp into rest area.									
AC	138.	0.	0.83	-	0.54	28.	0.	-	-
5A&1C	133.	7.8	1.0	1.99	-	30.	1494.	-	-
G-S-M	128.	10.0	1.0	2.01	-	31.	1843.	-	-
G-S-M	128.	5.4	1.0	1.40	-	27.	995.	-	-

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 17, I-287, ramp onto Harter Road.									
AC	138.	0.	0.88	-	0.54	28.	0.	-	-
5A	138.	8.9	1.0	2.49	-	33.	1769.	-	-
5A&1C	133.	9.2	1.0	2.20	-	32.	1762.	-	-
1C	128.	13.9	1.0	2.47	-	35.	2562.	-	-
Site No. 18. O-287 ramp to Route 24, Madison Avenue.									
AC	138.	0.	0.79	-	0.54	28.	0.	0.	0.
5A	138.	5.5	0.5	1.87	1.12	29.	1093.	854.	616.
1C	128.	5.1	1.0	1.36	0.82	27.	940.	719.	498.
S-M	130.	4.8	1.0	1.39	0.83	27.	899.	524.	150.
S-M	130.	6.4	1.5	1.63	0.98	28.	1198.	824.	449.
Site No. 19, I-287, ramp onto Route 24 (future).									
AC	138.	0.	0.96	-	0.54	28.	0.	-	-
S-M-G	128.	6.7	1.0	1.58	-	28.	1235.	-	-
S-M-G	130.	10.6	1.0	2.20	-	32.	1984.	-	-
C-M-S	130.	16.0	1.0	1.66	-	38.	2995.	-	-

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	K $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$	L_1 $(\frac{Btu}{cu\ ft})$	L_2 $(\frac{Btu}{cu\ ft})$
Site No. 20, I-287, acceleration ramp from future Route 24.									
PCC	140.	0.	0.79	-	0.57	30.	0.	-	-
1A	128.	11.3	1.0	2.16	-	33.	2083.	-	-
S-M-G	125.	10.7	1.0	1.92	-	31.	1926.	-	-
Site No. 21, I-287, ramp onto Main Street, Boonton.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
1A	128.	6.6	1.0	1.57	-	28.	1217.	-	-
C-M	125.	9.7	1.0	1.09	-	30.	1746.	-	-
C-M	125.	10.4	1.0	1.13	-	31.	1872.	-	-
Site No. 22, I-287, Gore Area, Exit 40B.									
PCC	140.	0	0.83	-	0.57	30.	0.	0.	0.
1A	130.	8.8	1.0	1.96	1.18	31.	1647.	1422.	1198.
S-M	125.	10.5	1.0	1.90	1.14	31.	1890.	1530.	1170.
S-M	125.	9.9	2.0	1.88	1.13	29.	1782.	1422.	1062.

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s ($\frac{Btu}{ft\ hr\ °F}$)	K ($\frac{Btu}{ft\ hr\ °F}$)	C ($\frac{Btu}{cu\ ft\ °F}$)	L ($\frac{Btu}{cu\ ft}$)	L_1 ($\frac{Btu}{cu\ ft}$)	L_2 ($\frac{Btu}{cu\ ft}$)
Site No. 23, I-287, exit ramp at north end of I-287.									
PCC	140.	0.	0.76	-	0.57	30.	0.	-	-
1A	128.	11.5	1.0	2.19	-	33.	2120.	-	-
M-S	125.	13.3	1.0	1.31	-	34.	2394.	-	-
Site No. 24, I-287, south bound, ramp to Myrtle Avenue, Boonton.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
1A	130.	7.6	1.0	1.80	-	30.	1423.	-	-
S-M	125.	9.7	1.0	1.81	-	30.	1746.	-	-
S-M	125.	11.6	1.0	2.02	-	32.	2088.	-	-
Site No. 25, I-287, south bound, ramp onto Route 46.									
PCC	140.	0.	0.75	-	0.57	30.	0.	-	-
1A	130.	7.6	1.0	1.80	-	30.	1423.	-	-
S	125.	9.7	1.0	1.81	-	30.	1746.	-	-
S	125.	11.6	1.0	2.02	-	32.	2088.	-	-
Site No. 26, Route 15, across from Rockaway maintenance yard.									
AC	138.	0.	0.33	-	0.54	28.	0.	-	-
1C	138.	4.9	0.42	1.76	-	29.	974.	-	-
S-M-G	125.	4.9	1.0	1.22	-	26.	882.	-	-
S-M-G	125.	6.7	1.0	1.46	-	28.	1206.	-	-
S-M-G	125.	7.5	1.0	1.55	-	28.	1350.	-	-

Table 4 (cont'd)

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s ($\frac{Btu}{ft\ hr\ °F}$)	K ($\frac{Btu}{ft\ hr\ °F}$)	C ($\frac{Btu}{cu\ ft\ °F}$)	L ($\frac{Btu}{cu\ ft}$)	L_1 ($\frac{Btu}{cu\ ft}$)	L_2 ($\frac{Btu}{cu\ ft}$)
Site No. 27, Route 15, truck lane (in fill).									
AC	138.	0.	0.63	-	0.54	28.	0.	-	-
5A	138.	5.8	0.67	1.93	-	29.	1153.	-	-
M-S-R	125.	4.3	1.0	0.66	-	25.	774.	-	-
M-S-R	125.	4.6	1.0	0.69	-	26.	828.	-	-
M-S-R	125.	1.8	6.0	0.32	-	23.	324.	-	-
Site No. 28, Route 15, north end of truck lane (rock cut).									
Rock at 36 in., no calculations.									
Site No. 29, Route 15, Mile post 10, incomplete exit ramp.									
AC	138.	0.	0.25	-	0.54	28.	0.	0.	0.
AC	138.	0.	0.33	-	0.54	28.	0.	0.	0.
5A	138.	7.0	0.5	2.15	1.29	31.	1391.	1152.	914.
1C	125.	8.5	1.0	1.67	1.00	29.	1530.	1314.	1098.
G-S-M	125.	9.0	2.0	1.73	1.04	30.	1620.	1404.	1188.
Site No. 30, Route 15, incomplete exit ramp, Sparta.									
AC	138.	0.	0.79	-	0.54	28.	0.	-	-
5A	138.	5.2	0.5	1.82	-	29.	1033.	-	-
1C	125.	5.8	0.5	1.34	-	27.	1044.	-	-
G-S-M	125.	6.9	1.0	1.48	-	28.	1242.	-	-
G-S-M	125.	4.7	3.0	1.20	-	26.	846.	-	-

Table 4 (cont'd)

*Symbols are for the following materials:

AC = asphaltic cement concrete pavement
PCC = Portland cement concrete pavement
5A = gravelly sand (1.2)
1A = gravelly sand (1.2)
1C = gravelly sand (1.2)
RS = red shale (1.2)
M-S-G = silt with sand and gravel (2.5)
M-C = silt with clay (3.5)
G = gravel (1.2)
S = sand (1.2)
S-M = sand with silt (2.0)
S-G = sand with gravel (1.2)
C-S = clay with sand (3.0)
G-S-M = gravel with sand and silt (1.2)
S-M-G = sand with silt and gravel (2.0)
S-M-C = sand with silt and clay (2.5)
C-M = clay with silt (4.0)
M-S = silt with sand (2.5)
M-S-R = silt with sand and rocks (2.5)
K_s = thermal conductivity based upon Kersten (1949) study
K = thermal conductivity based upon modification to Kersten values ($K = 0.6\ K_s$)
L = latent heat of soil moisture assuming all of pore water is frozen, $L = 144\ \gamma_d\ w$
L_1 = latent heat of soil moisture assuming portion of pore water is not frozen $L_1 = 144\ \gamma_d\ (w-w_u)$
L_2 = latent heat of soil moisture assuming larger portion of pore water is not frozen $L_2 = 144\ \gamma_d\ (w-2w_u)$
W_u = unfrozen moisture content. The value of this parameter is shown in parenthesis for each of the materials shown above.

Table 5. **Boundary** conditions, initial conditions and thermal properties varied for **sites given** a detailed **thermal** analysis.

Solution	1	2	3	4	5	6	7	8	9	10	11	12
Site No. 6	**Measured** frost depth = 38 in.											
Air Freezing Index, °F-days	446	446	446	446	446	446						
n-factor	0.55	0.55	0.9	0.55	0.55	0.55						
t, days	44	44	44	44	44	44						
MAT*, °F	54	35	35	35	35	35						
Thermal Cond.	K_s	K_s	K_s	K_s	K	K						
Latent Ht.	L	L	L	L_1	L_1	L_2						
X, in.	13	28	35	30	29	30						
Site No. 9	**Measured** frost depth = 40 in.											
Air or Surface Freezing Index, °F-days	93*	316	316	93*	93*	93*	316	446	600	700	446	316
n-factor	1.0*	0.45	0.55	1.0*	1.0*	1.0*	1.0	1.0	1.0	1.0	1.0	1.0
t, days	44	44	44	44	44	44	44	44	44	44	44	44
MAT, °F	35	35	35	35	35	35	35	35	35	35	35	35
Thermal Cond.	K_s	K_s	K_s	K_s	K	K	K_s	K_s	K_s	K_s	K	K_s
Latent Ht.	L	L	L	L_1	L_1	L_2	L	L	L	L	L_2	L_2
X, in.	14	18	20	16	16	17	28	33	38	42	41	39

* Mean Annual Temperature

Table 5 (Cont'd)

Solution	1	2	3	4	5	6	7	8	9	10	11	12
Site No. 11	Measured frost depth = 38 in.											
Surface Freezing Index, °F-days	388	388	388	388	388	388	388					
n-factor	1.0*	1.0*	1.0*	1.0*	1.0*	1.0*	1.0*					
t, days	45	45	72	72	72	72	45					
MAT, °F	51	35	35	35	35	35	35					
Thermal Cond.	K_s	K_s	K_s	K_s	K	K	K_s					
Latent Ht.	L	L	L	L_1	L_1	L_2	L_1					
X, in.	20	34	32	35	31	34	35					
Site No. 18	Measured frost depth = 37 in.											
Air Freezing Index, °F-days	768	768	768	768	768	768						
n-factor	0.55	0.65	0.45	0.55	0.55	.55						
t, days	72	72	72	72	72	72						
MAT, °F	35	35	35	35	35	35						
Thermal Cond.	K_s	K_s	K_s	K_s	K	K						
Latent Ht.	L	L	L	L_1	L_1	L_2						
X, in.	44	49	41	52	47	58						

Table 5 (Cont'd)

Solution	1	2	3	4	5	6	7	8	9	10	11	12
Site No. 22	Measured frost depth = 40 in.											
Air Freezing Index, °F-days	822	822	822	822	822	822						
n-factor	0.45	0.55	0.45	0.45	0.45	0.45						
t, days	72	72	45	72	72	72						
MAT, °F	35	35	35	35	35	35						
Thermal Cond.	K_s	K_s	K_s	K_s	K	K						
Latent Ht.	L	L	L	L_1	L_1	L_2						
X, in.	34	37	34	36	34	36						
Site No. 29	Measured frost depth = 52 in.											
Air Freezing Index, °F-days	1075	1075	1075	1075	1075	1075						
n-factor	0.55	0.55	0.65	0.55	0.55	0.55						
t, days	70	70	70	70	70	70						
MAT, °F	49	35	35	35	35	35						
Thermal Cond.	K_s	K_s	K_s	K_s	K	K						
Latent Ht.	L	L	L	L_1	L_1	L_2						
X, in.	32	49	56	53	46	48						

NOTES: *When the n-factor equals one (n=1) the measured surface freezing index was used rather than the air freezing index.

