CORPS OF ENGINEERS

U.S. ARMY

FROST INVESTIGATIONS
1949 - 1950

REPORT OF
PAVEMENT SURFACE TEMPERATURE
TRANSFER STUDY

PREPARED BY
FROST EFFECTS LABORATORY
CORPS OF ENGINEERS, U. S. ARMY
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NEW ENGLAND DIVISION

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BOSTON, MASS.

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SYNOPSIS

Mathematical equations for predicting depths of frost penetration were developed as part of the Frost Investigations during 1944-1945. In the derivation of these equations the mean temperature at the pavement surface was assumed to be the same as the mean air temperature and the Freezing Index utilized in the equations was based on mean daily air temperatures. This simplifying assumption introduced an error of unknown magnitude as a difference between mean daily air and mean daily pavement temperatures is known to exist which is dependent on such factors as solar intensity, wind velocity, humidity, precipitation, latitude, and the heat absorbing characteristics of the pavement.

This report presents the results of a study to determine the relationship between the Freezing Indexes computed using mean air temperature and those computed using pavement surface temperature. The study is based on subsurface temperature data available at the Frost Effects Laboratory consisting of periodic subsurface temperature readings throughout a complete normal freezing period from three airfields and limited readings from a fourth airfield, all located in the northern part of the United States. From these readings a factor for modifying the Air Freezing Index is obtained and applied to the theoretical equations, and a correlation made between the observed depth and predicted depth of frost penetration. On the basis of these studies, the modified Air Freezing Index, or the Pavement Freezing Index, is of the order of 75 percent of the Air Freezing Index for bituminous concrete pavements and of the order of 90 percent of the Air Freezing Index for portland cement concrete pavements. The effect of the application of these ratios in predicting depth of frost penetration is presented.

A more comprehensive study, based on continuous subsurface temperature readings correlated with mean daily air temperatures, should be undertaken to produce ratio coefficients which when used with existing mathematical equations will result in more accurate predictions of frost penetration.

PART I - INTRODUCTION

1-01. AUTHORIZATION. The Frost Investigations for 1949-1950, of which this investigation is a part, were authorized by the Chief of Engineers by teletype dated 22 November 1949, File: ENGMG.

Study of the temperature transfer characteristics of pavement surfaces was recommended as part of Miscellaneous Frost Studies by representatives of the Office, Chief of Engineers, during the Consultant's Conference held at the Frost Effects Laboratory, New England Division, on 28 and 29 November 1949. The recommendation followed a suggestion by Dr. Philip C. Rutledge of Northwestern University, that a study of the considerable subsurface temperature data available at the Frost Effects Laboratory might result in improvement of the existing theoretical methods of predicting the depth of frost penetration.

1-02. PURPOSE. The purposes of this study were (1) to determine the ratio of freezing indexes determined from mean air temperatures and mean pavement surface temperatures, respectively; and (2) to determine what degree of improvement results from introducing the ratios obtained into the existing mathematical equations for predicting depths of frost penetration.

1-03. SCOPE. The study has been entirely an office investigation, making use of already available field data from four airfields in the northern United States.

1-04. METHOD. The procedure followed in this study has been to:

a. Determine the temperature at the surface of the pavement from available subsurface temperature data by extrapolation, and, using this surface temperature, compute the Pavement Freezing Index and determine the ratios of Pavement Freezing Index to Air Freezing Index, for each site and each type pavement.

b. Compute the theoretical depth of frost penetration for the sites listed in Table 1 using the four theoretical equations developed in previous studies by the Frost Effects Laboratory(1) and modify the Air Freezing Indexes by applying the determined ratios of Pavement Freezing Index to Air Freezing Index as correction factors.

c. Conduct a statistical analysis by comparing the theoretical frost penetrations with the actual frost penetrations. Determine the reliability of predicting frost penetration with the mathematical equations.

d. Derive conclusions from the studies and list the limitations to facilitate future investigations.

1-05. DEFINITIONS. A proper understanding of the terms defined below will be of assistance to the reader in the study of this report.

FROST ACTION. Frost action is the accumulation of water in the form of ice lenses in a soil under natural freezing conditions.

FROST PENETRATION. The maximum depth from the surface to the bottom of the frozen soil.

(1) Report on Frost Investigation 1944-1945, dated April 1947, New England Division, Corps of Engineers, Boston, Mass.

DEGREE DAY. Each degree in any one day that the mean daily temperature varies from 32°F. is called a degree day. The difference between the daily mean temperature and 32°F. equals the degree-days for that day. The degree days are plus when the daily mean temperature is below 32°F. and minus when above. A cumulative degree-days-time curve is obtained by plotting cumulative degree-days against time.

AIR FREEZING INDEX. Air freezing index is a measure of the combined duration and magnitude of below-freezing air temperatures occurring during any given winter and is the maximum ordinate of the degree days-time curve based on air temperatures.

PAVEMENT FREEZING INDEX. Pavement freezing index is a measure of the combined duration and magnitude of below-freezing pavement surface temperatures occurring during any given winter and is the maximum ordinate of the degree-days-time curve based on pavement surface temperatures.

NORMAL FREEZING INDEX. Normal freezing index is computed for normal air temperatures based upon a long period of record, usually 10 years or more.

FREEZING PERIOD. The freezing period is the time during which the frost is in the ground and there is no reduction in strength of foundation material due to frost action.

NORMAL PERIOD. The normal period is the time of the year, Summer and Fall, when there is no reduction in strength of foundation materials due to frost action.

TEMPERATURE GRADIENT. Temperature gradient is the rate of change of temperature between two points.

FROZEN LAYER. The limits of depth within which the soil is frozen is referred to as the frozen layer.

PART II - FIELD TEMPERATURES

2-01. AIRFIELDS INVESTIGATED. The airfields, from which subsurface temperature data were available, are located in the New England Division and the Missouri River Division. The following tabulation summarizes the airfield locations, the years data were recorded, and types of pavement:

Location: Airfield	North Lat.	Winter	Type of Pavement
Dow Field, Bangor, Maine	45°	1946-1947	Portland Cement Conc. Bituminous Conc.
Presque Isle Airfield, Presque Isle, Maine	47°	1945-1946	Portland Cement Conc. Bituminous Conc.
Sioux Falls Airfield, Sioux Falls, So. Dakota	44°	1946-1947	Portland Cement Conc. Bituminous Conc.
Pierre Airfield, Pierre, So. Dakota	44°	March 1945	Portland Cement Conc. Bituminous Conc.

2-02. AIR FREEZING INDEXES. The Air Freezing Index at each of the four airfield sites was based on mean daily air temperatures obtained from recording thermographs located at the airfields. These thermographs were enclosed in stands five feet in height with four louvered sides. At Dow Field the thermograph was located approximately 3000 feet southeast of the subsurface temperature installations and at Presque Isle the thermograph was adjacent to the bituminous concrete area and one mile from the portland cement concrete installation. The temperature data at Sioux Falls and Pierre Airfields were obtained from weather stations located at the airfields.

2-03. <u>SUBSURFACE TEMPERATURES</u>. The logs of test pits and depths of the copper-constantan thermocouples at the Dow Field, Presque Isle and Sioux Falls airfields are shown on Plate 1. These thermocouple installations were made as part of the comprehensive frost investigations at these sites. Thermocouple readings were taken at intervals of three to five days throughout the complete freezing period at each of these installations. The subsurface temperatures were plotted against depth and the resulting thermal gradients extrapolated to intersect the pavement surface. The temperature at this point of intersection was considered to be the pavement surface temperature for that day. An attempt was made in extrapolating the thermal gradient to smooth out large fluctuations in the upper thermocouple which were considered to be influenced by effects of short duration and in this matter obtain a more average temperature condition.

At Pierre Airfield, hourly air temperatures were available for the period 13 March 1945 through 24 March 1945, inclusive. Hourly subsurface thermocouple readings from approximately 9 AM to 6 PM were available for the period 13 March through 16 March. For the period 17 March to 24 March, readings taken every 2½ hours were available. The pavement surface temperatures at this location were obtained by extrapolating to the surface. Plate 3 shows the relationship between air temperature and the extrapolated surface temperatures for both bituminous and portland cement concrete pavements. The period covered by the data presented on Plate 3 is a part of the thawing period, when the air temperature is higher than the pavement surface temperature and the movement of the heat is into the pavement.

2-04. PAVEMENT FREEZING INDEXES. The cumulative degree-day-time curves were plotted for each installation, using the average of two successive determinations as the pavement surface temperature for the interval of time between readings. A typical degree-day-time curve plotted from pavement surface temperature data and method of determining the Pavement Freezing Index are shown on Plate 2. The Pavement Freezing Index for each field investigated and the ratio of this index to the Air Freezing Index computed from mean daily air temperatures are as follows:

Location	Freezing Period	Air Freezing Index	Type of Pavement	Pavement Freezing Index	RATIO: Pavement Index to Air Index
Dow Field	1946-1947	965	Bit.Con.	722	0.75
Presque Isle	1945-1946	2304	Bit.Con.	1802	0.78
Sioux Falls	1946-1947	1314	Bit.Con.	716	0.55(1)
Dow Field	1946-1947	965	PCC	838	0.87
Presque Isle	1945-1946	2304	PCC	2190	0.95
Sioux Falls	1946-1947	1314	PCC	1206	0.92

Note:
(1) Thermocouples had been installed at depths of 0.16 feet and 0.90 feet below the pavement surface. The other installations had three thermocouples in the top one foot layer. It appears that, if another thermocouple had been installed approximately midway between 0.16 and 0.90 feet, the resulting extrapolation to the surface generally would result in lower temperatures and consequently a higher Pavement Freezing Index.

