Field Evaluation of Criteria for Frost Susceptibility of Soils

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Field data on frost heave, thaw weakening, and frost penetration acquired over a period of 3 years at the Winchendon field test site are analyzed. These data show that simple grain-size criteria such as the percent of particles smaller than 0.075 or 0.02 mm correlate weakly with field performance. Although soils with few fines (particles smaller than 0.075 mm) performed well in the field test, some of those with intermediate and many fines performed well and some poorly, with a great deal of scatter. The U.S. Army Corps of Engineers Frost Design Classification System and tabulated freeze test data provided very wide ranges of frost susceptibility compared with the field performance of the 12 test soils. Comparisons of the field frost heave data with data on soils in freezing conditions from the Massachusetts Department of Public Works heave stress test on nonplastic soils and with data from the new freeze-thaw test of the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) show excellent correlations. The thaw-weakening California bearing ratio (CBR) data from the CRREL freeze-thaw test correlated well with the resilient deflections from repeated plate bearing (RPB) tests in the field. Frost penetration depths calculated by the modified Berggren formula are in general agreement with, but somewhat larger than, the frost penetrations measured at the Winchendon field test site. This may possibly be due to the effects of freezing-point depressions of soil moisture, approximations in the adjustment of air to ground surface temperatures, and other factors not accounted for in the field test.

In order to develop field performance data on various New England soils, the Massachusetts Department of Public Works (MDPW), in a cooperative effort with the Federal Highway Administration (FHWA), constructed a field test site in Winchendon, Massachusetts, where 12 representative soils were subjected to three winters of freezing temperatures (*1*). Temperature (ground and air), precipitation, groundwater level, frost heave, frost penetration, and frozen water content at the site were monitored during the winters of 1977–1978, 1978–1979, and 1979–1980. The resulting 3 years' worth of field test data are analyzed and interpreted in detail.

The purpose of this research is an improved understanding of the mechanics of frost action in various soils leading to implementation of improved highway design criteria, guidelines, and specifications. This research may lead to reduced highway construction and maintenance costs from the reduced use of special borrow to replace natural soils that do not satisfy existing overconservative criteria and possible reductions in present requirements for base and subbase thicknesses.

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WINCHENDON FIELD TEST SITE AND TEST SOILS

The Winchendon field test site, located in north-central Massachusetts, was constructed by the MDPW during the fall of 1977. The site consists of 12 test cells, each a minimum of 28 ft wide (by 8 ft long in plan view) and consisting of a lower and an upper roadway (Figure 1). The base of the test soils extended to a minimum of 6 in. below the groundwater level. The paved surface of the lower roadway of the cell was approximately 3 ft above the groundwater level and that of the upper roadway, approximately 5 ft above the groundwater level. A bituminous concrete paved surface 8 ft wide and 3 in. thick was placed on both the upper and lower roadways of the test cell.

A wide range of test soils was selected with varying degrees of frost susceptibility. The data in the summary of laboratory index properties (Table 1) suggest that the soils may be placed into three groups: few fines (less than about 15 percent smaller than 0.075 mm); intermediate fines (between about 15 and 25 percent smaller than 0.075 mm), and many fines (more than 25 percent smaller than 0.075 mm). Edgers and Bono have assembled the complete data in a separate data report (*2*).

WINCHENDON FIELD TEST DATA

Data on soils in freezing conditions were obtained by the MDPW during three consecutive winter seasons, 1977–1978, 1978–1979, and 1979–1980 (*1*). Pavement surface deflections caused by frost heave were measured at nine control points on both the upper and lower roadways over each soil by means of an engineer's transit. Frost penetrations were measured using a frost-depth indicator consisting of a transparent pipe containing a dye that turns colorless upon freezing at 32°F. Figure 2 shows typical air temperature and precipitation data at the Winchendon test site. Figure 3 shows typical plots of the frost heave, frost penetration, and groundwater observation data. The maximum amounts of heave, average heave rates, and frost

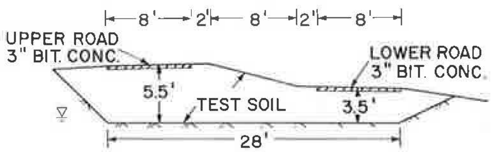

FIGURE 1 Transverse profile of typical test cell.

penetration depths for both upper and lower roadways for each winter are summarized in Table 2. The average heave rate was determined by taking the average slope of the heave-versus-time curves during the active freeze period, approximately 6 weeks after heaving began, as shown in Figure 3.

The average heave data in Table 2 demonstrate the effects on field performance of the depth to the groundwater table. For all but one of the soils (Morin clay), the maximum amount of heave was greater for the lower roadway than for the upper roadway, where the pavement was farther from the groundwater table. For three soils—Hart Brothers sand, Keating stone dust, and Worcester till—the difference between the two roadways is large. For the other nine soils, there are smaller differences in heave from the upper to the lower roadway.