K_s indicates values from Kersten's equations were used for thermal conductivity of the soils.

K indicates modified values of K_s were used. For this study $K = 0.6\ K_s$.

Values for the latent heat of fusion were determined from:

$$L = 144\ \gamma_d\ w$$

$$L_1 = 144\ \gamma_d\ (w - w_u)$$

$$L_2 = 144\ \gamma_d\ (w - 2w_u)$$

given on pages 23-25 in the earlier study by Berg and McGaw (1978). At sites 9 and 11 surface temperatures were measured; thus surface freezing indexes were computed directly from temperature measurements. At the other four sites surface freezing indexes were obtained by multiplying the air freezing index by the applicable n-factor from Table 2.

Initially frost depth computations were made using values of thermal conductivity (K_s) obtained from Kersten's (1949) equations and mean annual temperatures (MAT) which were thought to be representative of the sites, see Solution 1 for Sites 6, 11 and 29 (Table 5). The resulting computed frost depths (13, 20 and 32 in.) were much lower than the observed values (38, 38 and 52 in.) in all cases. The author felt that using the average soil temperature existing immediately prior to onset of freezing would be more realistic than using the mean annual temperature which is typically used in modified Berggren equation solutions. Subsurface soil temperatures are measured at unpaved areas near New Brunswick and Newton and are reported in the monthly weather summaries (NOAA 1976).

Data from these sites for 20 December 1976 indicated that temperatures to a depth of 40 in. ranged from 33°F to 43°F. As snow was allowed to accumulate on these plots and as the surface was vegetated (or bare) rather than paved, one would expect that the amount of cooling beneath the paved areas would probably have been more extensive than beneath the observed plots. Therefore calculations were made using an initial soil temperature of 35°F. For the three sites (Nos. 6, 11, 29) the only difference between Solution 1 and Solution 2, Table 5, is the change in MAT. The computed frost depths (28, 34 and 49 in.) agreed much more closely with measured depths with this change. It was felt that 35°F was a reasonable assumption for an average temperature within the seasonal frost zone prior to freezing. This value then was used for the MAT in all of the other calculations.

At Site No. 6, the n-factor was increased to 0.9 for Solution 3, and the resulting calculated frost depth (35 in.) was slightly less than the measured depth (38 in.). At Site 9, the measured surface freezing index, 93°F-days, was used in Solution 1. The computed frost depth (14 in.) was about one-third of the measured depth (40 in.). For Solutions 2 and 3 at Site 9, the air freezing index and n-factors for PCC and AC pavements, respectively, were used. Resulting computed frost depths (18 and 20 in.) were only about 50% of the observed depth. Consequently additional computer trials with various surface freezing indexes were used in an attempt to more closely approximate the observed depth of freezing. Solutions 7-10 at Site 9 contain these results and indicate that a surface freezing index of about 650 °F-days would have been required to produce the observed frost depth using these soil properties.

This exercise shows that a surface index in excess of the air index (316°F-days) would have been necessary, an untenable situation. Solution 11 indicates that if the latent heats of fusion are further reduced to L_2 (Table 4) and the thermal conductivites are reduced to reflect more representative values (K) anticipated for New Jersey soils, a surface freezing index of 446 °F-days would result in 41 in. of frost penetration. Using L_2 with Kersten's thermal conductivity value (K_s) and a surface freezing index of 316 °F-days resulted in a predicted 39 in. of frost penetration. It appears that, for frost to penetrate to the measured depth of 40 in., a significant amount of unfrozen moisture must exist in the soils at Site 9. Unfortunately no information is available concerning the amount of unfrozen moisture in the New Jersey soils; however, the existence of unfrozen water in soils at temperatures below 32°F is a well accepted phenomenon. A typical relationship between unfrozen water content and below freezing temperatures is shown in Table 6, from Lovell (1957). The influence of unfrozen water content is particularly significant in the finer grained soils at temperatures just below the freezing point.

Table 6. Comparative phase composition at selected temperatures.

Soil	Unfrozen moisture content w_u (%)			
	26.6°F	5°F	-13°F	Ratio $\frac{26.6°F}{-13°F}$
Clayey Silt	4.4	3.1	2.8	1.55
Silty Clay	11.05	8.0	7.2	1.53
Clay	23.6	15.8	13.9	1.70

Soil	Percentage moisture frozen $\frac{w-w_u}{w}$ 100			
	26.6°F	5°F	-13°F	Ratio $\frac{-13°F}{26.6°F}$
Clayey Silt	73.4	81.0	82.9	1.13
Silty Clay	41.8	58.0	62.1	1.48
Clay	16.3	44.0	50.6	3.11

For each of the 6 sites, Solutions 4, 5 and 6 were identical except as follows:

a) Solution 4 used K_s and L_1

b) Solution 5 used K and L_1

c) Solution 6 used K and L_2

Frost depths computed using these three conditions did not differ greatly except at Site 18. The pavement at this site was constructed over a low-moisture content silty sand subgrade and the reduction in the latent heat of fusion in Solution 6 caused a significantly larger increase in computed frost penetration than at the other five sites.

At Sites 11 and 22, the effects of longer or shorter freezing seasons with the same freezing index were studied. The only difference between Solutions 2 and 3 at Site 11 was the length of the freezing season. The shorter season and its colder average temperatures caused a slight increase in frost penetration (34 vs. 32 in.). At Site 22, Solutions 1 and 3 were identical except that the freezing season was shorter in Solution 3. Computed frost depths are the same (34 in.) in both solutions. From study of these two sites, it is concluded that the length of the freezing season does not significantly affect computed frost depths. This conclusion may not be valid for freezing seasons shorter than about 40 days, however.

A careful study of Solutions 4, 5 and 6 for each site and comparison of results using the same values for the air freezing index, n-factor, length of freezing season and mean annual temperature (MAT) with thermal properties K_s and L indicates that no significant increase in accuracy of the computations is achieved by modifying the thermal conductivity or the latent heat of fusion. Table 7 summarizes this comparison.

The mean difference, $\bar{x}$, was computed from:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

where x_i is the difference for the ith computation and n is the number of computations. The standard deviation, s, listed in the table is the standard deviation from the mean difference and is determined from:

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n}}$$

In comparing computed and measured frost penetration depths, the mean difference and the standard deviation from the mean using K_s and L_1 were 3.8 in. and ± 11.6 in. Using K and L_1 the values were 7.0 in. and ± 9.9 in., and using K_s and L_2 the values were 3.7 in. and ± 12.9 in.

Table 7. Comparison of measured and computed frost depths at sites given a detailed thermal analysis.

Site	Measured F.P.*	K_s, L_1 (Solution 4) Computed F.P.	x_i	K, L_1 (Solution 5) Computed F.P.	x_i	K, L_2 (Solution 6) Computed F.P.	x_i	K_s, L (Various solutions) Soln.	Comp. F.P.	x_i
6	38	30	8	29	9	30	8	2	28	10
9	40	16	24	16	24	27	23	1	14	26
11	38	35	3	31	7	34	4	3	32	6
18	37	52	-15	47	-10	58	-21	1	44	-7
22	40	36	4	34	6	36	4	1	34	6
29	52	53	-1	46	6	48	4	2	49	3
Mean difference		3.8		7.0		3.7			7.3	
Standard deviation		± 11.6		± 9.9		± 12.9			± 9.9	

*F.P. = frost penetration, in.

x_i = measured FP - computed FP, in.

Because the computations using K_s and L are much more direct and make use of the Modified Berggren equation without alteration, these values were used in the computations for the other 24 sites. Initial and upper boundary conditions for the 24 sites are shown in Table 8; computed frost depths are shown in Table 9. The mean difference between computed and measured results was 3.8 in. with a standard deviation of ±7.8 in. It is observed, however, that the mean difference for the first ten sites was 8.9 in. with a standard deviation of ±7.8 in. (If Site 9 is omitted the mean error and standard deviation reduce to 6.9 in. and ± 5.5 in., respectively.)

For the remaining 18 sites (11-30), the mean difference between measured and computed frost depths was 1.0 in. with a standard deviation of ± 6.2 in. The first ten sites have surface freezing indexes less than about 250 °F-days, indicating that the reliability of the computed frost depths for the lower freezing indexes is less than for the higher indexes. Since the first 10 sites are south of Somerville (Figure 1a), it is recommended that a lower reliability be placed on computed frost depths south of this location.

Computed frost penetrations may have agreed slightly better with measurements had a combination of K_s and L_1 or K and L_1 been used; however, based on results presented in Table 7, improvement would have been relatively minor. More accurate computations would probably have been made if the average soil temperature at the beginning of the freezing season were known and/or if the surface freezing index were measured at each site. Calculated frost depths (Table 5) indicate that significant changes in frost depth occur with relatively small changes in surface freezing index.

Moulton and Dubbe (1968), in a similar study, used a slightly different form of the modified Berggren equation, but their results were similar to those presented in this report. They concluded that accurate calculated results would be obtained provided reasonable values of the controlling parameters were used. They state, "These parameters include the pavement surface freezing index, an initial soil temperature equal to the average soil temperature at the start of pavement surface freezing and reasonably accurate values of the thermal properties of the pavement elements and subgrade soils."

Results from our study also indicate that the modified Berggren equation provides reasonable estimates of the frost depth when accurate values of the initial and boundary conditions are provided. The equation will provide reasonable estimates of frost penetration depths and can be used by NJDOT to assess frost penetration beneath various pavement cross sections with differing thermal properties.

Table 8. Initial and upper boundary conditions for test sites.

Site No	Air or surface freezing index (°F-days)	n-factor	Length of season days	Initial temperature (°F)
1	446	0.55	44	35.
2	446	0.55	44	35.
3	446	0.55	44	35.
4	446	0.45	44	35.
5	446	0.45	44	35.
6		See Table 4		
7	446	0.55	44	35.
8	446	0.55	44	35.
9		See Table 4		
10	446	0.45	44	35.
11		See Table 4		
12	388	1.00	70	35.
13	388	1.00	70	35.
14	388	1.00	70	35.
15	388	1.00	70	35.
16	822	0.55	70	35.
17	822	0.55	70	35.
18		See Table 4		
19	822	0.55	70	35.
20	822	0.45	70	35.
21	822	0.45	70	35.
22		See Table 4		
23	822	0.45	70	35.
24	822	0.45	70	35.
25	822	0.45	70	35.
26	303	1.00	70	35.
27	1075	0.55	70	35.
28		No Calculations		
29		See Table 4		
30	1075	0.55	70	35.