The number of installations and the frequency of temperature readings are considered adequate only for preliminary determinations of the ratios of Pavement Freezing Index to Air Freezing Index.

From the available data as analyzed in this study the ratio of Pavement Freezing Index to Air Freezing Index is indicated to be of the order of 0.75 for bituminous pavements and 0.90 for portland cement concrete pavements. By applying these ratios as correction factors to the Air Freezing Indexes at locations where the Pavement Freezing Indexes have not been determined, estimated Pavement Freezing Indexes may be obtained.

2-05. ACCURACY OF OBSERVATIONS. The ratios of Pavement Freezing Index to Air Freezing Index are based on limited information as previously noted, particularly in respect to the frequency of observations. In general, the observations were taken at intervals of 3 to 5 days between 10 AM and 2 PM. Plate 3 indicates that the surface temperature lags behind the air temperature and the cooling or warming effect of the air does not produce a surface temperature as low or as high as the air temperature. It also is apparent that the pavement surface temperature may vary greatly in any one day and a freezing index based on one daily reading would still be an approximation. From observations by Wollny[1] reproduced on Plate 4, it can be seen that the difference between the temperature of the air and the temperature of the soil varies appreciably throughout a 24 hour period. Likewise, from observations by Smith[1] also reproduced on Plate 4, it will be noted that a considerable temperature differential exists throughout the year. Therefore, a ratio based on one reading every three or four days would not necessarily give a true relationship.

(1) Soil Physics by L. D. Baver (John Wiley and Sons)

2-06. <u>RESULTS OF OTHER INVESTIGATORS</u>. The Permafrost Division of the St. Paul District, Corps of Engineers evaluated correction factors using air temperatures and temperatures on various type horizontal surfaces at the Permafrost Research Area, Fairbanks, Alaska. The correction factor is defined as the ratio of the degree days above or below zero degrees Centigrade computed from surface temperatures to the degree days computed from air temperatures during the same period. The winter correction factor for pavements is therefore the same as the ratio of Air Freezing Index to Pavement Freezing Index as used in this report.

The correction factors based on available data at the time of preparation by the Permafrost Division of the Comprehensive Report - Investigation of Airfield Construction in Arctic and Subarctic Regions, as revised in February 1950 were as follows:

Surface	C = Correction Factor Summer	C = Correction Factor Winter
Spruce trees, brush and moss over peat soil	0.37	0.29
Cleared of trees and brush but with moss in place over peat soil	0.73	0.25
Silt loam surface cleared and stripped of trees and vegetation	1.22	0.33
Gravel surface	2.00	0.70
Concrete surface	2.03	0.77
Bituminous surface	2.19	0.72

PART III - STATISTICAL ANALYSIS

3-01. ANALYSIS. The predicted depths of frost penetration using both the Air Freezing Indexes and the Pavement Freezing Indexes and the existing conditions at the 48 paved test locations investigated are presented in Table 1. Turfed locations shown in this table were not considered. The Pavement Freezing Indexes were determined by applying correction factors of 0.75 for bituminous concrete areas and 0.90 for portland cement concrete areas to the Air Freezing Indexes. A statistical analysis was made to determine the reliability of the mathematical equations utilized in determining the depth of frost penetration and the effect of applying correction factors to the Freezing Indexes at the 48 test locations tabulated in Table 1. Statistical interpretation of the dispersion was undertaken using the standard equations listed:

(a) arithmetic mean $\overline{X} = \frac{\Sigma(X)}{N}$

X = data expressed in individual items

N = total number of items

(b) median = $\frac{N}{2}$ th observation = (Middle item when items are arranged according to size)

(c) mode = $L_{mo} + \frac{f_a}{f_a + f_b} C$

L_{mo} = lower limit of modal group

f_a = frequency of class interval above modal group

f_b = frequency of class interval below modal group

C = size of class interval

(d) standard deviation $\sigma = \sqrt{\frac{\Sigma(x^2)}{N}}$

x = deviation from arithmetic mean

(e) skewness = $\dfrac{mean - mode}{\sigma}$

(f) The method of least squares was employed to determine the array of consistency of the computed depths to the observed depths

$$\sum (X_i - X_o)^2$$

X_i = computed depth

X_o = observed depth

3-02. <u>COMPARISON OF OBSERVED WITH COMPUTED RESULTS.</u> The data were arranged on the basis of percent variation between observed and predicted depths of frost penetration with plus values indicating predicted depths greater than the observed and minus values denoting predicted depths less than the observed. The values were grouped in class intervals of ten percent and the statistical analysis made. The results of the statistical analysis are presented below which show the variation of the predicted from the observed depths of frost penetration.

a. Using the Air Freezing Index:

	Equation Number				
	83	93	154	154+ Pave.	Design Curve
Mean	+ 57.4%	+ 30.2%	-5.6%	+ 9.8%	+ 2.2%
Median	+ 40.1%	+ 22.5%	-13.2%	+ 2.2%	0.0%
Mode	+ 36.5%	+ 17.5%	-14.2%	-3.1%	0.0%
Standard Deviation	51.8%	37.0%	26.2%	30.9%	21.6%
Skewness	+0.403	+0.343	+0.338	+0.417	+0.102
Sum of Least Squares	31,762	12,144	5,387	4,282	2,597

The least dispersion from the observed depths of frost penetration as determined by the method of least squares was the Design Curve's predicted depths. Equation 154 plus pavement was dispersed slightly more, followed by equations 154 and 93. Equation 83 indicated considerable dispersion.

b. Using the Pavement Freezing Index:

	Equation Number			
	83	93	154	154+ Pave.
Mean	+ 26.5%	+ 20.1%	-14.7%	-1.6%
Median	+ 10.4%	+ 12.5%	-20.8%	-12.5%
Mode	+ 7.3%	+ 6.9%	-23.0%	-13.3%
Standard Deviation	42.2%	32.2%	23.8%	21.6%
Skewness	+0.432	+0.410	+0.349	+0.409
Sum of Least Squares	9,072	6,201	7,878	4,377

The introduction of the Pavement Freezing Index produced a marked improvement with equations 83 and 93, created somewhat additional dispersion with equation 154 and had very slight effect with 154 plus pavement. Equation 93 became more consistent than equation 154 while equation 154 plus pavement and equation 83 maintained their original positions as to dispersion.

3-03. GRAPHICAL PRESENTATION. Graphical presentation of the dispersion of computed values with respect to the observed depths of penetration for each equation is shown on Plate 5.

3-04. VARIATION FROM OBSERVED DEPTHS OF FROST PENETRATION. The number of predicted depths of frost penetration which fall within six inches of the observed depth is greatly increased by the use of the Pavement Freezing Index in equations 83 and 93 while in equations 154 and 154 plus pavement somewhat greater variations result, as indicated in the following tabulation.

a. Using the Air Freezing Index:

Equation	No. of Predicted Values ± 6" of Observed Values	No. of Predicted Values Which Are Closest to Observed Value
83	3	0
93	14	8
154	20	9
154+Pave.	26	14
Design Curve	30	25

b. Using the Pavement Freezing Index:

Equation	No. of Predicted Values ± 6" of Observed Values	No. of Predicted Values Which Are Closest to Observed Value
83	24	10
93	29	11
154	12	3
154+Pave.	19	6
Design Curve	30	20

PART IV - CONCLUSIONS

4-01. RATIOS. This limited study indicates that the ratio of Pavement Freezing Index to Air Freezing Index is of the order of 0.75 for a bituminous concrete pavement, and is of the order of 0.90 for a portland cement concrete pavement.

4-02. APPLICATION OF RATIOS. The modifications of the Freezing Indexes by introducing the above ratios into the mathematical equations used to predict frost penetrations greatly increase the correlation of the theoretical penetrations to the observed frost penetrations for equations 83 and 93, and conversely, slightly decrease the correlation for equations 154 and 154 plus pavement.

4-03. RELIABILITY OF THEORETICAL EQUATIONS. The design curve is the most consistent method of theoretically predicting the depth of frost penetration in a non-frost susceptible soil. The order of reliability for the equations considered, based on the least squares method, using the Air Freezing Index, is:

a. Equation 154 plus pavement

b. Equation 154

c. Equation 93

d. Equation 83

and with the application of the Pavement Freezing Index the sequence becomes

a. Equation 154 plus pavement

b. Equation 93

c. Equation 154

d. Equation 83

4-04. LIMITATIONS. a. Since the design curve is an empirical relationship obtained by using the same field data, the close agreement between observed and predicted depth is to be expected.

b. Variations between the predicted and the observed depths of frost penetration are caused by several factors other than surface temperature differences.

PART V - RECOMMENDATIONS

5-01. PAVEMENT SURFACE TEMPERATURE. The extrapolated surface temperature from subsurface readings is affected very little by readings below one foot but lack of readings in the top one foot layer causes wide differences. The subsurface readings should begin as close to the surface as possible and it is recommended that in future studies at least three thermocouples be placed in the top one foot layer.

5-02. FREQUENCY OF READINGS. Two important conditions which effect the airfield pavement surface temperatures are (a) the direct effect of the sun's rays and (b) the temperature of the air - assuming there is no snow coverage. It is obvious that both of these factors are varying constantly. Therefore, in any future analysis of theoretical prediction of frost penetration, a continuous record of subsurface temperature readings would be necessary to facilitate correlation between mean air temperature and pavement surface temperature.