Repeated plate bearing (RPB) tests were performed by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) to determine the

TABLE 1 LABORATORY INDEX PROPERTIES OF WINCHENDON TEST SOILS

	Test Soil	% Finer By Weight .02 mm	% Finer By Weight .075 mm	Uniform Coeff.	Plasticity Index
Many Fines	Moulton Pit Silt	52-69	96-99	3.4-4.2	N.P.
	Graves Silt Sand	8-12	44-47	5.2-6.2	N.P.
	Morin Clay	77-82	95-98	--	10.8
	Hyannis Sand	4-20	32-90	2.7-5.1	N.P.
	Ikalanian Silt-Sand	6-10	38-57	4.0-4.2	N.P.
	Sibley Till	17-21	32-37	Over 100	4.2
Intermed. Fines	Worcester Till	7-8	14-21	Over 100	N.P.
	Keating Stone Dust	~12	17-20	~100	N.P.
	Hart Brothers Sand	4-5	15-18	6.0	N.P.
Few Fines	Mason Pit Sand	1-3	5-9	5.8-6.7	N.P.
	Keating Dense Graded	~6	6-10	25-100	N.P.
	Corbosiero Sand	2-4	12-16	4.0-4.3	N.P.

N.P. = Non-plastic

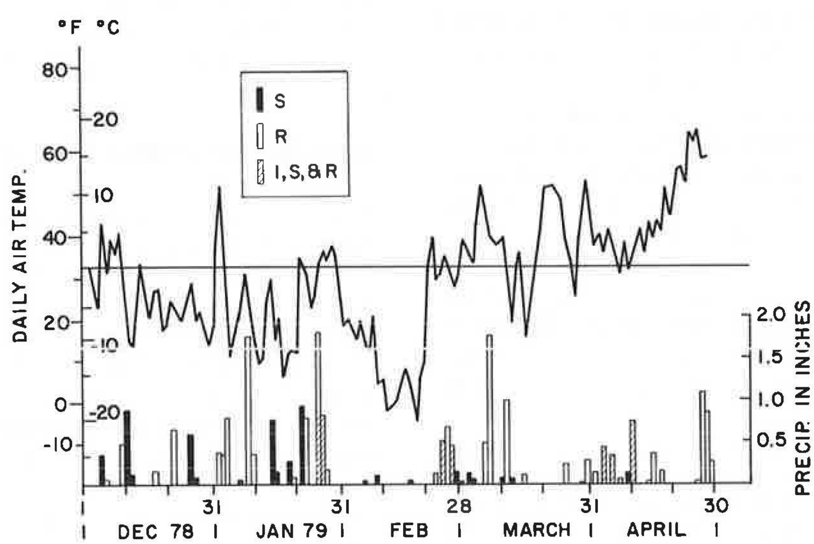

FIGURE 2 Weather data for 1978–1979 frost season.

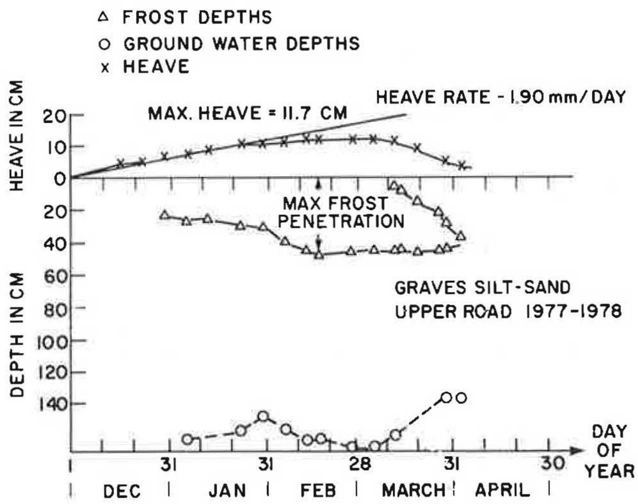

FIGURE 3 Typical frost depth, groundwater depth, and heave data.

seasonal changes in the supporting capacity of the soils as they freeze, thaw, and recover from the thaw-weakened condition (*3*). The RPB test applies loads through a 304-mm-diameter plate, repeating the load 50 to 1,000 times. The pulse duration was about 1 sec and the cycle time about 3 sec (20 cycles per minute). Figure 4 shows typical measured vertical displacements from RPB tests conducted at various stages of the freeze-thaw cycle.

Preliminary analyses of the effect of the severity of the winter on the observed field performance data (Table 2), showed a general trend of larger amounts and rates of heave with a larger freezing index and a great deal of scatter. Factors such as preconditioning of the soil structure during the first freezing season and detailed water-table and temperature variations before and during the freezing season may strongly influence the observed field performance. Thus the maximum amounts of heave and heave rates were averaged over the three seasons for the detailed analyses.