NOTE: An n-factor of 1.00 indicates that the surface freezing index was used.

Table 9. Measured and calculated depths of maximum frost penetration during the 1976-1977 winter.

Site No	Measured (in.)	Maximum frost depth calculated with K_s (in.)	Difference* (in.)
1	29.0	25.0	4.0
2	35.0	25.0	10.0
3	28.5	25.0	3.5
4	32.0	21.5	10.5
5	35.5	24.0	11.5
6	38.0	38.0**	10.0
7	20.5	26.0	-5.5
8	29.0	24.0	5.0
9	40.0	14.0**	26.0
10	33.5	20.5	13.5
11	38.0	32.0**	6.0
12	38.0	32.0	6.0
13	38.5	32.0	6.5
14	36.0	32.0	4.0
15	35.0	33.5	1.5
16	27.5	39.5	-12.0
17	37.0	37.0	0.0
18	37.0	44.0**	-7.0
19	38.0	36.0	2.0
20	40.5	32.5	8.0
21	37.5	33.5	4.0
22	40.0	34.0**	6.0
23	40.0	30.0	10.0
24	33.5	35.0	-1.5
25	32.0	35.0	-3.0
26	35.0	38.5	-3.5
27	****	61.0	-
28	***	***	-
29	52.0	49.0**	3.0
30	43.5	55.0	-11.5

Mean Difference = 3.8
Standard Deviation = ± 7.8

* Difference = [Measured - Calculated].

** See Table 5 for calculated frost depths.

*** Bedrock at 30.5-in. depth. Frost penetration exceeded this depth.

**** Possible error in observed data.

DRAINAGE LAYERS

Berg and McGaw's (1978) results indicated that the use of stabilized or unstabilized open graded drainage layers would not significantly increase the maximum seasonal frost penetration beneath pavements in New Jersey. To further evaluate effects of these layers on maximum frost penetrations, pavement profiles incorporating drainage layers were assumed to exist at four of the test sites. Two of the four sites used Portland cement concrete pavements and the other two used asphaltic concrete pavements. Both stabilized and unstabilized drainage layers were assumed beneath the PCC pavements but only stabilized drainage layers were assumed beneath the asphaltic concrete pavements. Drainage layer properties were similar to those used by Berg and McGaw (1978). All or part of the base course or subbase course material at each of the sites was replaced by the drainage layer. The four sites and the properties of materials within the hypothetical pavements are shown in Table 10. Upper boundary conditions and initial conditions are the same as those shown in Tables 5 and 8. For Site No. 22, Solution 1 conditions (Table 5) were used and for Site No. 29, conditions of Solution 2.

In Table 11, calculated frost depths for the assumed pavements incorporating drainage layers were compared with computed frost depths shown in Table 9 for the pavements without drainage layers. In all cases, calculated frost depths for pavements with drainage layers were equal to, or slightly less than, those for similar pavements without drainage layers.

Table 11. Calculated frost depths for hypothetical pavements with drainage layers.

Site No.	Calculated frost penetration (in.) Without drainage layer	With drainage layer Stabilized	Unstabilized
4	21.5	21.5	20.5
8	24.0	21.5	-
22	34.0	30.0	27.5
29	49.0	42.0	-

Table 10. Properties of materials in hypothetical pavements with drainage layers.

Material property*	γ_d (lb/cu ft)	w (%)	d (ft)	K_s $(\frac{Btu}{ft\ hr\ °F})$	C $(\frac{Btu}{cu\ ft\ °F})$	L $(\frac{Btu}{cu\ ft})$
Site No. 4, stabilized OGL*.						
PCC	140.	0.	0.83	0.57	30.	0.
OGL* (stab)	120.	4.	0.50	0.51	25.	691.
G	125.	12.8	0.50	2.14	33.	2304.
S	125.	14.0	1.0	2.05	35.	2556.
Site No. 4, unstabilized OGL.						
PCC	140.	0.	0.83	0.57	30.	0.
OGL (unstab)	121.	4.5	0.50	0.40	26.	784.
G	125.	12.8	0.50	2.14	33.	2304.
S	125.	14.0	1.0	2.05	35.	2556.
Site No. 8, stabilized OGL.						
AC	138.	0.	0.79	0.54	28.	0.
OGL (stab)	120.	4.	0.42	0.51	25.	691.
5A	138.	12.0	0.42	3.01	36.	2385.
G-S-M	130.	12.5	1.0	2.44	34.	2340.
Site No. 22, stabilized OGL.						
PCC	140.	0.	0.83	0.57	30.	0.
OGL (stab)	120.	4.0	0.5	0.51	25.	691.
1A	130.	8.8	0.5	1.96	31.	1647.
S-M	125.	10.5	1.0	1.90	31.	1890.
S-M	125.	9.9	2.0	1.88	29.	1782.
Site No. 22, unstabilized OGL.						
PCC	140.	0.	0.83	0.57	30.	0.
OGL (unstab)	121.	4.5	0.5	0.40	26.	784.
1A	130.	8.8	0.5	1.96	31.	1647.
S-M	125.	10.5	1.0	1.90	31.	1890.
S-M	125.	9.9	2.0	1.88	29.	1782.
Site No. 29, stabilized OGL.						
AC	138.	0.	0.25	0.54	28.	0.
AC	138.	0.	0.33	0.54	28.	0.
OGL (stab)	120	4.0	0.50	0.51	25.	691.
1C	125.	8.5	1.0	1.67	29.	1530.
G-S-M	125.	9.0	2.0	1.73	30.	1620.

*Open graded drainage layer.

DESIGN FROST PENETRATION DEPTHS

The 1976-1977 winter was much colder than normal in New Jersey as well as most of the northeastern part of the U.S. Maximum depths of frost penetration were also probably greater during the 1976-1977 winter than in more "normal" winters. As a result of this study frost depths were measured at several locations within the state of New Jersey during this cold winter; these recorded depths could be used for pavement design purposes. Computed results indicate that frost depths beneath pavements containing open-graded drainage layers will not be significantly greater than beneath "conventional" pavements in New Jersey.

If the designers choose to compute design frost penetration depths for New Jersey pavements, the modified Berggren equation can be used. Air freezing indexes from the 1976-1977 winter could be used with the appropriate n-factors reported herein (Table 2) for the upper boundary condition. A temperature of 35°F should be assumed for the soil prior to the onset of freezing temperatures and the length of the freezing season at a particular site should be obtained from NOAA (1976-1977) records nearby. Thermal properties of the soils and pavement materials used herein can be used in the computations. Kersten's (1949) values for thermal conductivity and volumetric latent heat of fusion are adequate for pavement design in New Jersey.

CONCLUSIONS AND RECOMMENDATIONS

The modified Berggren equation can be used to estimate frost penetration beneath New Jersey pavements. For the most accurate estimates, values of the initial and upper boundary conditions and the thermal properties and moisture contents of the pavement materials must be representative of those at the site.

These calculations and those by Berg and McGaw (1978) indicate that open graded drainage layers will probably have very little effect on the maximum seasonal frost penetration beneath pavements in New Jersey. In all of the calculations, however, it was assumed that the pavement surface temperature over a drainage layer is the same as that over a conventional base course. It was also assumed that the moisture conditions beneath a drainage layer are the same as those in a more conventional pavement. Errors in either or both of these assumptions could cause a somewhat greater frost penetration, in the order of 10 to 15% maximum.

It is probably useful to consider the likelihood that these assumptions are incorrect. As discussed in the "Other Considerations" portion of the previous report (Berg and McGaw 1978), the placement of insulating layers in pavements can cause icing conditions similar to those occurring on bridge decks. A relatively dry open-graded drainage layer may act somewhat similar to an insulating layer and thereby cause a higher surface freezing index. However, the surface freezing index over a pavement incorporating an open-graded drainage layer would have to increase over 30% to cause a 15% increase in the computed frost depth. It is believed that a change this large is very unlikely.

Should the moisture conditions not be similar beneath "conventional" pavements and pavements containing an open-graded drainage layer, both the thermal conductivity and the volumetric latent heat of fusion terms in the modified Berggren equation would change. To cause an increase of 15% in frost penetration, the ratio K/L in the equation would also be required to change more than 30%. Such a difference may occur. For example, a sandy soil having a density of 110 lb/cu ft and a moisture content by dry weight of 10% has L = 1584 Btu/cu ft, equation (2), and unfrozen K_s = 1.16 Btu/ft hr °F, equation (3). If the moisture content for this soil were 15%, L = 2376 Btu/cu ft and K_s = 1.29 Btu/ft/hr °F. In this case the ratio of K_s/L would vary by about 26%.

Calculated frost depths beneath hypothetical pavements incorporating drainage layers are not significantly different from those beneath more conventional pavements which use dense-graded base and/or subbase course materials. It is recommended, however, that prior to widespread use of open graded drainage layers in New Jersey highway pavements test sections in at least two different environmental conditions be evaluated.

The structural adequacy of the open graded drainage layers must also be evaluated.

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Kersten, M.S. (1949). Laboratory research for the determination of the thermal properties of soils. Final report ACFEL Technical Report 23.

Lovell, W. (1957). Temperature effects on phase composition and strength of partially frozen soil. Highway Research Board Bulletin 168, p. 74-95.

Moulton, L.K. and E.C. Dubbe (1968). Prediction of the depth of frost penetration in West Virginia for pavement design purposes, Final report. Submitted to the State Road Commission of West Virginia.

National Oceanic and Atmospheric Administration (1976-1977). Climatological data, New Jersey. National Climatic Center, Ashville, N.C.

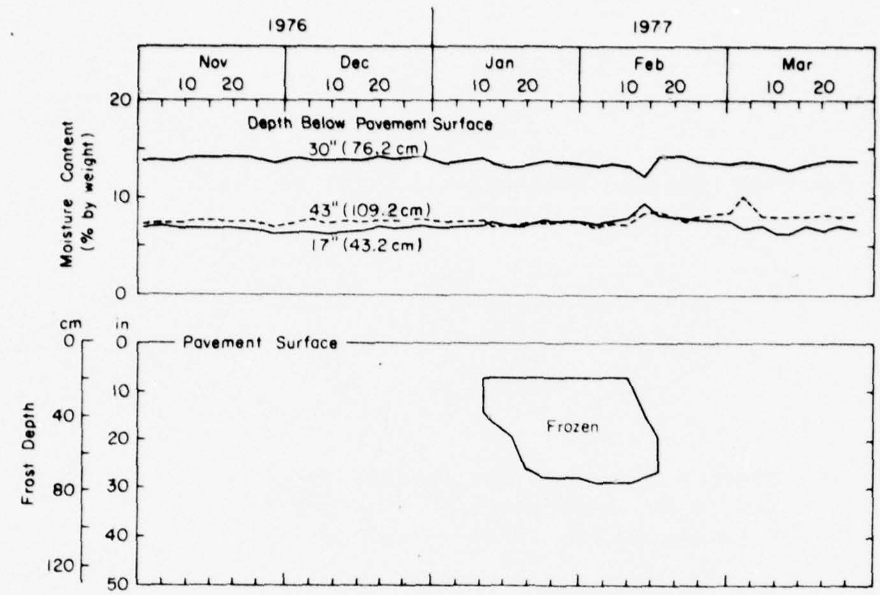
NJDOT-Cosaboom (1977). Personal communication.