5-03. FUTURE INVESTIGATIONS. Continuous pavement surface or ground surface temperature data obtained at several locations with varying latitudes and climatological conditions would produce reliable factors for the correction of the Air Freezing Index for use with present mathematical equations for predicting depths of frost penetration in areas subject to seasonal freezing or depths of thaw in permafrost areas.

With the data recently made available on the thermal properties of soil[1], the use of the mathematical equations for predicting depths of freezing and depth of thaw give promise of greater reliability for varying conditions of soil and moisture than the empirical design curve which applies only to non-frost susceptible soils at average moisture conditions. It is recommended that additional information be obtained on surface temperature transfer characteristics so that additional refinement in the use of the mathematical equations will result.

(1) Final Report, Laboratory Research for the Determination of Thermal Properties of Soil dated June 1949, St. Paul District, Corps of Engineers, U. S. Army

SITE	TEST AREA	YEAR	MEAN ANNUAL AIR TEMP. °F (v_0)	FREEZING INDEX °F DAYS (F)	FREEZING INDEX DURATION DAYS (t)	PAVEMENT (I) TYPE	PAVEMENT THICK. IN INCHES	BASE (II) (III) CLASS.	BASE THICK. IN INCHES	BASE WATER CONTENT % (w)	BASE DENSITY LBS/FT.³ (γ)	SUBGRADE (II) (III) CLASS.	SUBGRADE THICK. IN INCHES	SUBGRADE WATER CONTENT % (w)	SUBGRADE DENSITY LBS./FT.³ (γ)	AVG. VOL. HEAT B.T.U./(FT.³)(°F) (C)	AVG. LATENT HEAT B.T.U./FT.³ (L)	(IV) OBSERVED DEPTH OF FREEZING IN INCHES	AIR FREEZING INDEX EQ. 83	AIR FREEZING INDEX EQ. 93	AIR FREEZING INDEX EQ. 154	AIR FREEZING INDEX EQ. 154 + PAVE.	AIR FREEZING INDEX EQ. 158	DESIGN CURVE	PAVEMENT FREEZING INDEX EQ. 83	PAVEMENT FREEZING INDEX EQ. 93	PAVEMENT FREEZING INDEX EQ. 154	PAVEMENT FREEZING INDEX EQ. 154 + PAVE.
DOW	I AND III	1943-1944	42.5	1515	108	B.C.	4.0	GW	17	9.9	135	CL	-	30.5	81	39.6	2920	48	68	62	44◀	▶48◀		54◀	51◀	54◀	38	42◀
	II			1690	123	B.C.	3.5	GW	36	4.2 *	135 *	CL	-	19.3 *	107 *	39.5	1300	50	108	87	62	65		57	82	77	▶54◀	58
	IV TO VII			1745	130	P.C.C.	7.0	GW	15	9.2	133	CL GC	38 -	28.4 28.4 (1)	92 92 (1)	42.8	3900	48	63	58	41	▶48◀		58	57	62	44◀	51◀
	A	1944-1945		1445	104	P.C.C.	7.0	GW	15	11.1	119	CL GC	42 -	25.7 25.4 NF	98 103 NF	44.1	3035	54	65	58◀	41	48◀		▶53◀	59◀	▶55◀	39	46
	B			1445	104	B.C.	3.5	GW	31	8.9	131	CL	-	31.1 24.2 NF	93 92 NF	39.2	2310	52	75	66	47◀	50◀		▶53◀	56◀	58◀	41	45
	C			1345	88	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109	40.0	1960	60	79	67	47	50		51	▶59◀	▶59◀	42	46
	C			1445	104	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109	40.0	1995	62	81	69	49	52		53	▶61◀	▶61◀	43	47
	TURF			1445	104	T.S.	6.0	-	-	-	-	CL	-	23.4 15.2 NF	99 112 NF	39.0	3300	24					37					
	D	1945-1946		1420	99	B.C.	3.5	GW	40	13.5 *	128 *	CL	-	17.7 *	115 *	42.1	2530	50	71	62	44◀	▶47◀		▶53◀	▶53◀	55◀	39	43
	E			1420	99	B.C.	3.5	GW	36	10.1 *	136 *	CL	-	22.4 *	101 *	41.5	2205	48	76	66	▶47◀	50◀		53◀	57	58	41	45◀
	E			1090	75	B.C.	3.5	GW	36	10.1 *	136 *	CL	-	22.4 *	101 *	41.6	2110	44	68	59	42◀	▶45◀		47◀	51	52	37	41◀
	F			1060	74	P.C.C.	7.0	GW	20	8.1 *	138 *	CL	-	22.5 *	110 *	44.6	2700	54	59◀	52◀	37	44		46	▶53◀	52◀	37	44
	TURF			1420	99	T.S.	6.0	-	-	-	-	CL	-	22.4 (1)	101 (1)	42.0	3210	26					37					
PRESQUE ISLE	A	1944-1945	39.0	2060	115	P.C.C.	7.0	GW	33	6.3	134	GC	-	17.9 16.2 NF	108 113 NF	38.7	1945	70	98	85	60	67◀		63	69	82	58	65◀
	B			2060	115	B.C.	4.0	C.R. GW	4 30	- 6.5	- 134	GC	-	14.8 14.2 NF	114 114 NF	37.4	1870	71	99	87	62	▶70◀		63	74◀	77◀	54	56
	TURF			140	25	T.S.	5.0	-	-	-	-	GC	-	18.6 15.9 NF	105 110 NF	39.1	2790	13					12◀					
	A	1945-1946		2240	126	P.C.C.	7.0	GW	32	10.4 *	133 *	GC	-	17.0 *	117 *	41.1	2450	78	91	80◀	57	64		65	82	▶77◀	54	61
	C			2230	120	B.C.	3.5	C.R. GW	3.5 26	- 6.3 *	- * 132	GC	-	13.6 *	115 *	37.0	1785	68	106	92	▶65◀	72◀		▶65◀	80	80	57	61
	D			2230	124	B.C.	3.5	C.R. GW	3.5 25	- 10.5 **	- ** 142	GC	-	18.4 **	120 **	44.0	2740	69	85	76	54	61		65◀	64◀	▶67◀	47	51
	TURF			2240	128	T.S.	5.0	-	-	-	-	GC	-	13.6 (1)	115 (1)	37.5	2230	50					56◀					
BEDFORD	A	1945-1946	46.5	825	99	P.C.C.	6.0	GW	18	4.8 *	119 *	SW	-	5.3 *	103 *	26.0	800	40	96	76	54	60		▶41◀	86	72	51	57
	B			695	87	B.C.	5.0	GW	14	4.8 (1)	119 (1)	SW	-	5.3 (1)	103 (1)	26.0	805	26	88	70	49	54		▶38	66	61	43	48
	B			345	41	B.C.	5.0	GW	14	4.8 (1)	119 (1)	SW	-	5.3 (1)	103 (1)	26.0	805	26	62	49	35	40		▶27◀	46	41	29	34
OTIS	A	1944-1945	48.7	300	60	B.C.	6.0	-	-	-	-	SF OR ML SP GP	30 24 -	9.5 ** 23.5 ** 1.2 0.8	** 124 ** 87 119 126	27.4	2285	26	34	31◀	22◀	28◀		▶26◀	▶26◀	▶26◀	18	24◀
HOULTON	A	1944-1945	40.5	1605	107	B.C.	1.5	S.CEM.	6	16.3	113	GF GC	30 -	14.7 8.3 10.1 NF	110 134 NF 116	34.8	2180	49	81	72	▶51◀	52◀		56	61	64	45◀	▶47◀
TRUAX	A	1944-1945	46.0	1210	88	B.C.	2.5	C.R. GF	8 15	- 5.3 *	- * 141	CL SF CL	23 38 -	21.1 * 6.1 * 21.1 *	108 * 115 * 108 *	39.9	2385	48	68	58	41	51◀		▶48◀	51◀	50◀	35	38
	B			1245	95	B.C.	2.5	C.R. GF	18 25	- 7.7	- 122	CL	-	27.0	99	43.9	1805	56	78	64	45	65		50◀	58◀	▶56◀	40	43
	C			1245	97	P.C.C.	6.0	GF	48	12.7	112	CL	-	30.0	82	38.8	2070	55	74	62	44	50◀		50◀	▶56◀	60◀	42	48
	A	1945-1946		1020	93	B.C.	2.5	C.R. GF	8 18	- 6.0 *	- * 140	CL SF CL	26 36 -	27.5 * 19.8 * 27.5 *	95 * 118 * 95 *	43.7	2430	46	62	53	37	47◀		▶45◀	47◀	▶46◀	33	36
	C			1060	100	P.C.C.	7.0	GF	30	10.1 *	* 129	CL SF	32 -	35.5 * 20.4 *	87 * 113 *	43.9	2550	48	61	53◀	37	44◀		▶46◀	55	▶50◀	35	42◀
	D			1055	99	B.C.	2.5	C.R. GF	20 30	- 5.6 *	- * 139	CL	-	25.9 *	99 *	43.2	1580	59	78	63◀	44	66		46	▶58◀	55◀	39	42
SELFRIDGE	B	1945-1946	47.8	645	81	P.C.C.	10.0	GF	12	11.5	99	ML SF CL	13 30 -	18.0 22.3 * 36.2 *	112 100 * 85 (1)	44.6	2280	35	50	43	30◀	40◀		▶36◀	45	41◀	29◀	39◀
PIERRE	A	1944-1945	47.5	960	104	P.C.C.	7.0	GF	7	8.7 *	135 *	CL CH	32 -	15.1 * 23.5 *	105 * 90 *	37.9	2150	42	63	54	39◀	46◀		▶44◀	56	52	37◀	▶44◀
	B			695	71	B.C.	5.5	GF	9	6.4 *	140 *	CL	-	14.1 *	97 *	32.9	1640	25	62	52	37	42		38	46	46	▶33	39
	TURF			660	69	T.S.	4.0 (1)	-	-	-	-	CL CH	60 -	12.1 * 18.7 *	98 * 90 *	33.6	1680	6					34					
	A	1945-1946		1025	99	P.C.C.	7.0	GF CL	7 6	7.4 * 15.9 *	* 142 * 110	CL CH	27 -	21.6 * 21.7 **	97 * 97 **	39.1	2625	46	59	52◀	37	44◀		▶45◀	53◀	49	38	42◀
	C			1025	99	B.C.	6.0	GF CL	8 7	6.7 * 13.6 *	* 128 * 115	CL	-	12.7 *	92 *	30.0	1670	44	74	63	▶45◀	51		▶45◀	56	55	39◀	▶45◀
SIOUX FALLS	A	1944-1945	46.2	915	76	B.C.	2.0	GC CL	10 12	7.0 * 16.7 *	* 132 * 112	CL OR CH	-	23.8 * 30.9 *	95 * 84 *	40.6	2640	40	56	49	35◀	▶37◀		▶43◀	42◀	42◀	30	32
	A	1945-1946		1220	82	B.C.	2.0	GC CL	10 12	7.1 * 21.4 *	* 137 * 103	CL OR CH SF-CL	48 -	29.0 * 15.9 *	89 * 97 *	36.5	3020	47	60	53◀	38	40		49◀	46◀	▶49◀	34	36
	B			1310	100	P.C.C.	6.0	-	-	-	-	CH CL SC	90 11 -	33.0 * 27.5 ** 15.9 (1)	85 * 87 ** 97 (1)	36.9	3980	42	54	50	35	41◀		61	49	46◀	34	▶40◀
WATER-TOWN	A	1944-1945	42.5	660	62	P.C.C.	8.0	-	-	-	-	SF-OL OL-CL GP	32 20 -	14.6 * 23.8 * 3.8 *	112 * 87 * 120 (1)	30.7	2325	38	58	52	▶37◀	45		42◀	52	49	35◀	43◀
	B			840	59	B.C.	5.0	GF	6	4.9 *	139 *	SF-OL OL-CL GP	22 11 -	14.1 * 22.1 * 4.4 *	103 * 88 * 120 (1)	29.9	1970	42	62	55	39◀	44◀		▶41◀	47◀	48◀	34	39◀
	TURF			660	64	T.S.	8.0	-	-	-	-	SF-OL GP	52 -	6.4 * 4.4 *	136 * 120 (1)	30.6	1240	42					43◀					
	A	1945-1946		1715	98	P.C.C.	9.0	-	-	-	-	SF-OL OL-CL GP	24 22 -	14.6 (1) 23.8 (1) 3.8 (1)	112 (1) 87 (1) 120 (1)	29.7	2010	75 TH	88	▶77◀	55	64		58	79◀	▶73◀	62	61
	B			1715	98	B.C.	5.0	GF	12	4.9 (1)	139 (1)	SF-OL GP	30 -	14.1 (1) 4.4 (1)	103 (1) 120 (1)	29.6	1330	79 TH	108	90	64	69		58	▶81◀	82◀	58	63
FARGO	A	1944-1945	39.2	1395	79	B.C.	1.5	S.CEM. CL-SF	6.5 14	11.1 * 10.6 *	* 122 * 126	OH-CH CH	8 -	26.7 * 31.1 *	99 * 89 *	43.2	2965	46	65	59	42◀	▶43◀		52◀	▶49◀	52◀	37	39
	A	1945-1946		2465	125	B.C.	1.5	S.CEM. CL-SF	6.5 11	11.1 (1) 10.6 (1)	122 (1) 126 (1)	OH-CH CH	12 -	26.7 (1) 31.1 (1)	99 (1) 89 (1)	42.3	3395	72 TH	81	▶73◀	52	53		69◀	61	65	46	48
GREAT BEND	A	1944-1945	55.0	50	5	P.C.C.	7.0	SW OR SF	6	2.0 *	120 *	SF-CL OR CL-SF CL	35 -	15.1 * 13.1 * 17.0 *	109 * 102 * 100 *	36.4	325	13	37	18◀	▶13◀	20		11◀	33	17◀	12◀	19
	A	1945-1946		130	11	P.C.C.	7.0	SF	5	2.0 (1)	120 (1)	SF-CL OR CL-SF CL	35 -	15.1 (1) 13.1 (1) 17.0 (1)	109 (1) 102 (1) 100 (1)	36.2	1600	24 TH	27◀	21◀	15	▶22◀		17	▶24◀	20◀	14	21◀
BISMARCK	A	1944-1945	39.0	1280	86	B.C.	4.5	SC	6	4.7 *	130 *	CL-ML SP	49 -	16.8 * 8.1 *	87 * 99 *	28.7	1905	46	78	70	50◀	54		▶50◀	58	61	43◀	▶48◀
CASPER	A	1944-1945	47.4	355	59	P.C.C.	7.0	-	-	-	-	SF-CL SF SP	29 12 -	11.4 * 6.8 * 5.3 *	114 * 120 * 111 *	29.2	1850	30	42	36◀	26◀	33◀		▶27◀	38	35◀	25◀	▶32◀
	B			355	59	B.C.	5.0	GW	7	3.8 *	131 *	SF-CL SP SF-CL	12 32 -	6.2 * 3.5 * 6.2 *	117 * 109 * 117 *	29.7	870	16	61	47	34	39		▶27	46	41	29	34
FAIRMONT	A	1944-1945	52.0	380	70	P.C.C.	8.0	-	-	-	-	CL CH	25 -	28.0 * 23.0 *	89 * 88 *	38.1	3550	15	31	28	20◀	28		28	28	26	▶18◀	26
GARDEN CITY	A	1944-1945	55.0	25	7	B.C.	1.5	SC	10	5.0 *	128 *	CL CH OR CH-CL	36 -	15.9 * 19.1 * 16.3 *	107 * 95 * 97 *	36.2	990	12	15◀	▶11◀	8◀	9◀		8◀	▶11◀	10◀	7◀	9◀