It is not clear whether maximum heave or average heave rate is a more useful summary of field performance. The maximum amount of heave serves as an index of the amount of pavement distress and surface roughness observed in the field and can be easily related to a performance criterion. However, the heave rate for any one soil may be less sensitive to the length of the active freeze period and may permit easier comparison of data collected during freezing seasons of different lengths. Detailed analyses performed with both maximum amounts of heave and heave rates showed, as will be discussed later, that there is no apparent statistical advantage to using either heave or heave rate in analyzing the Winchendon data. For the sake of brevity, the remainder of this paper will emphasize the analyses of maximum field heave data.

CRREL (*4*) has proposed field performance criteria including an adjective classification scale based on heave rates (Table 3). The maximum heave presented in Table

TABLE 2 FIELD PERFORMANCE MEASUREMENTS

	1977-78 WINTER			1978-79 WINTER			1979-80 WINTER			AVERAGE		
	Heave Rate (mm/day)	Frost Pene. (cm)	Max. Heave (cm)	Heave Rate (mm/day)	Frost Pene. (cm)	Max. Heave (cm)	Heave Rate (mm/day)	Frost Pene. (cm)	Max. Heave (cm)	Heave Rate (mm/day)	Frost Pene. (cm)	Max. Heave (cm)
UPPER ROAD												
Moulton Pit Silt	1.90	39	16.3	1.93	-	14.6	1.71	-	10.1	1.85	39	13.7
Graves Silt Sand	1.90	48	11.7	0.88	62	8.5	1.27	40	6.4	1.35	50	8.9
Morin Clay	1.19	55	8.7	1.22	-	6.7	0.71	42	4.6	1.04	48.5	6.7
Ikalanian Silt Sand	0.73	64	4.6	0.54	78	2.4	0.32	-	2.1	0.53	71	3.03
Worcester Till	0.95	88	5.6	0.98	105	4.9	0.59	74	3.3	0.84	89	4.6
Keating Stone Dust	0.66	97	2.6	0.76	109	3.4	0.68	53	4.3	0.70	86.3	3.4
Hart Brothers Sand	0.76	87	3.7	0.34	-	1.8	0.19	-	1.2	0.43	87	2.2
Sibley Till	0.54	108	2.1	0.49	128	1.5	0.42	86	1.5	0.48	107.3	1.7
Mason Pit Sand	0.34	85	1.7	0.29	96	1.5	0.27	66	0.9	0.30	82.3	1.4
Hyannis Sand	0.43	80	1.8	0.24	95	1.2	0.11	56	0.6	0.26	77	1.2
Dense Graded Stone	0.49	93	1.7	0.32	113	1.5	0.22	88	0.6	0.34	98	1.3
Corbosiero Sand	0.24	75	0.8	0.51	91	1.8	0.27	68	0.3	0.34	78	0.97
LOWER ROAD												
Moulton Pit Silt	2.19	34	18.3	2.00	47	14.9	1.90	-	8.2	2.03	40.5	13.8
Graves Silt Sand	2.15	43	15.7	1.00	-	9.4	1.02	34	6.1	1.39	38.5	10.4
Morin Clay	0.95	53	6.9	1.41	72	6.4	0.66	40	3.3	1.01	55	5.5
Ikalanian Silt Sand	0.93	46.5	6.5	0.93	64	4.0	0.52	-	1.8	0.79	55.3	4.1
Worcester Till	1.17	-	7.8	1.22	-	7.0	1.71	96	4.9	1.37	96	6.6
Keating Stone Dust	1.15	68	9.2	1.44	86	7.6	0.98	54	7.3	1.19	69.3	8.0
Hart Brothers Sand	1.44	67	9.3	1.75	-	5.8	0.71	55	4.6	1.3	61	6.6
Sibley Till	0.44	84	3.0	0.58	100	3.7	0.54	64	2.1	0.52	82.7	2.9
Mason Pit Sand	0.73	69	2.7	0.80	88	2.1	1.24	48	2.4	0.92	68.3	2.4
Hyannis Sand	0.60	71	3.3	0.49	88	1.5	0.38	-	1.2	0.49	79.5	2.0
Dense Graded Stone	0.54	67	2.4	0.97	83	2.4	0.24	66	1.2	0.58	72.0	2.0
Corbosiero Sand	0.56	74	2.5	0.46	86	1.5	0.27	52	2.1	0.43	70.7	2.0