NJDOT (1978). Personal communication.

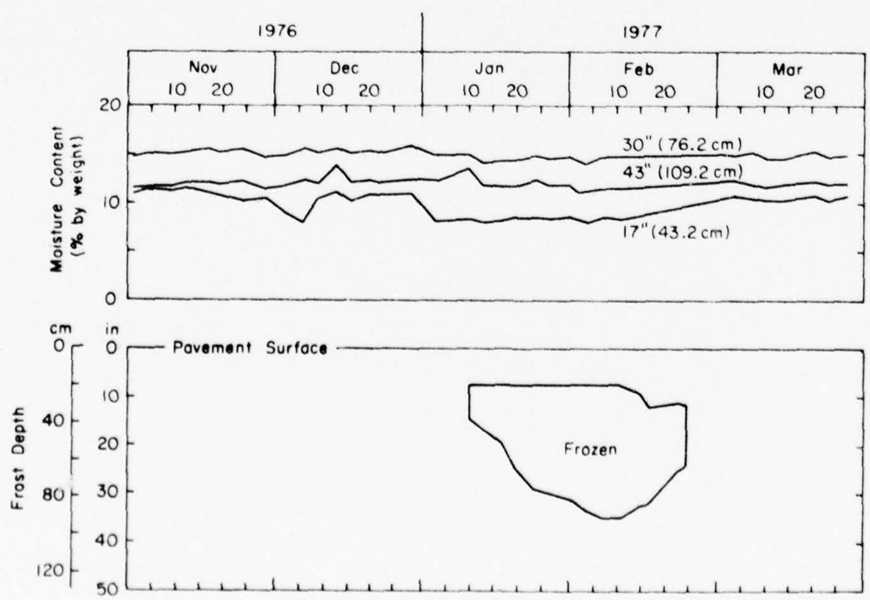
APPENDIX A

Observed Moisture Contents and Frost Depths

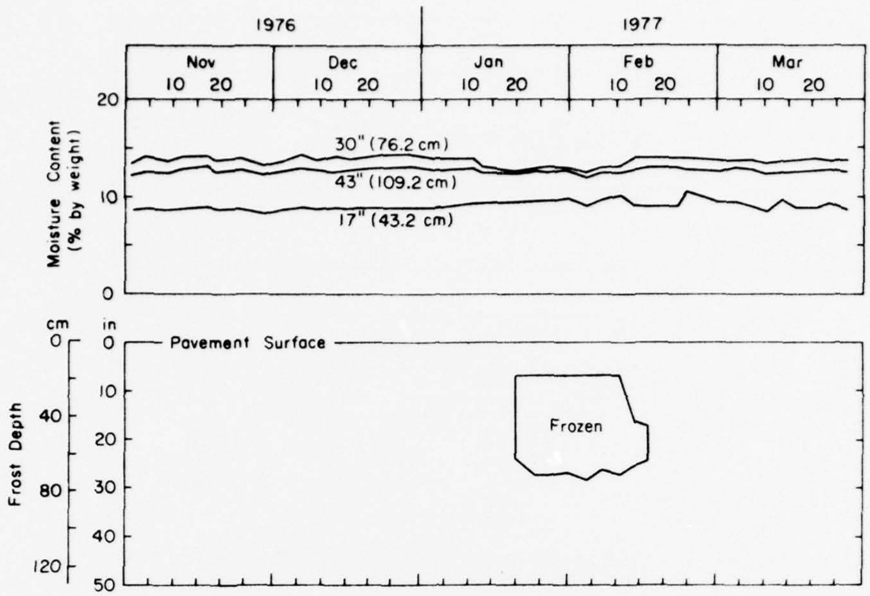
Plotted from data obtained by the New Jersey Department of Transportation during the 1976-1977 winter.


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
Depth Below Pavement Surface
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
Moisture Content (% by weight)
20
10
0
cm
in
Pavement Surface
Frozen
Frost Depth
40
80
120
50

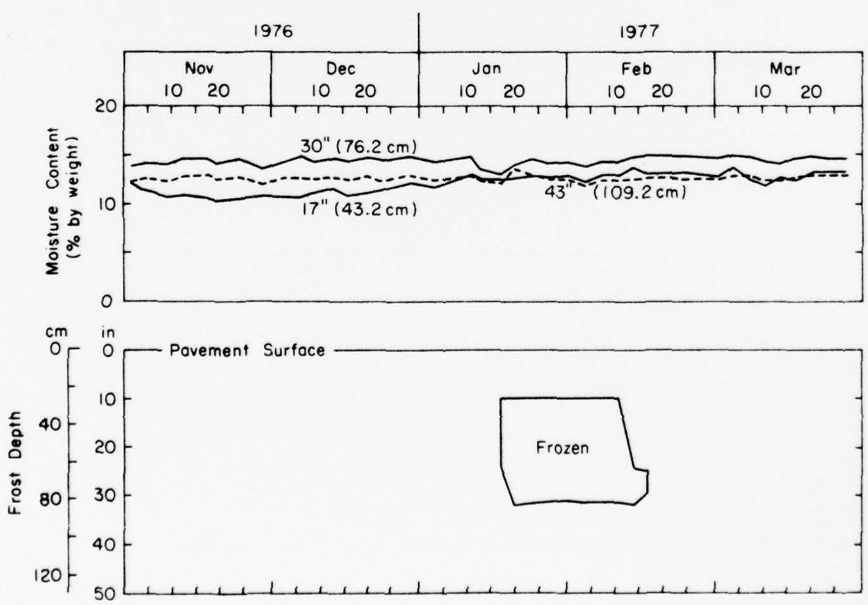
Site 1


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
Moisture Content (% by weight)
20
10
0
cm
in
Pavement Surface
Frozen
Frost Depth
40
80
120
50

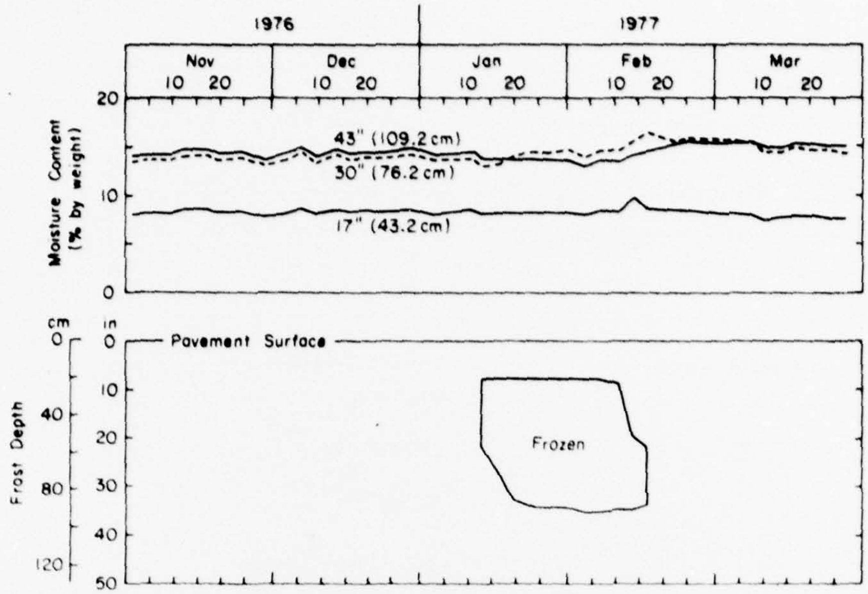
Site 2


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
Moisture Content (% by weight)
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
cm
in
Pavement Surface
Frozen
Frost Depth

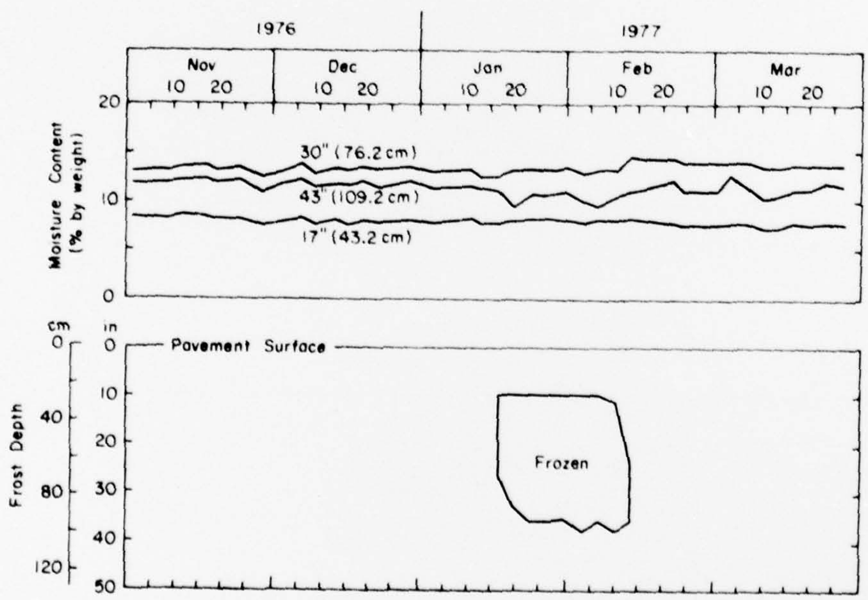
Site 3


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
Moisture Content (% by weight)
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
cm
in
Pavement Surface
Frozen
Frost Depth