EQUATIONS:

83 $$x = \sqrt{\frac{48\,kF}{L}}$$

93 $$x = \sqrt{\frac{48\,kF}{L + C\left(v_0 - 32 + \frac{F}{2t}\right)}}$$

154 $$x = \sqrt{\frac{24\,kF}{L + C\left(v_0 - 32 + \frac{F}{2t}\right)}}$$

DESIGN CURVE – FIG. 2, E.M. PART XII, CHAPT. 4, MARCH 1946

x = DEPTH OF FROST PENETRATION IN FEET.
k = THERMAL CONDUCTIVITY IN B.T.U./(FT.)(°F)(HR.)
F = FREEZING INDEX IN DEGREE-DAYS
L = AVERAGE LATENT HEAT IN B.T.U./FT.³
C = AVERAGE VOLUMETRIC HEAT IN B.T.U./(FT.³)(°F)
v_0 = MEAN ANNUAL AIR TEMPERATURE IN °F
t = DURATION OF FREEZING INDEX IN DAYS
d = THICKNESS OF INSULATION LAYER IN FEET

AN AVERAGE VALUE FOR THERMAL CONDUCTIVITY (K) = 1.3 B.T.U./(FT.)(°F)(HR.), IS USED THROUGHOUT THESE CALCULATIONS.

NOTES:

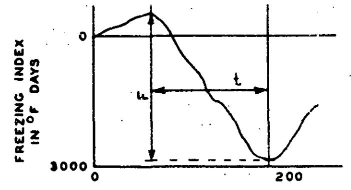
(I) PAVEMENT TYPES ARE AS FOLLOWS:
B.C. – BITUMINOUS CONCRETE.
P.C.C. – PORTLAND CEMENT CONCRETE.
T.S. – TOPSOIL (TURFED AREAS ONLY).

(II) VALUES USED FOR WATER CONTENT AND DENSITY ARE FOR FREEZING PERIOD WHEN AVAILABLE. EXCEPTIONS ARE NOTED AS FOLLOWS:
* – VALUES FOR NORMAL PERIOD.
** – VALUES FOR FROST MELTING PERIOD.
(1) – ASSUMED VALUES.
NF – VALUES FOR NON-FROZEN SUBGRADE SOIL (FREEZING PERIOD).

(III) SOIL CLASSIFICATION FOR AIRFIELDS EXCEPT AS FOLLOWS:
C.R. – CRUSHED ROCK.
S.CEM. – SOIL CEMENT.

(IV) DEPTHS OF FREEZING OBTAINED FROM TEST PIT OBSERVATIONS EXCEPT AS FOLLOWS:
TH – DEPTHS OF FREEZING OBTAINED FROM THERMOMETER AND THERMOCOUPLE OBSERVATIONS.

▶ CLOSEST VALUE TO OBSERVED DEPTH.
◀ VALUE WITHIN ± 6 INCHES OF OBSERVED DEPTH.