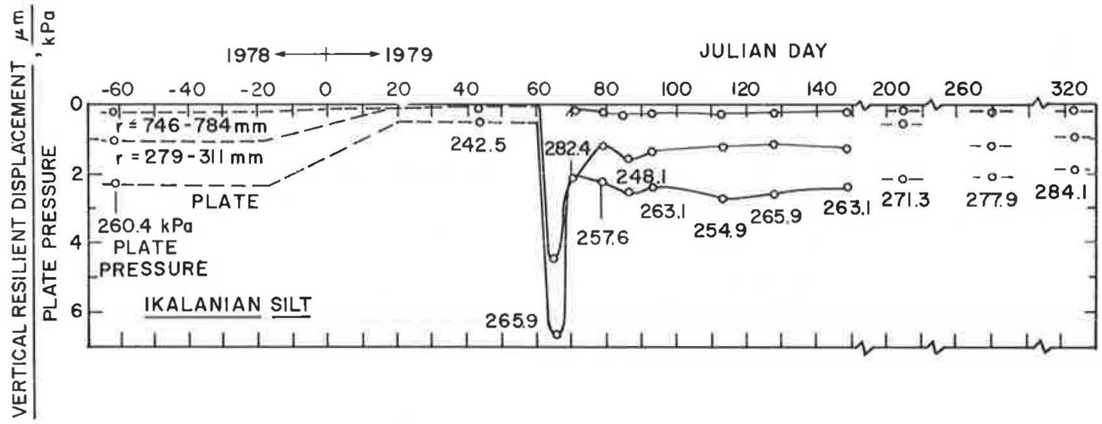

FIGURE 4 Example of resilient pavement deflections from RPB tests (*3*).

3 was computed by multiplying these heave rates by an assumed average active freeze period of 50 days. The data in Table 2 may be compared with the criteria for Table 3 to give a general impression of the relative field performance of the 12 soils tested. For example, soils that heaved less than 2.5 cm or at an average heave rate of less than 0.5 mm/day indicate negligible to very low frost susceptibility in Table 3, and thus show satisfactory performance.

LABORATORY DATA VERSUS FIELD PERFORMANCE

Introduction

Chamberlain (*5*) provides a comprehensive review of index tests for evaluating the frost susceptibility of soils, which has been updated by Bono (*6*). On the basis of these reviews, the following index tests and classification methods were selected for further evaluation in the analysis of the Winchendon field performance data:

1. Grain-size correlations of 0.02 and 0.075 mm,
2. U.S. Army Corps of Engineers Frost Design Classification System,
3. Correlations with tabulated freeze-test data,
4. MDPW heave stress test, and
5. New CRREL freeze-thaw test.

The grain-size correlations consist of relating the percentage of particles finer than 0.02 or 0.075 mm by weight in each soil to the observed field behavior. For example, the Casagrande (*7*) frost susceptibility criterion, based on the percent finer than 0.02 mm, states:

> One should expect considerable ice segregation in non-uniform soils containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than ten percent smaller than 0.02 mm.

This type of grain-size criterion is easy to apply, commonly used, but generally imprecise (*8*).

The U.S. Army Corps of Engineers Frost Design Classification System is based on the percent finer than 0.02 mm by weight, the Unified Soil Classification, data collected from extensive laboratory freeze tests, and field observations of reduced bearing capacity during thaw. The system organizes soils by frost design groups such as NFS, F1, F2, F3, and F4, based on the classification data, and then assigns a frost susceptibility classification, from negligible to very high, based on the collected laboratory heave and field thaw data.

Correlations with tabulated freeze test data (*5*) use the same laboratory data base as the U.S. Army Corps of Engineers Frost Design Classification System. However, the correlations use the original data from the freezing tests directly rather than grouping the soils into frost design groups. The correlation method and the classification sys-

TABLE 3 PERFORMANCE CRITERIA FOR WINCHENDON FIELD TEST DATA (*4*)

	Heave Rate(mm/day)	Maximum Heave(cm)
Negligible	< 0.25	< 1.25
Very Low	0.25-0.50	1.25-2.5
Low	0.50-1.0	2.5-5.0
Med	1.0-2.0	5-10
High	2.0-4.0	10-20
Very High	> 4.0	> 20

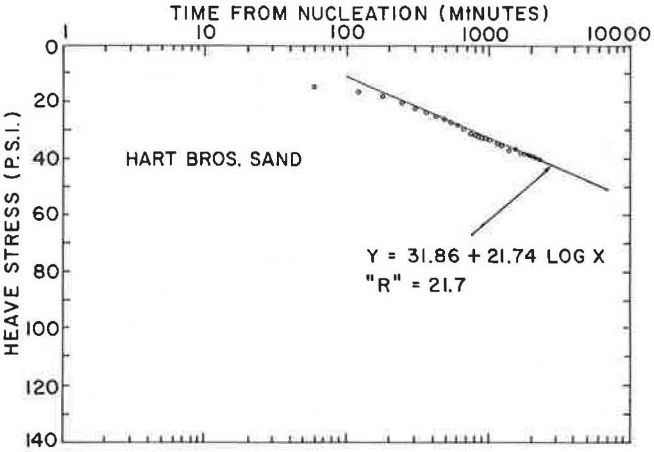

FIGURE 5 Heave stress versus log time (*9*).