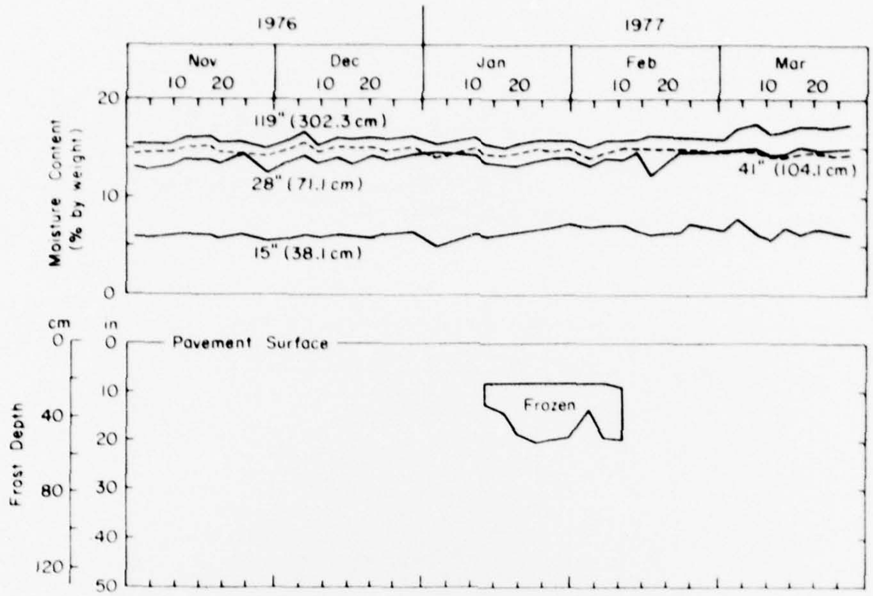
Site 4


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
Moisture Content (% by weight)
43" (109.2 cm)
30" (76.2 cm)
17" (43.2 cm)
cm
in
Pavement Surface
Frost Depth
Frozen

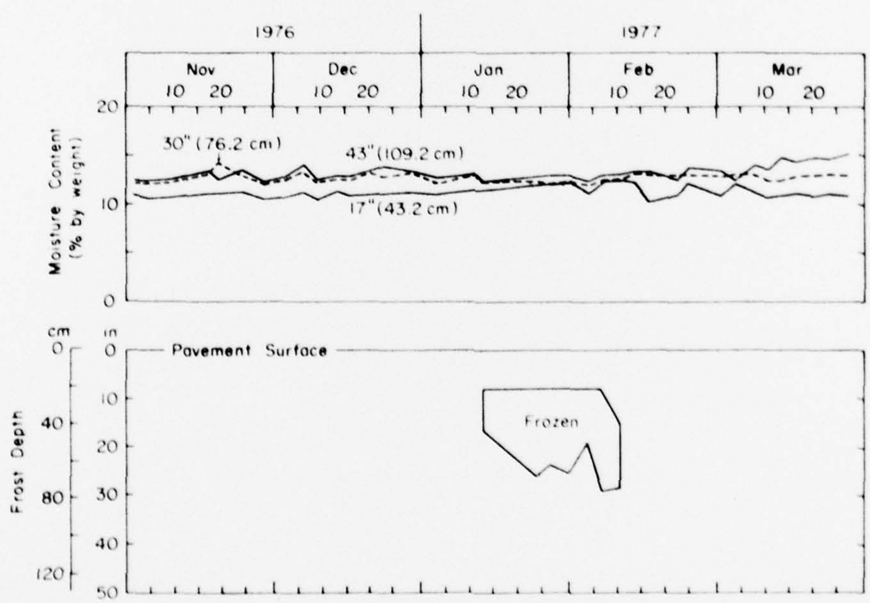
Site 5


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
Moisture Content (% by weight)
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
cm
in
Pavement Surface
Frost Depth
Frozen

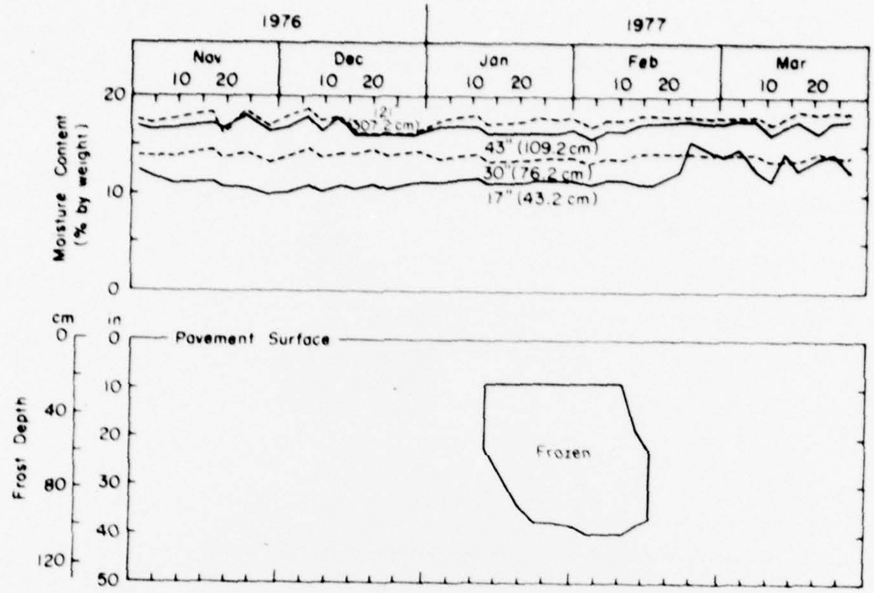
Site 6


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
20
10
0
Moisture Content (% by weight)
119" (302.3 cm)
28" (71.1 cm)
41" (104.1 cm)
15" (38.1 cm)
cm
in
Pavement Surface
Frost Depth
40
80
120
30
40
50
Frozen

Site 7


1976
1977
Nov
Dec
Jan
Feb
Mar
10 20
20
10
0
Moisture Content (% by weight)
30" (76.2 cm)
43" (109.2 cm)
17" (43.2 cm)
cm
in
Pavement Surface
Frost Depth
40
80
120
30
40
50
Frozen

Site 8



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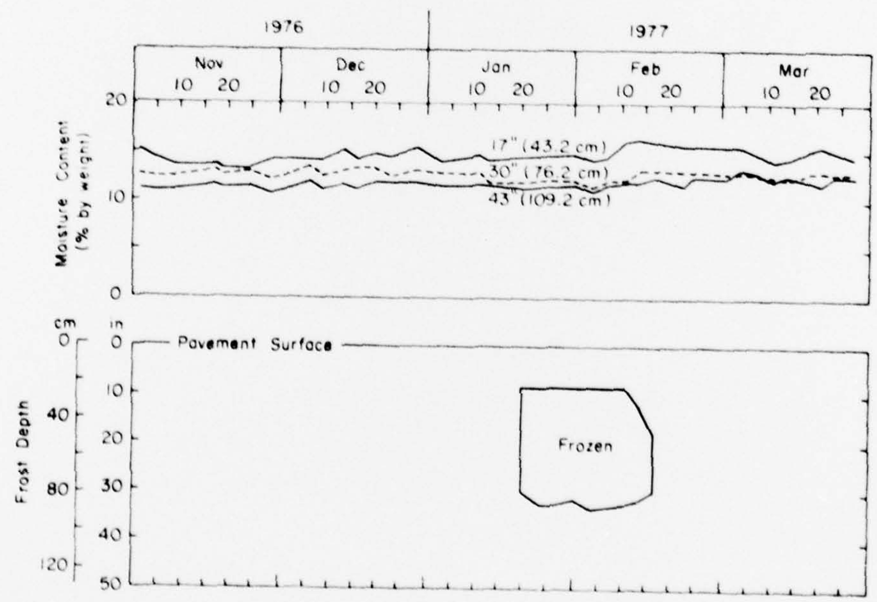

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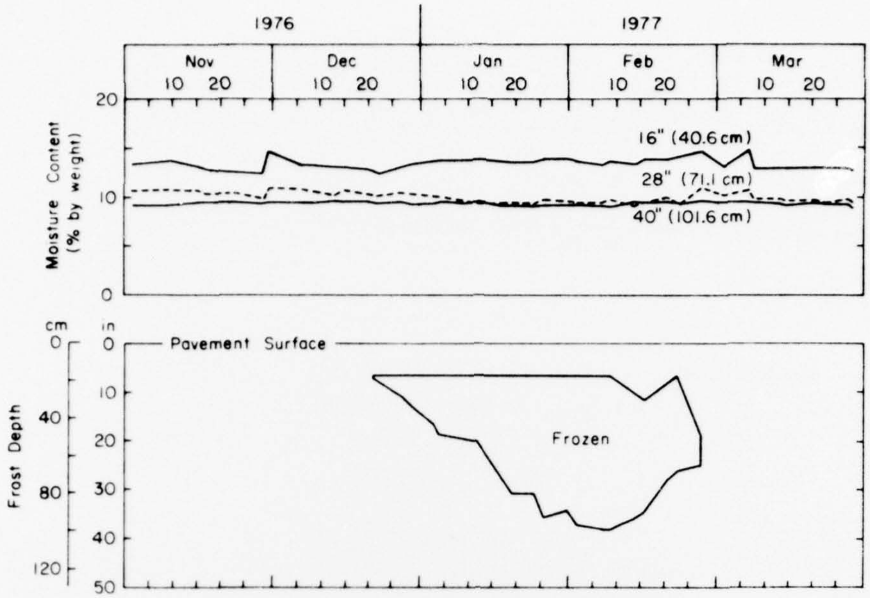

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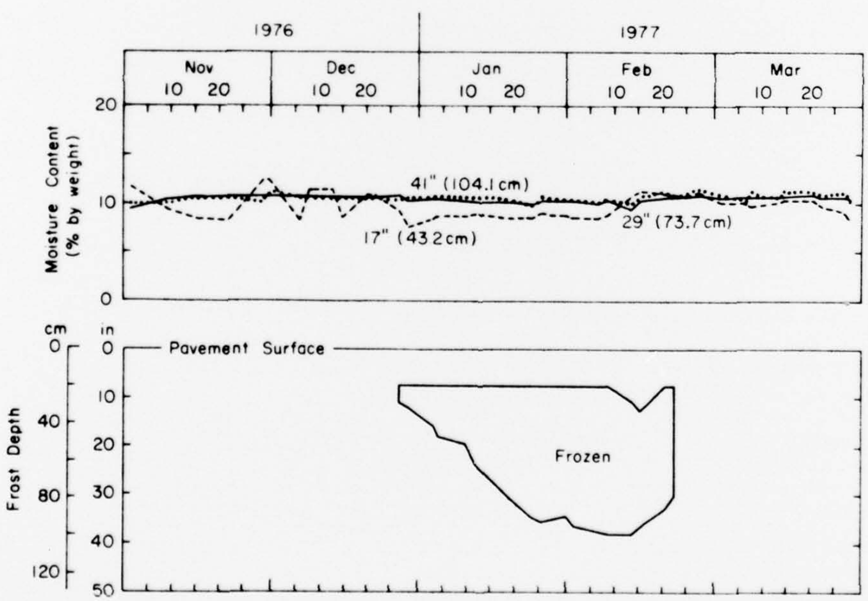