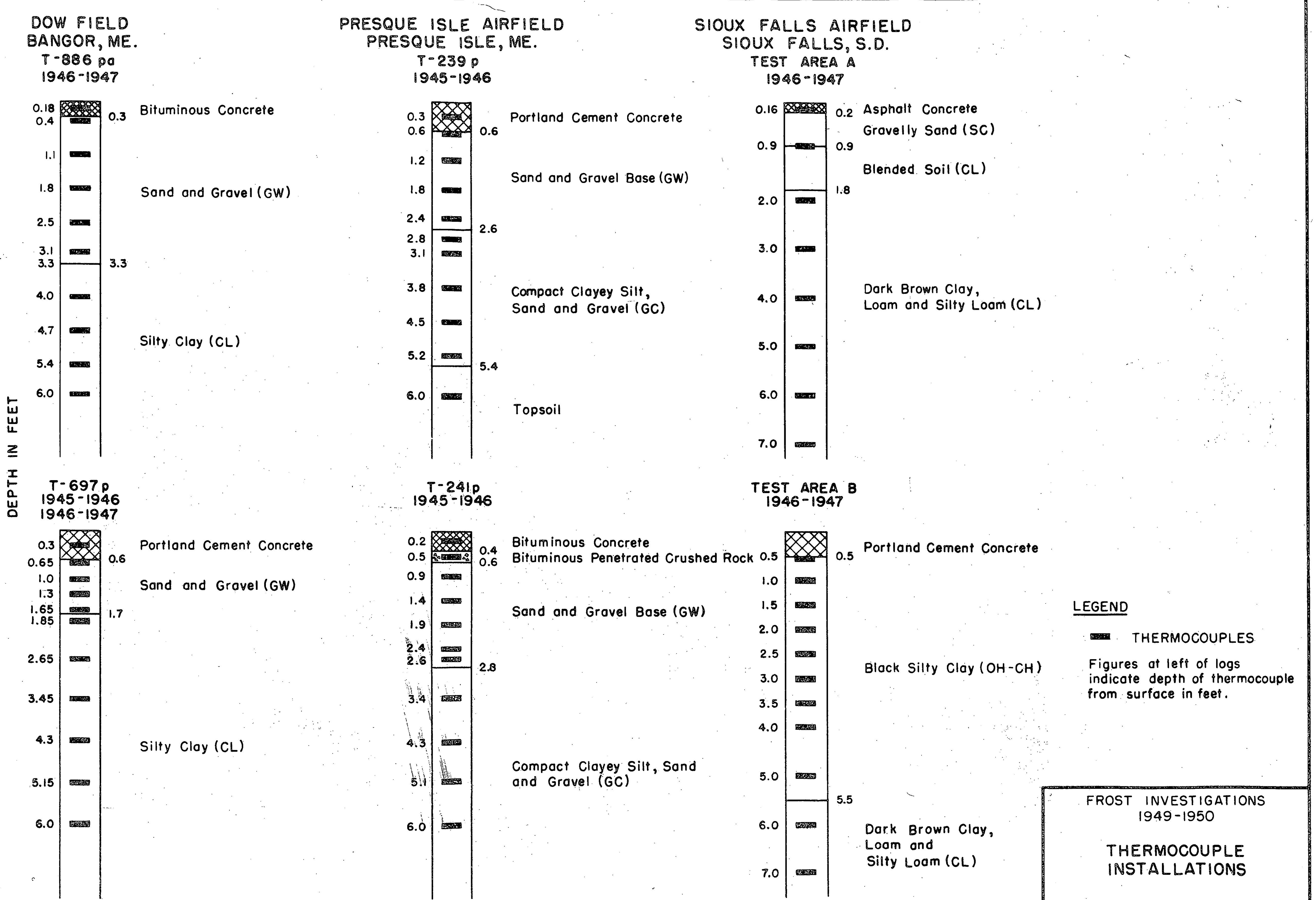
RELATIONSHIP BETWEEN F & t

FROST INVESTIGATION
1949-1950

PREDICTION OF FROST PENETRATION

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1950

TABLE 1



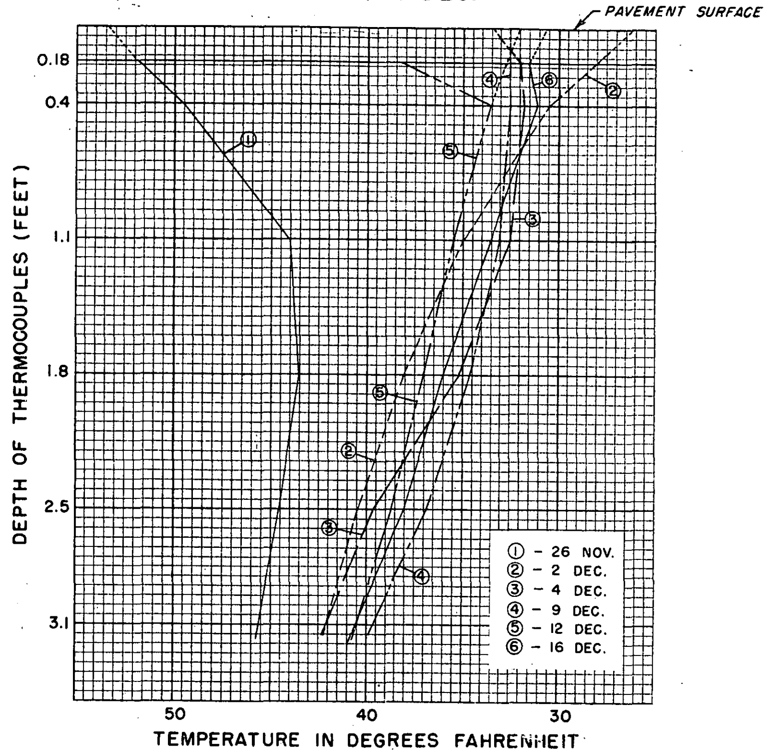
FROST INVESTIGATIONS
1949-1950

THERMOCOUPLE
INSTALLATIONS

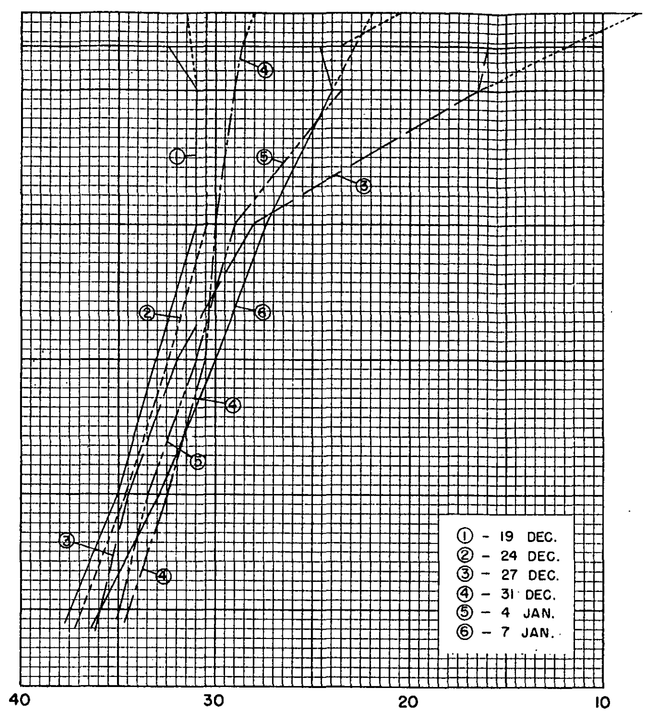
JUNE 1950
FROST EFFECTS LABORATORY, BOSTON, MASS.

THERMOCOUPLE INSTALLATION T-886 pa
DOW FIELD, BANGOR, MAINE

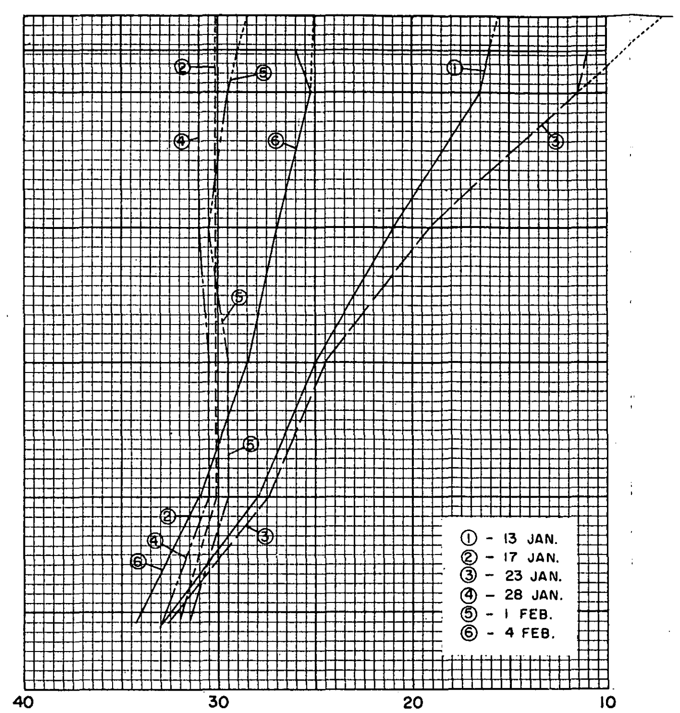
26 NOV.-16 DEC.