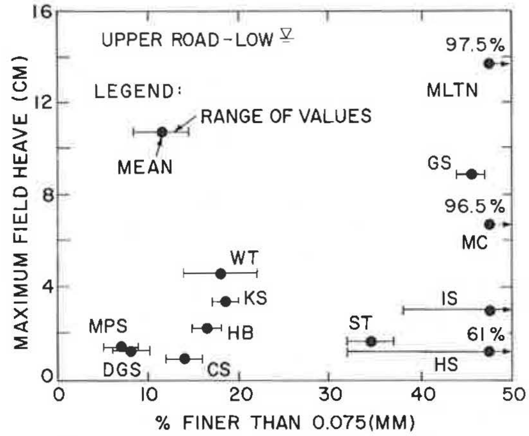

FIGURE 7 Maximum heave versus percent finer than 0.075 mm, upper roadway.

tem were selected for further study because they are inexpensive, easy to use, and possibly more accurate than grain-size correlations.

The MDPW heave stress test and the new CRREL freeze-thaw test were selected for comparison with Winchendon field performance because they offer the possibility of more accurate predictions of field performance. The MDPW heave stress test (*9, 10*) produces a plot of heave stress versus the log of time (Figure 5). The linear slope of this relationship, defined as the *R*-parameter, is taken as an index measure of in situ frost susceptibility. A high *R*-value indicates rapid development of heave stress with log time and hence high heave potential.

The new CRREL freeze-thaw test (*4*) is an improved version of earlier tests in that it is performed in an apparatus with low side friction, has a shorter duration, and measures thaw-weakening susceptibility. The test is performed in a multiring freezing cell (Figure 6), with a rubber membrane liner designed to minimize side friction. The standard test consists of two freeze-thaw cycles and requires only 5 days to complete. After the second thaw, California bearing ratio (CBR) tests are conducted to evaluate thaw-weakening susceptibility. The soil samples are then removed to determine the moisture content profile. The new CRREL freeze-thaw test is one of the simplest and most rapid freezing tests available and has great promise in making accurate predictions of frost heave and thaw-weakening behavior in the field.

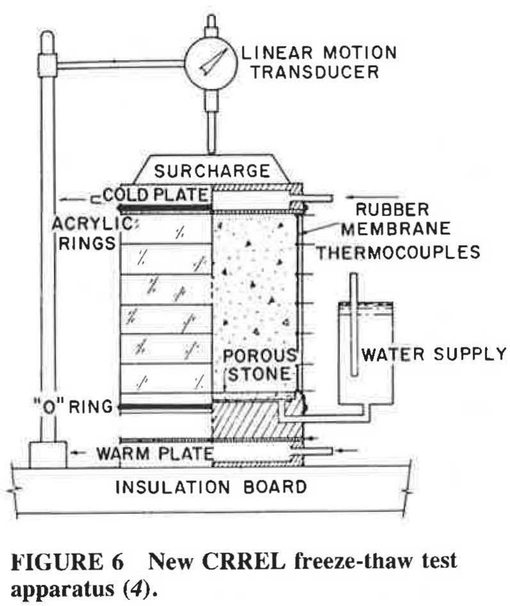

FIGURE 6 New CRREL freeze-thaw test apparatus (*4*).

Grain-Size Correlations: 0.075 mm

Figures 7 and 8 are plots of maximum field heave from the upper and the lower roadways versus percent of particles finer than 0.075 mm. The data show a large amount of scatter, indicating that the percent finer than 0.075 mm is not accurately related to field performance. For all the soils except Morin clay, the heaves were greater for the lower roadway (3 ft to groundwater) than for the upper roadway (5 ft to groundwater).

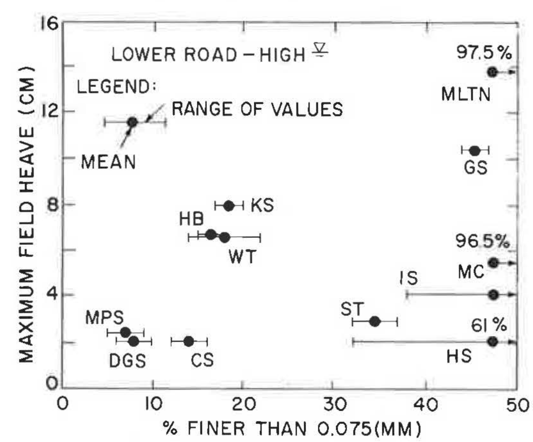

FIGURE 8 Maximum heave versus percent finer than 0.075 mm, lower roadway.

These plots also reveal differences in performance among the soils with few, intermediate, and many fines. The first group, which consists of the three soils with less than 14 percent fines, heaved small amounts, less than 2.5 cm, and performed satisfactorily according to the criteria in Table 3. The variation in depth to the groundwater table has only a small effect on these three soils. The second group, which consists of the three soils with from 15 to 21 percent fines, is sensitive to depth to the groundwater table. For the upper roadway these three soils heaved from 2 to 5 cm (Figure 7), whereas for the lower roadway they heaved from 6 to 9 cm (Figure 8). The last group, soils with more than 30 percent fines, shows a large range in field performance—from approximately 2.0 to 14.0 cm total heave. The depth to the groundwater table had little effect on the performance of these six soils. Two of the six [Morin clay (MC) and Sibley till (ST)] have plastic fines (Table 1), and the other four [Moulton pit silt (MLTN), Graves silt-sand (GS), Ikalanian silt-sand (IS), and Hyannis sand (HS)], nonplastic fines.