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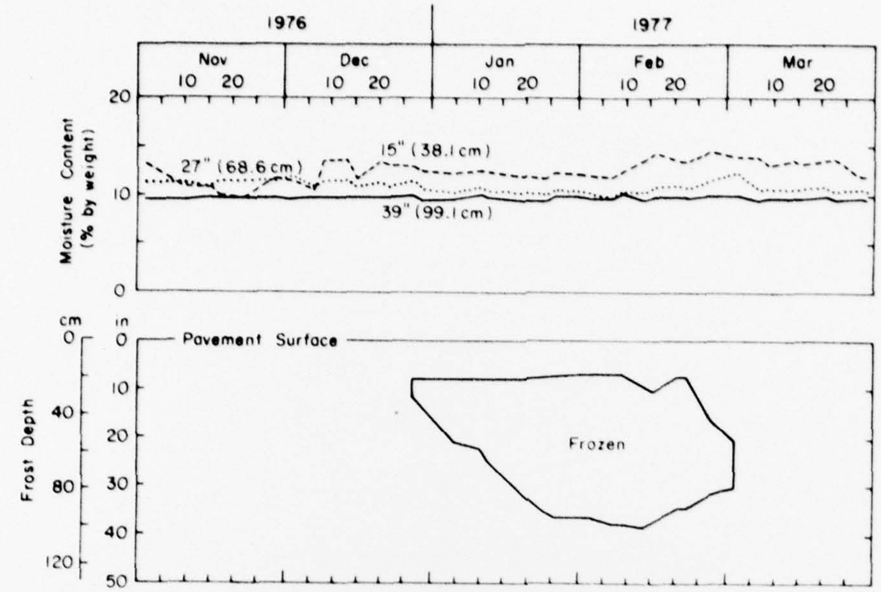

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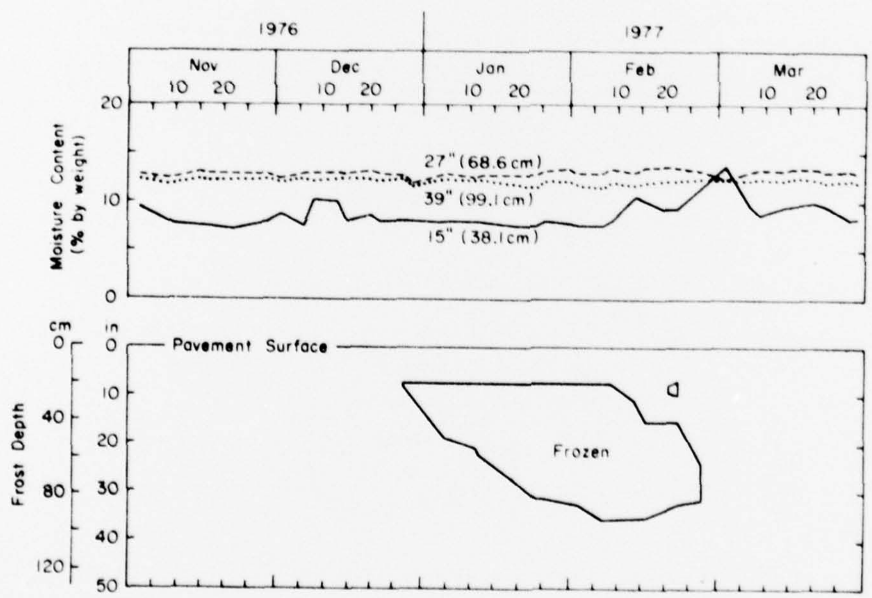

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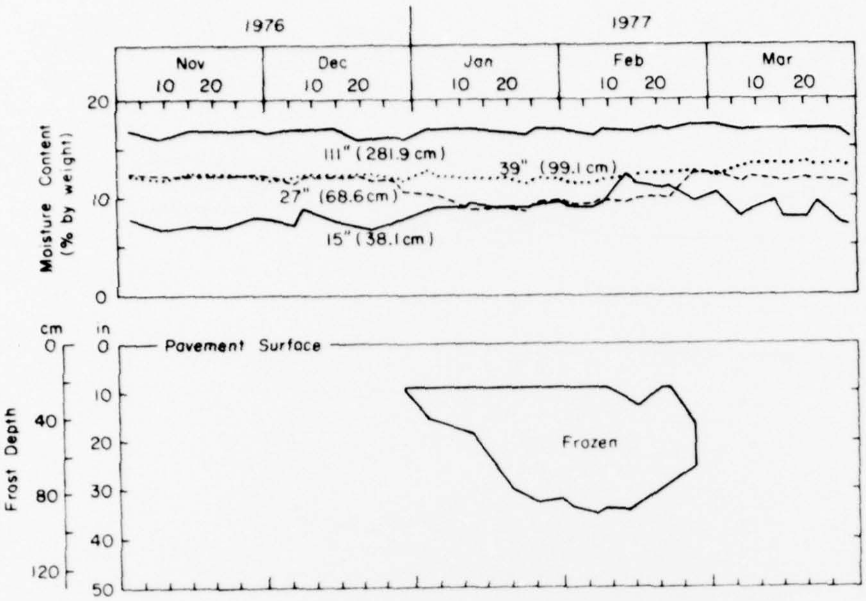

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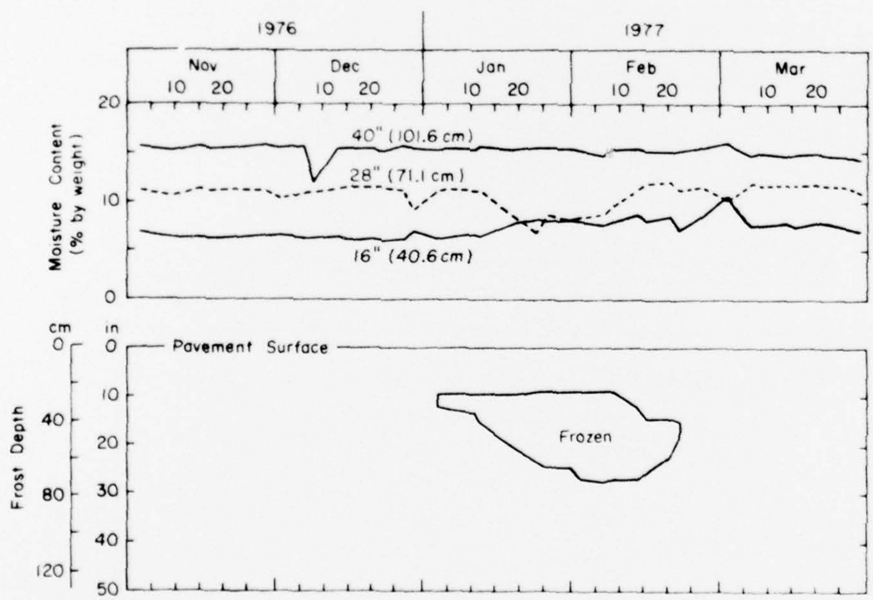

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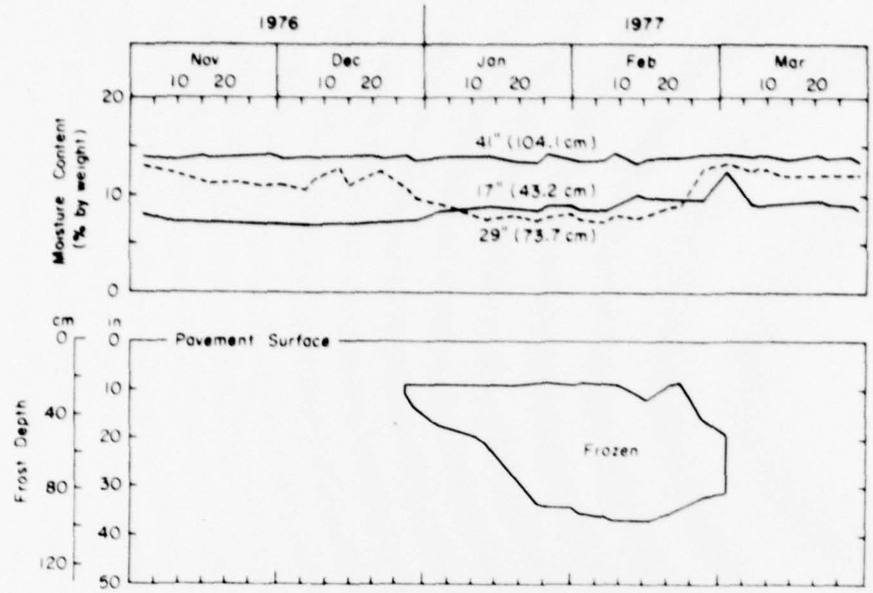

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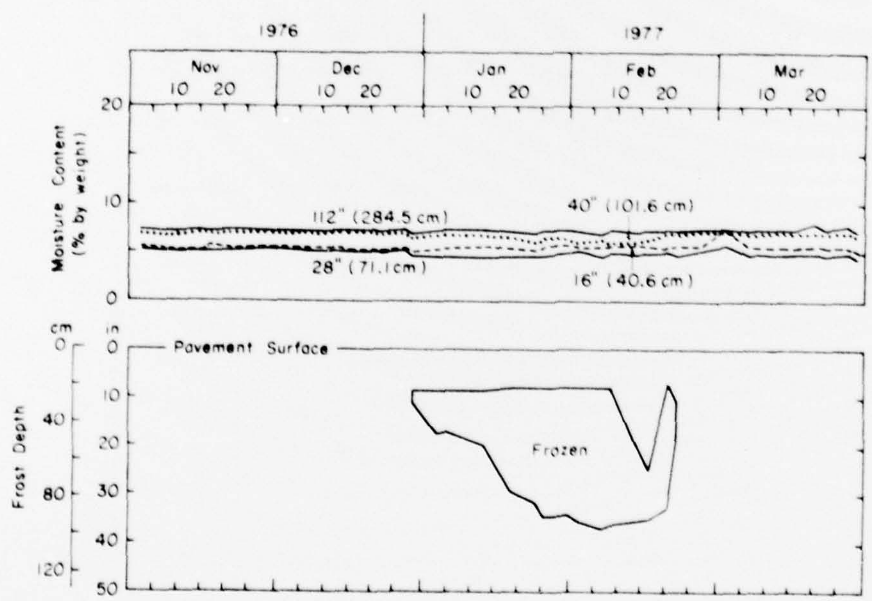