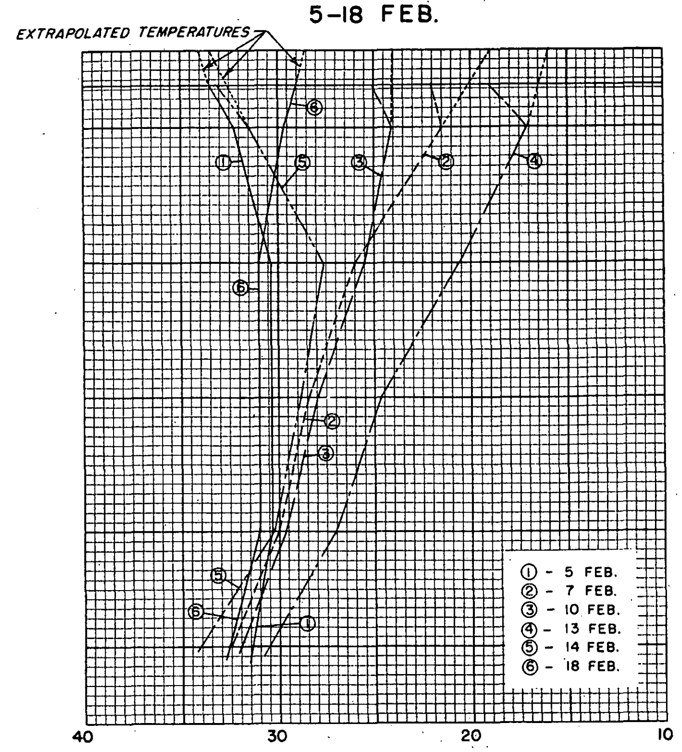
19 DEC.-7 JAN.



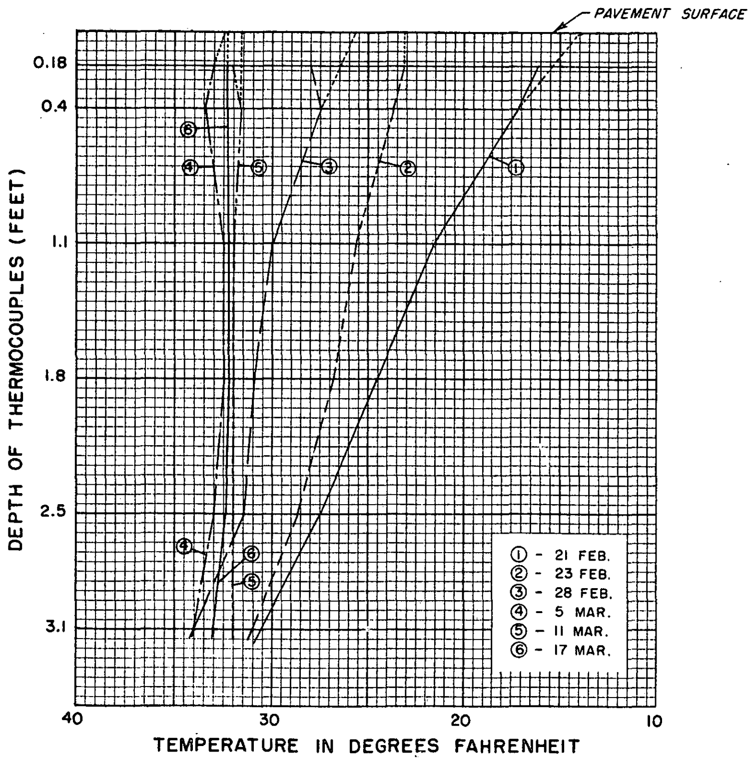
13 JAN.-4 FEB.



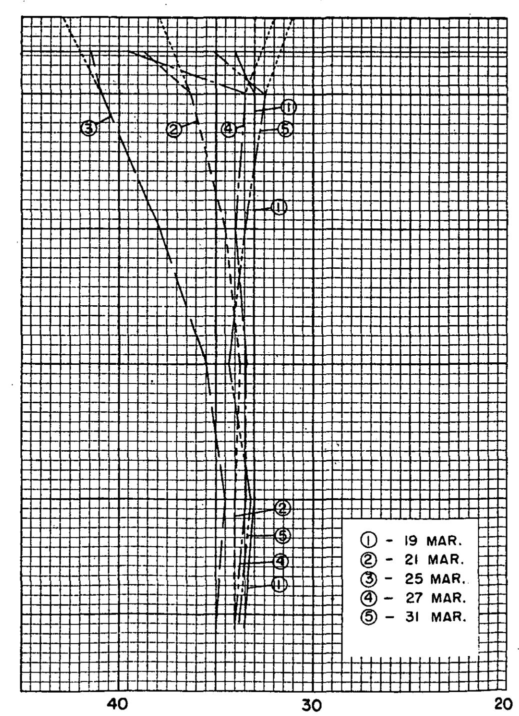
5-18 FEB.



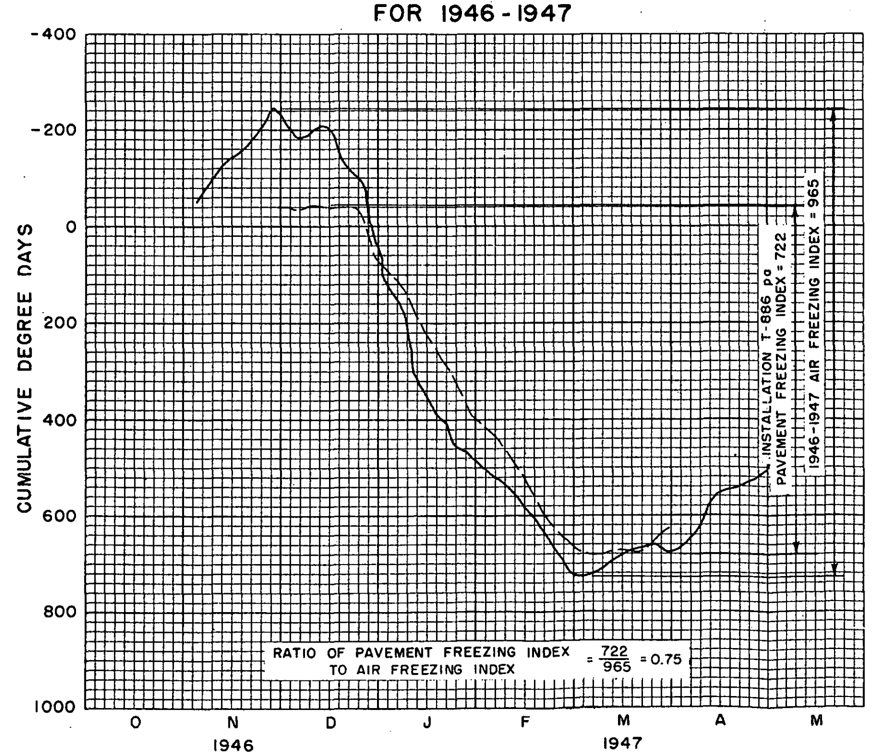
21 FEB.-17 MAR.



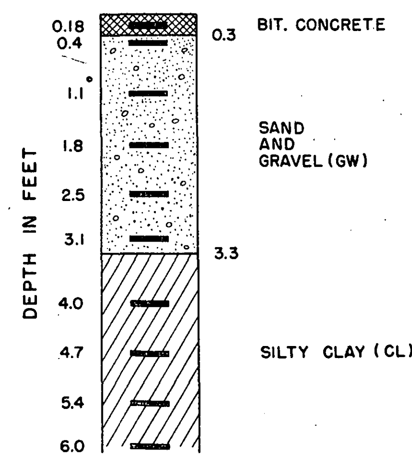
19-31 MAR.