The establishment of a critical percentage of fines that, if exceeded, would result in some amount of frost action and thaw weakening is difficult. This critical percentage depends on the plasticity of fines, void ratio, and depth below the pavement surface. For example, uniform fine sands such as the Hyannis and Corbosiero sands can have much higher void ratios than dense well-graded soils. These sands can tolerate a much higher fines content before they become frost susceptible. On the other hand, Esch et al. (*11*), in a very extensive field study of 120 pavement structures in Alaska, show that for dense-graded aggregates typically used in pavement structural layers, fines contents in excess of 6 percent begin to result in some degree of thaw weakening as well as some level of frost heaving in laboratory tests.

Grain-Size Correlations: 0.02 mm

Figure 9 shows maximum amounts of heave versus percent finer than 0.02 mm by weight from the upper roadway. These data show a large amount of scatter, indicating that the percent finer than 0.02 mm is not accurately related to field performance. Comparison of Figure 9 with Figures 7 and 8 shows no apparent difference in the amount of scatter. This suggests that the additional work required to determine the percent finer than 0.02 mm (e.g., a hydrometer test) does not necessarily provide a stronger correlation with field performance measure than the use of the percent less than 0.075 mm.

The uniformity of the 12 soils is coded in Figure 9 by different symbols. According to the Casagrande 0.02-mm criterion, Corbosiero sand (CS), Mason pit sand (MPS), and Ikalanian silt-sand (IS) would be classified as acceptable soils. However, the field performance of Ikalanian silt-sand does not quite meet the requirements of negligible to very low frost susceptibility (Table 3). Also, dense graded stone was rejected by the Casagrande criterion even though it has few fines and performed well at the field test site. These data therefore show some inconsistencies between the 0.02-mm Casagrande criterion and the Winchendon field data.

U.S. Army Corps of Engineers Frost Design Classification System

The frost susceptibility according to the U.S. Army Corps of Engineers Frost Design Classification System was determined for each of the 12 Winchendon soils, as shown in Figure 10 for Ikalanian silt-sand. The frost susceptibility classification was then used as a prediction of field performance. Table 4 gives the frost groups, percent finer than 0.02 mm, and frost susceptibility predicted by the Corps of Engineers system.

Figure 11 shows a comparison of the frost susceptibility classifications of Ikalanian silt-sand by the Corps of Engineers system and observed field heave rates and maximum amounts of heave using the field performance criteria of Table 3. The data show that the Corps of Engineers classification system provides a large range of frost classifi-

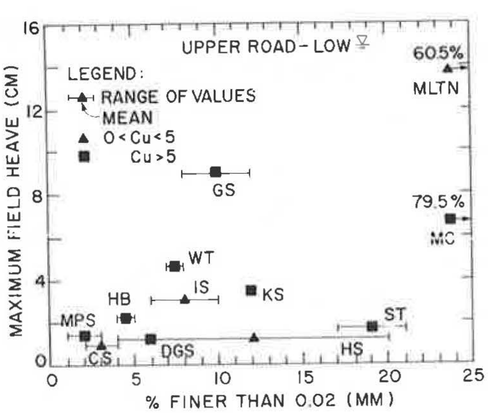

FIGURE 9 Maximum heave versus percent finer than 0.02 mm, upper roadway.

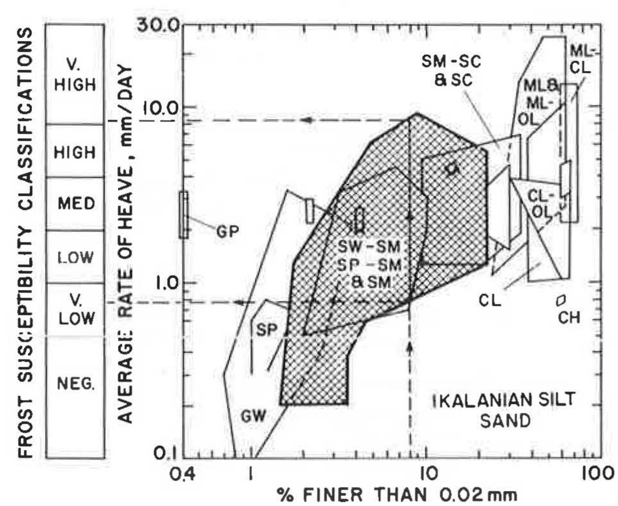

FIGURE 10 Corps of Engineers frost susceptibility classification, Ikalanian silt-sand.