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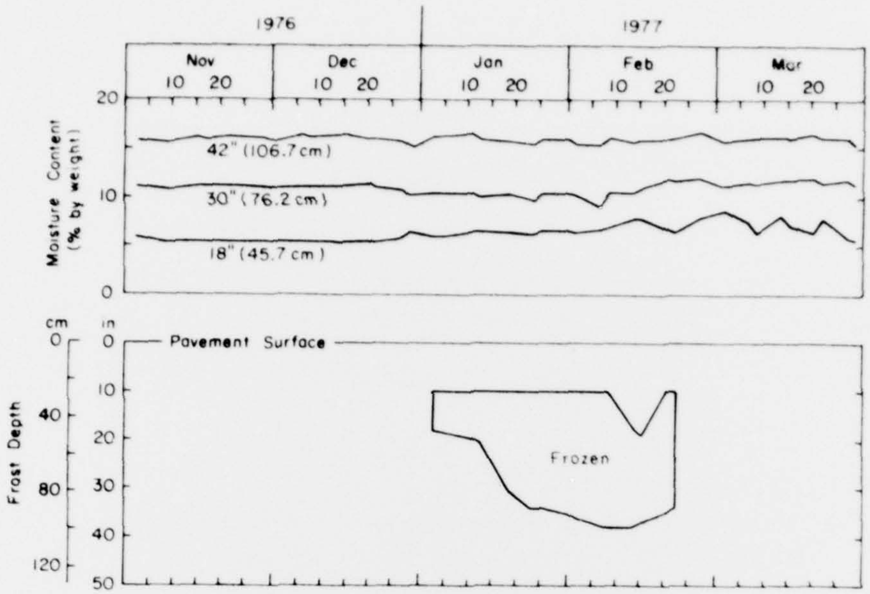

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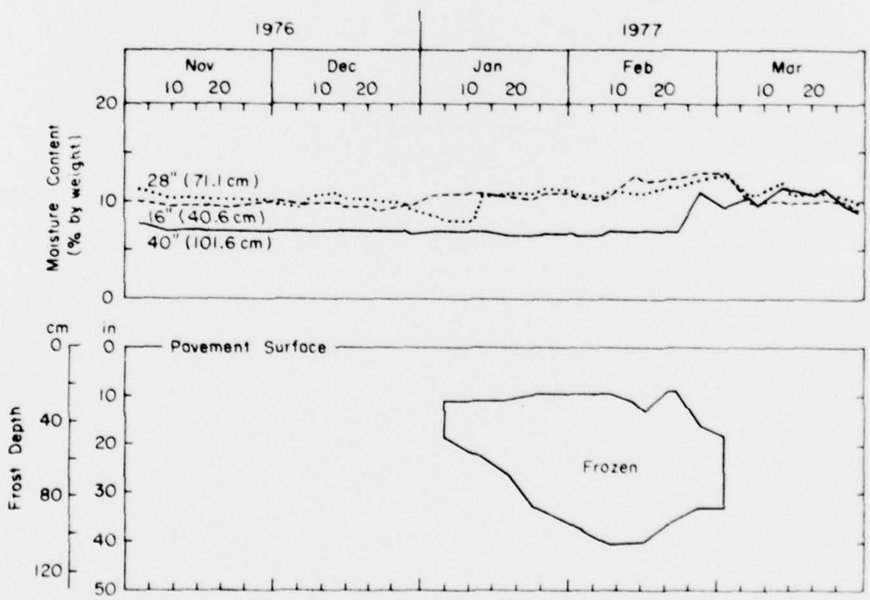

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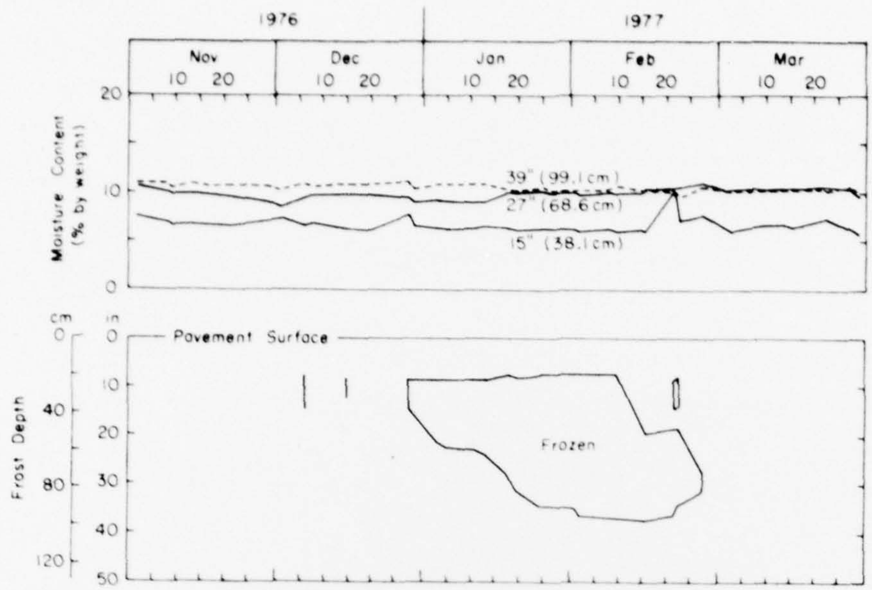

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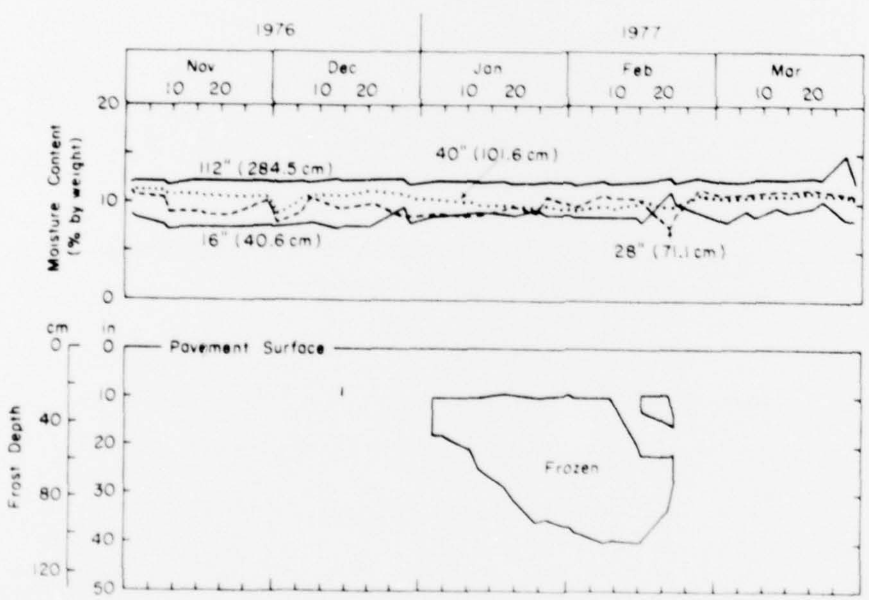

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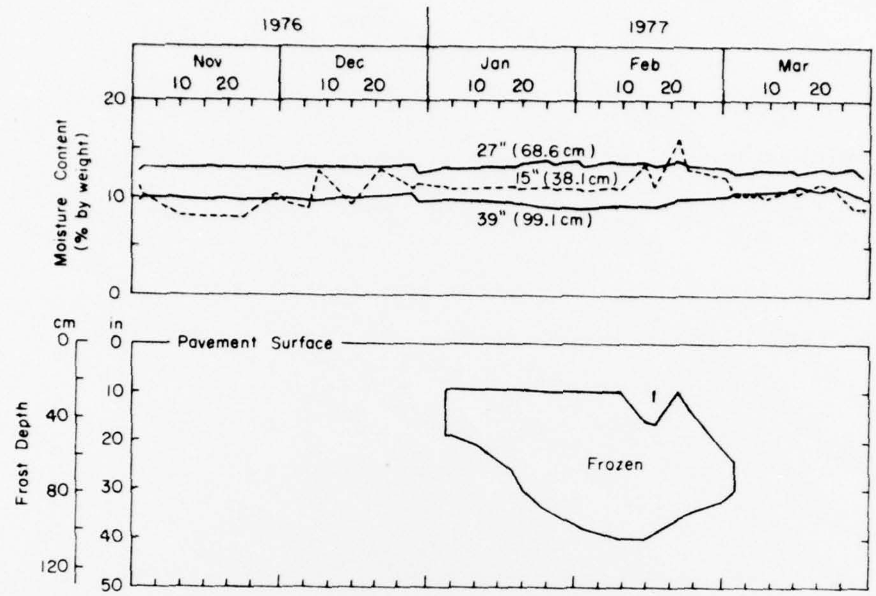

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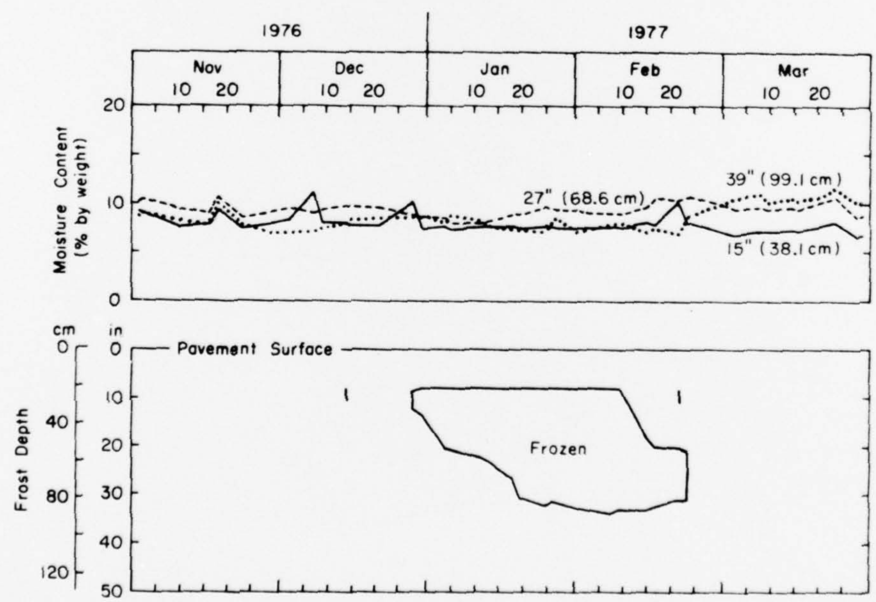

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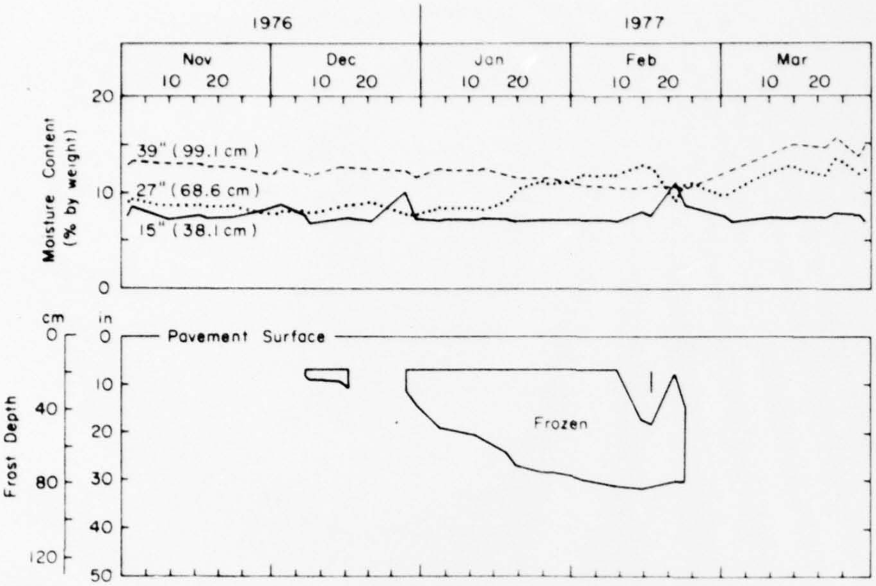