CUMULATIVE DEGREE DAY CURVES
FOR 1946-1947



DOW FIELD
BANGOR, ME.
T-886 pa
1946-1947



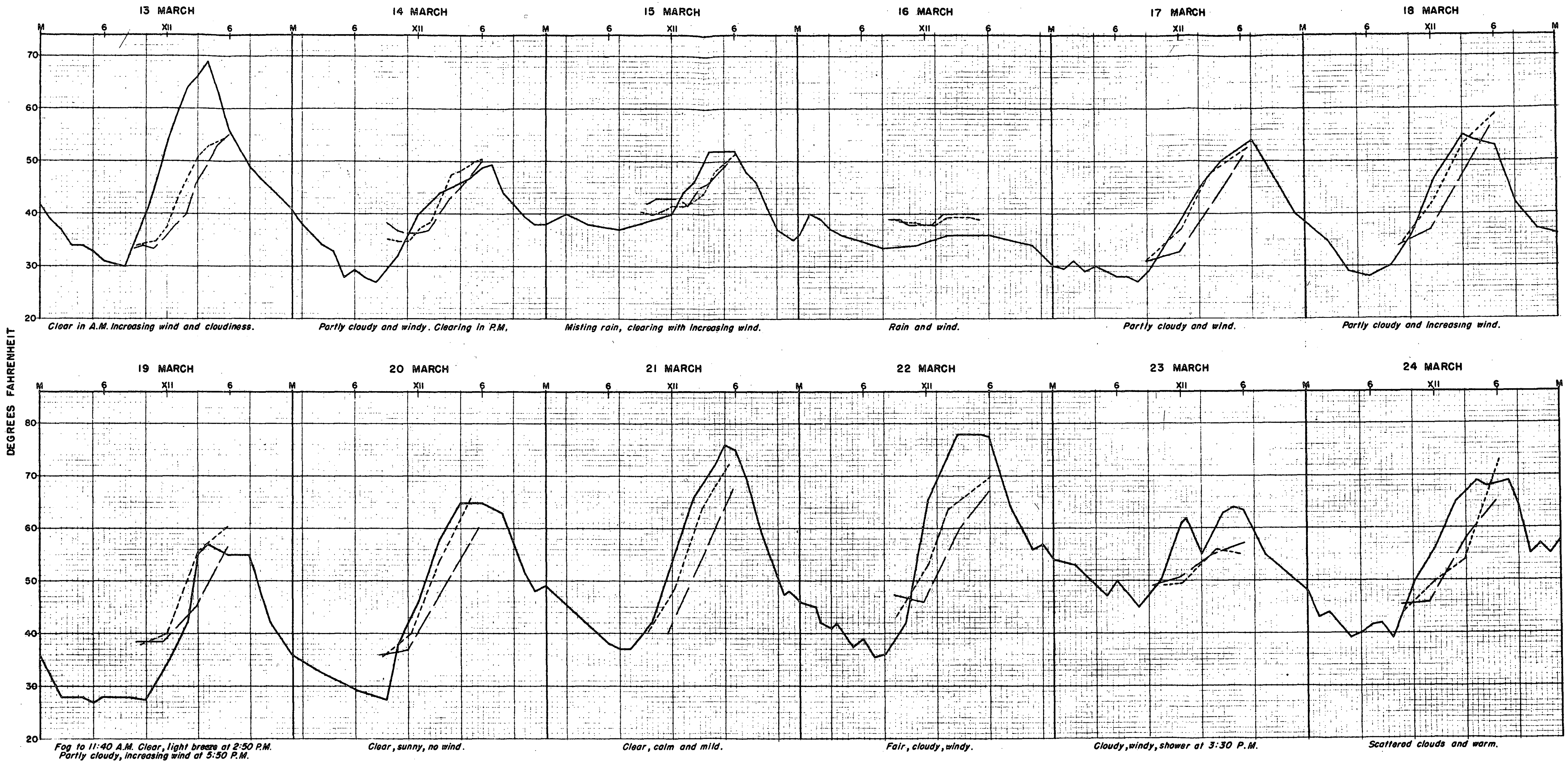
LEGEND:
Thermocouples

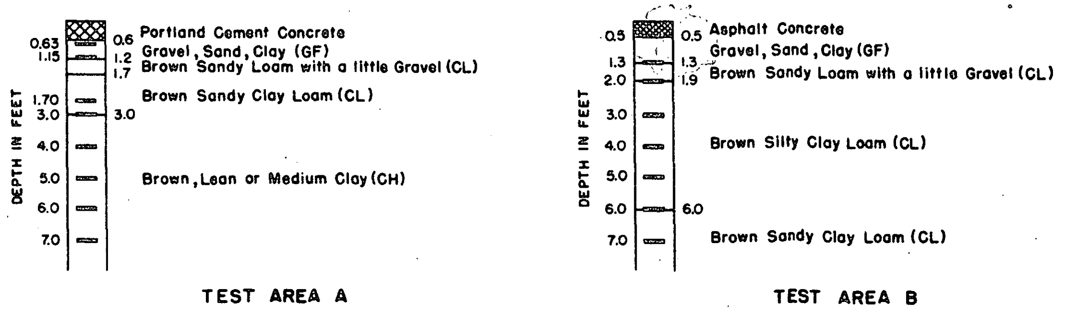
NOTES:
All pavement surface temperatures obtained by extrapolation as shown by short dashed lines above the location of the upper thermocouples. Figures at left of log indicate depths of thermocouples from surface in feet.

FROST INVESTIGATION
1949-1950

TYPICAL PAVEMENT FREEZING INDEX COMPUTATION

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGINEERS
BOSTON, MASS. JUNE 1950





THERMOCOUPLE POSITIONS

LEGEND

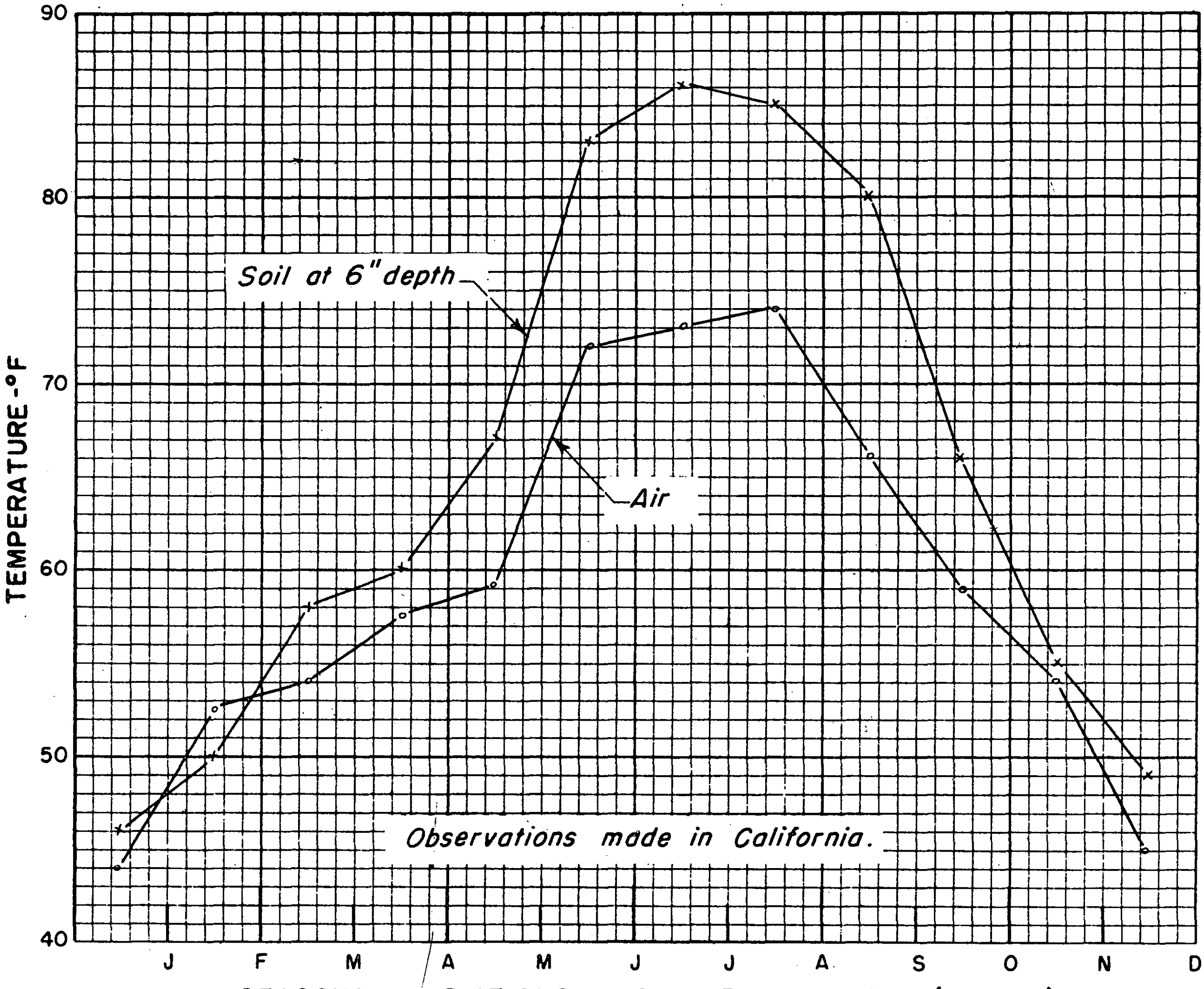
- ——— Hourly Air Temperature
- — — Pavement Surface Temperature - Cement Concrete Pavement - Test Area A
- ----- Pavement Surface Temperature - Bituminous Concrete Pavement - Test Area B
- ▭ Thermocouples

FROST INVESTIGATIONS
1949-1950

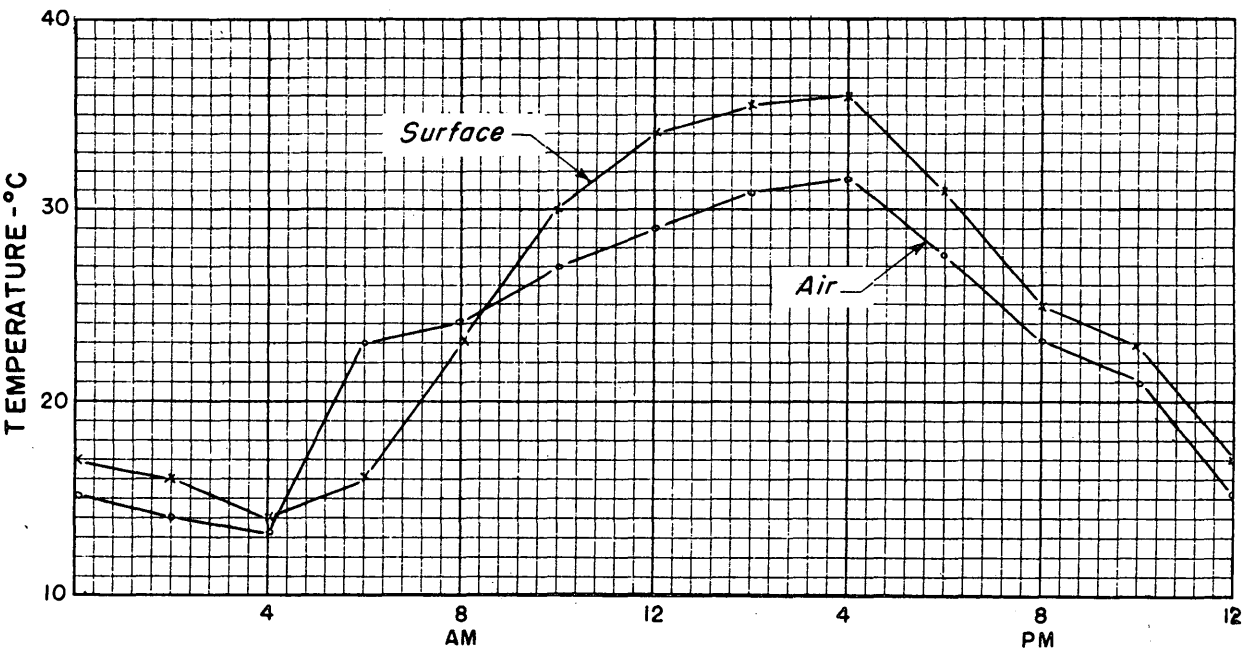
AIR AND PAVEMENT TEMPERATURES PIERRE AIRFIELD, PIERRE, S.D. 13-24 MARCH 1945

JUNE 1950
FROST EFFECTS LABORATORY, BOSTON, MASS.