TABLE 4 U.S. ARMY CORPS OF ENGINEERS FROST DESIGN CLASSIFICATION SYSTEM

Soil	Unified Class.	AASHTO Class.	% finer than 0.02 mm	Frost Group	Frost Susceptibility
Moulton Pit Sand	ML	A-4(0)	73	F4	Med to Very High
Graves Silt Sand	SM	A-4(0)	12	F2	Low to High
Morin Clay	CL	A-6(8)	82	F4	Low to Very High
Sibley Till	SM-SC	A-2-4(0)	19	F3	Low to High
Worcester Till	GM	A-1-b(0)	8	F1	Very Low to Medium
Hyannis Sand	SM	A-4(0)	9.5	F2	Very Low to Very High
Ikalanian Silt Sand	SM	A-4(0)	7.5	F2	Very Low To High
Hart Bros. Sand	SP-SM	A-2-4 (0)	4.7	S2	Very Low to High
Corbosiero Sand	SP-SM	A-2-4-(0)	2.5	NFS	Neg to Med.
Mason Pit Sand	SP-SM	A-3(0)	2.5	NFS	Neg to Med.
Dense Graded Stone	GP-GM	A-1-a (0)	6	S1	Very Low to High
Keating Stone Dust	SM	A-1-b	12	F2	Low to High

cations, that is, very low to high, compared with a low frost susceptibility given by the field performance of Ikalanian silt-sand. This same type of comparison for the other Winchendon soils shows similar results. The Corps of Engineers system provides ranges of frost susceptibility that are too broad to provide accurate predictions of field performance.

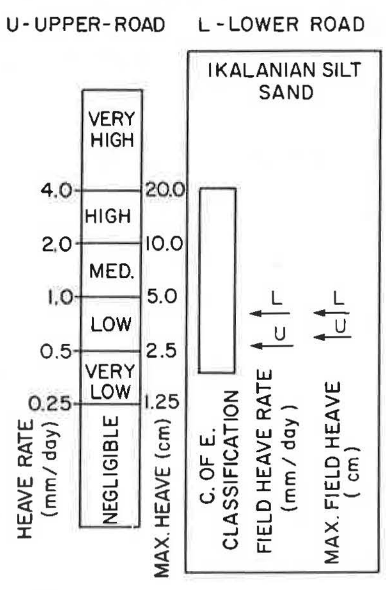

FIGURE 11 Comparison of field performance with Corps of Engineers frost susceptibility classification, Ikalanian silt-sand.

Comparison of Tabulated Freeze Test Data with Field Performance

In this section we compare data from 377 laboratory freeze tests tabulated by the U.S. Army Corps of Engineers with the observed field performance (*12*). The laboratory data base used to develop the Corps of Engineers system (Figure 10) is compared directly with field performance. For each of the 12 Winchendon soils a group of soils that have similar characteristics was selected from the 377 tabulated tests. Emphasis was placed on matching percent finer than 0.075, 0.02, and 0.01 mm; density; and uniformity coefficient when soils were selected. The tabulated laboratory freeze test performance of the selected group of soils was then compared with the field performance of the matching Winchendon soil.

Figure 12 compares the heaves from the tabulated laboratory data (*12*) with measured field heaves for the lower roadway. Overall the tabulated data provide a wide range of frost heave compared with the field heave measured for any one soil. Varying amounts of surcharge and various types of cylinders used in the tabulated freeze tests can have a significant effect on the heave measured during testing. A low value of laboratory heave, say, less than 30 percent in Figure 12, corresponds to a wide range of field observations and does not necessarily correspond to low