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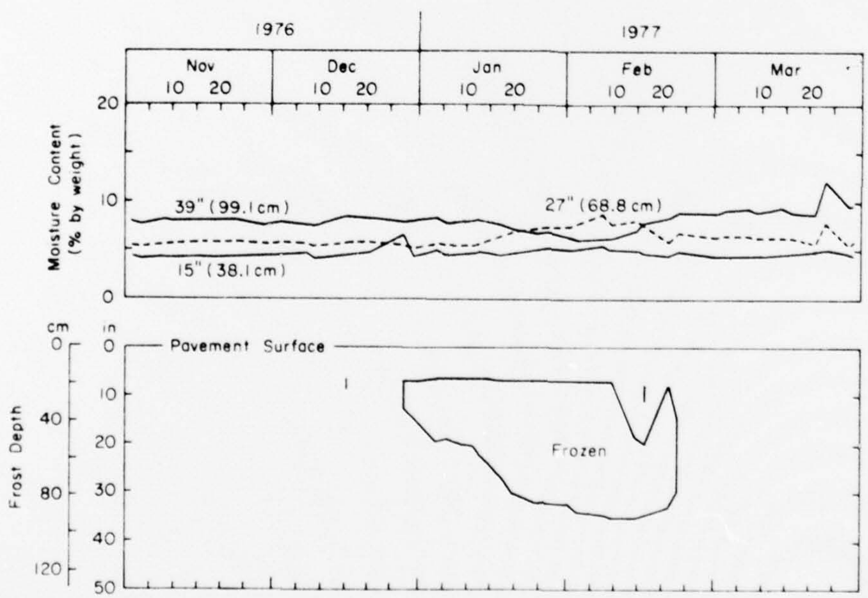

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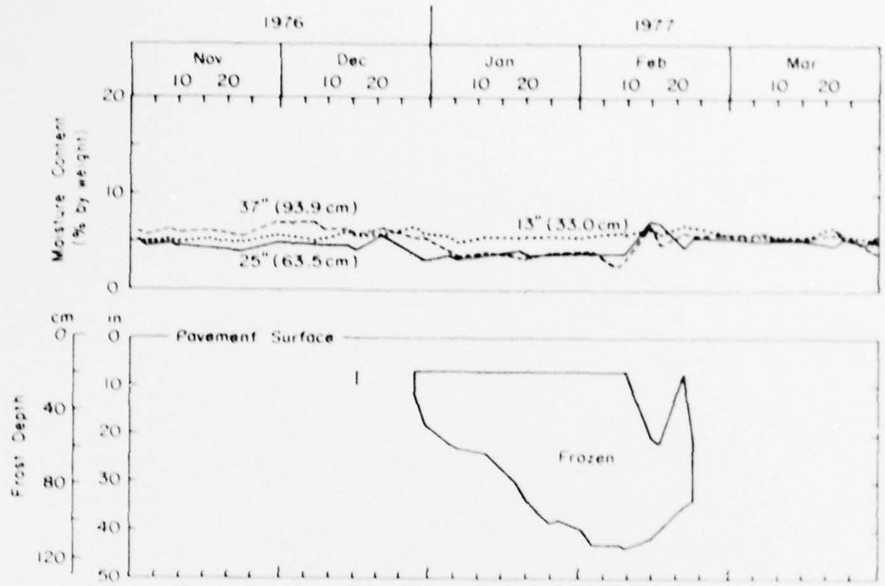

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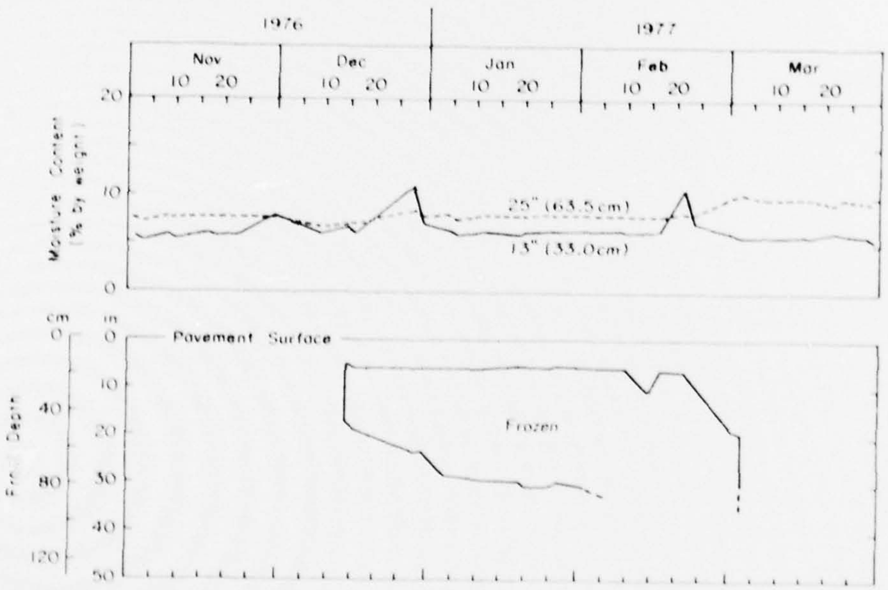

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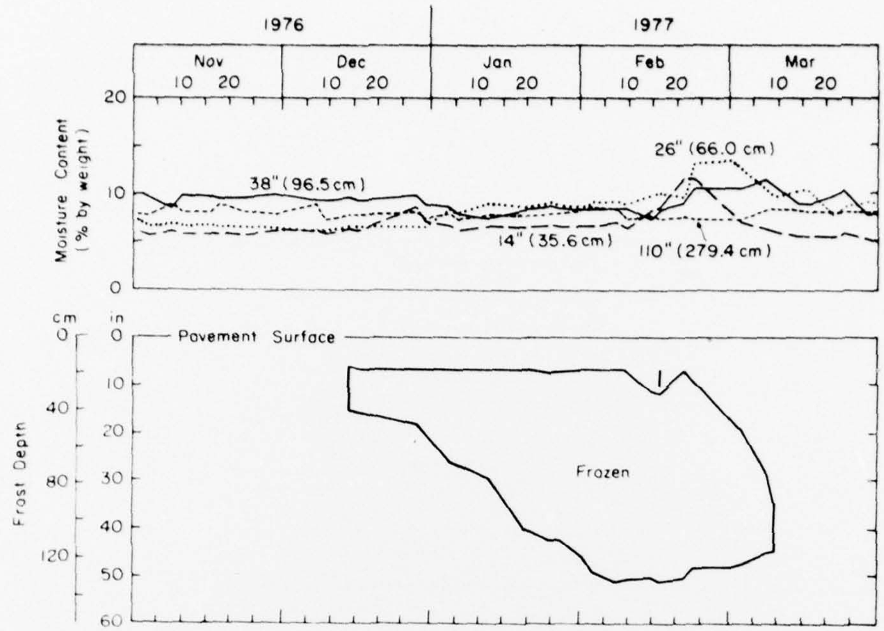

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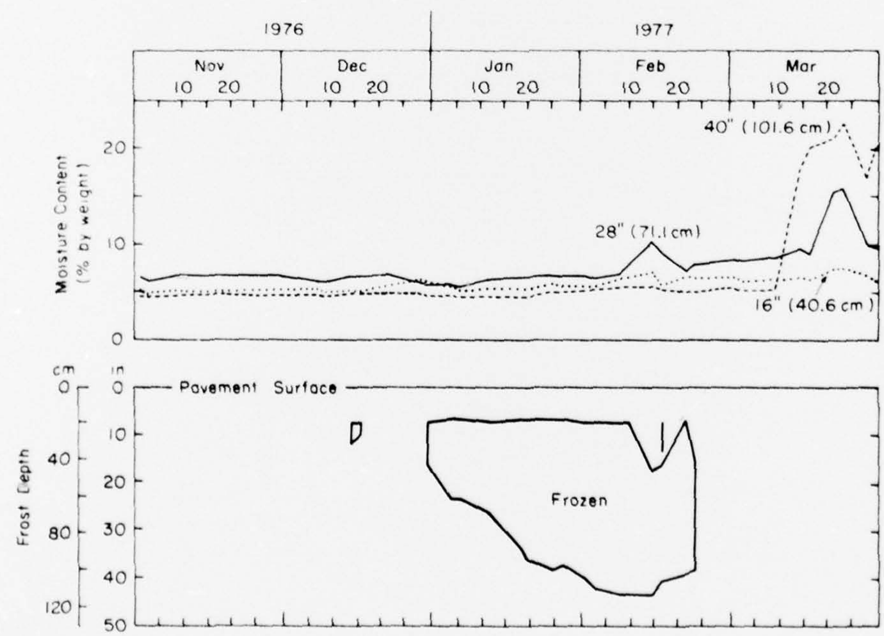

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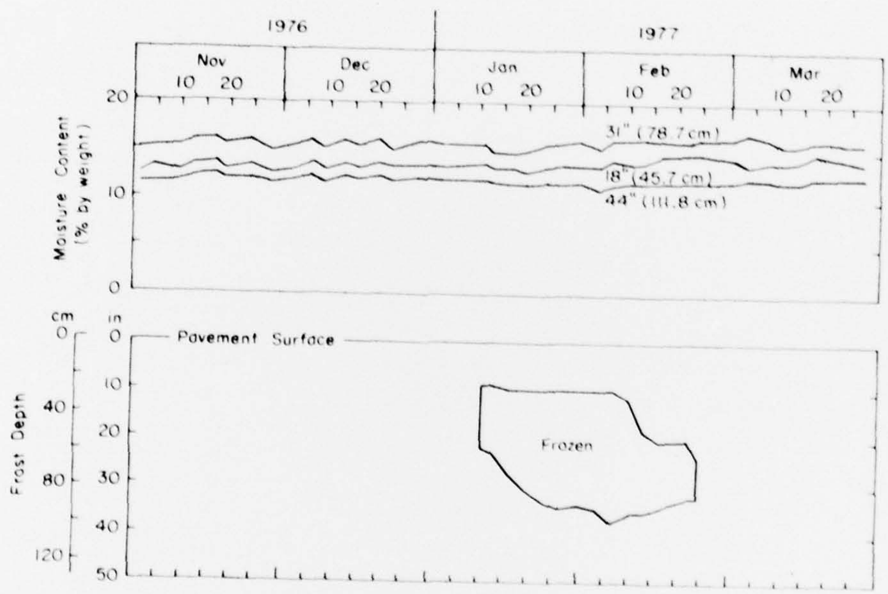

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