PLATE 3

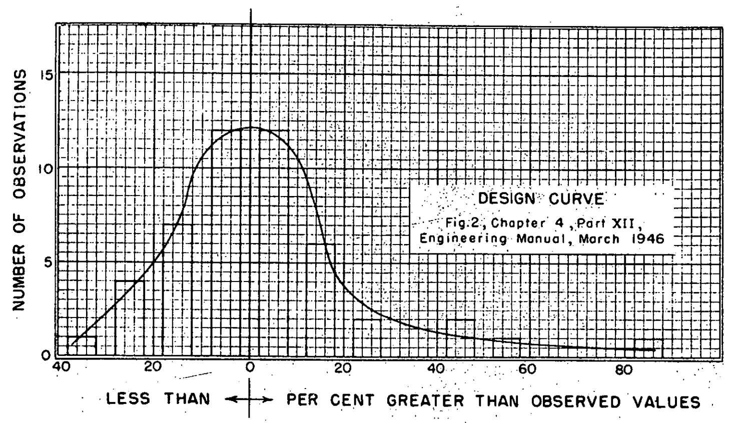


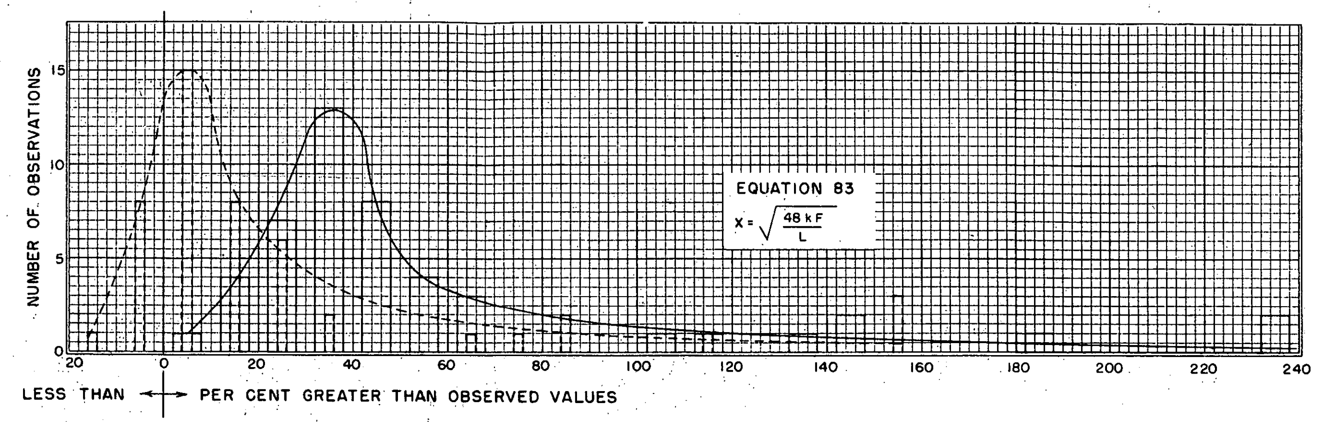
SEASONAL VARIATIONS IN SOIL TEMPERATURE (SMITH)



DIURNAL CHANGES IN SOIL TEMPERATURE IN BARE SOIL (WOLLNY)

PLATE 4





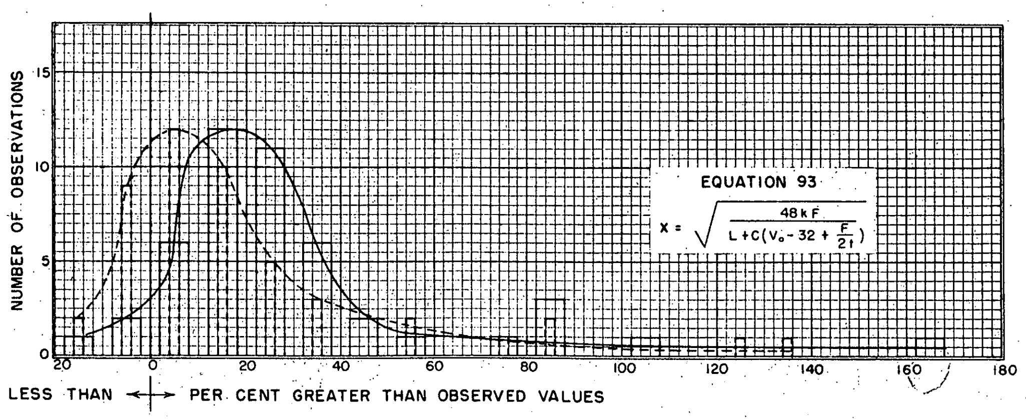
RESULTS OF STATISTICAL ANALYSIS

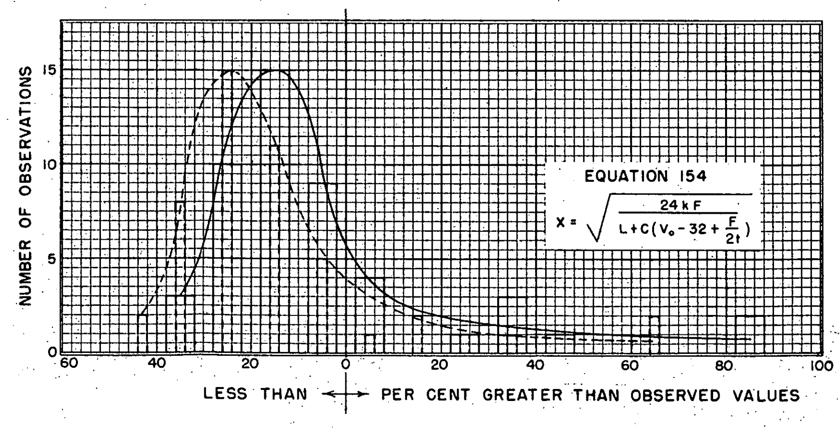
AIR FREEZING INDEX

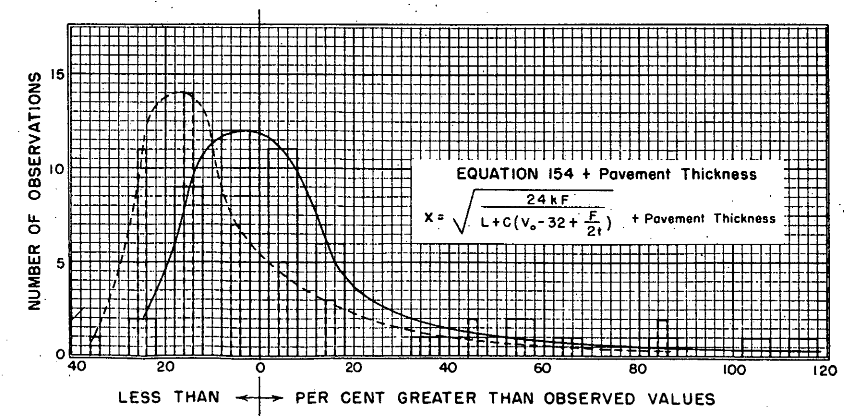
EQUATION NUMBER	83	93	154	154 PLUS PAVEMENT	DESIGN
Mean	+57.4	+30.2	-5.6	+9.8	+2.2
Standard Deviation	+51.8	+37.0	+26.2	+30.9	+21.6
Skewness	+0.403	+0.343	+0.338	+0.417	+0.102
Sum of Least Squares	31,762	12,144	5,387	4,282	2,597

PAVEMENT FREEZING INDEX

EQUATION NUMBER	83	93	154	154 PLUS PAVEMENT	DESIGN
Mean	+26.5	+20.1	-14.7	-1.6	–
Standard Deviation	+42.2	+32.2	+23.8	+21.6	–
Skewness	+0.432	+0.410	+0.349	+0.409	–
Sum of Least Squares	9,072	6,201	7,878	4,377	–







NOTES:

Distribution curves shown are based on 48 observations tabulated on TABLE I.

Distribution Curves:

——— Using Air Freezing Index.

- - - - Using Air Freezing Index modified by correction factors of 0.75 for bituminous pavements and 0.90 for portland cement concrete pavements.

FROST INVESTIGATION
1949-1950

CORRELATION OF THEORETICAL AND OBSERVED FROST PENETRATIONS

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION
BOSTON, MASS.
CORPS OF ENGINEERS
JUNE 1950

PLATE 5