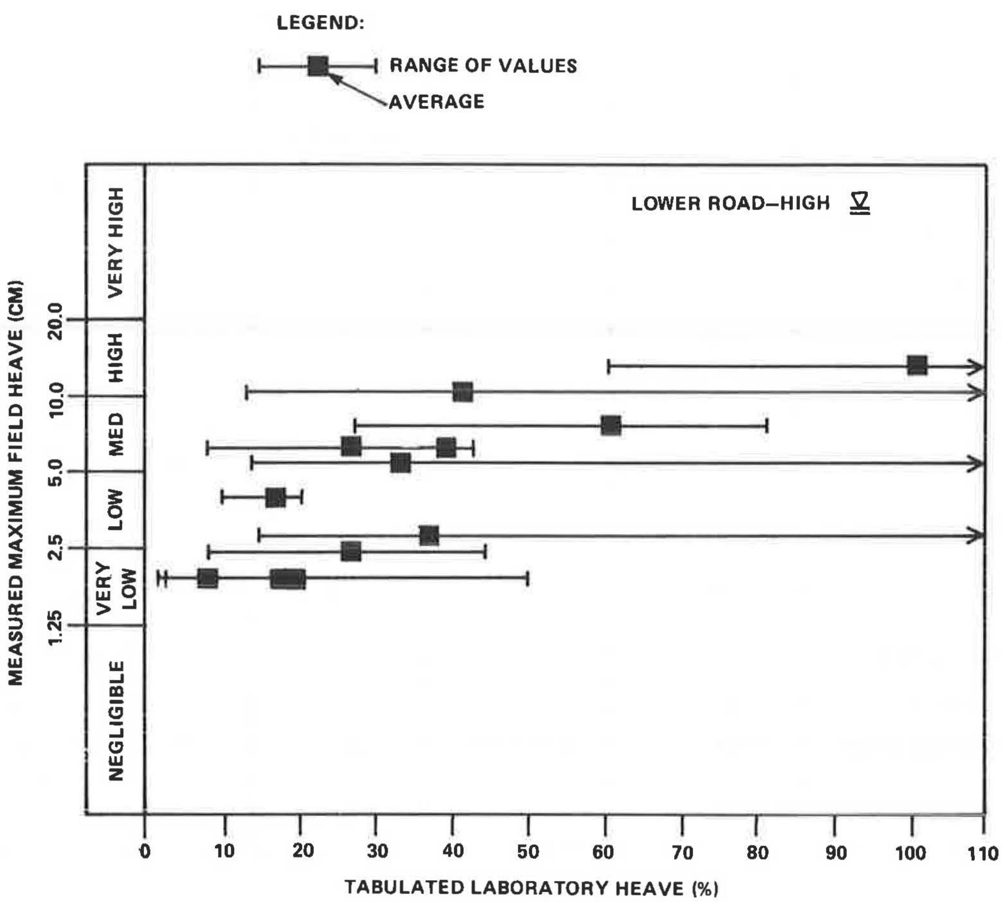

FIGURE 12 Field heave versus laboratory heave of matching soils from Corps of Engineers tabulation, lower roadway.

frost heave in the field. Thus, the method does not identify satisfactory soils. Similar comparisons were made on the basis of laboratory and field heave rates (*2*).

MDPW Heave Stress Test

Figure 13 presents maximum field heave versus the *R*-parameter for the lower roadway. A strong relationship is shown between increasing heave and increasing values of *R* for 10 of the 12 soils. The two soils that do not follow this relationship, Sibley till and Morin clay, contain plastic fines. These soils may have responded more strongly in the laboratory than in the field because of the greater availability of water in the laboratory test. These data suggest that the MDPW heave stress test may be a useful frost susceptibility indicator for nonplastic materials. All soils having an *R*-value less than 18 performed satisfactorily in the field (Table 3).

New CRREL Freeze-Thaw Test

Figure 14 presents the maximum field heave from the lower roadway versus the maximum laboratory heave from the new CRREL freeze-thaw test. The heaves for only the first cycle of the CRREL laboratory test were used because the first cycle was judged to be more representative of Winchendon field conditions (*6*). Figure 14 shows a nonlinear relationship of increasing field heave and increasing laboratory heave. The field heaves are larger than the

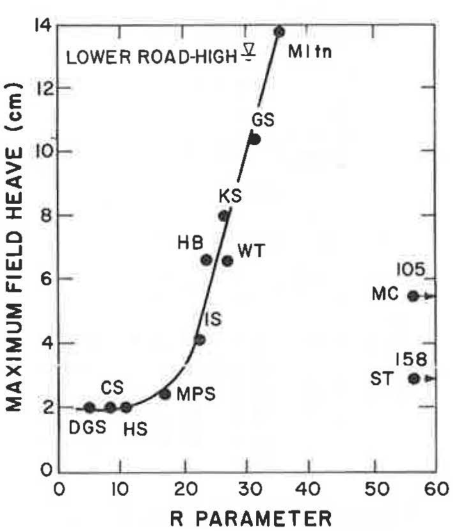

FIGURE 13 Maximum field heave versus *R*-parameter, lower roadway.

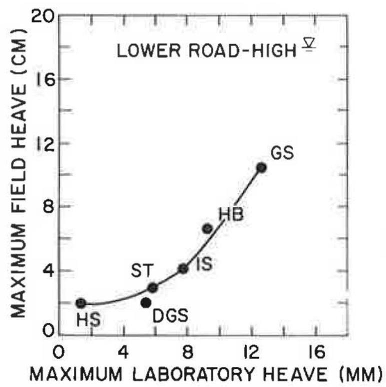

FIGURE 14 Field heave versus laboratory heave measured in new CRREL freeze-thaw test.

laboratory heaves because of the longer duration of freezing in the field. The laboratory heave rates (not shown) are numerically larger than the corresponding field values because of the more severe conditions of moisture availability and temperature in the laboratory test. Nevertheless, these field and laboratory data show strong correlations with little scatter.

Statistical Analyses

Linear regression analyses were performed with the laboratory and field data to provide quantitative measures of the strength of the correlations between them. The best fits through each set of data points and the coefficient of determination (r^2) were calculated. A coefficient of determination equal to 1.0 indicates that the field and laboratory measures are perfectly correlated. A coefficient of determination equal to 0.0 indicates that the values are uncorrelated (*13*). These regression analyses considered both linear relationships and linear transformations.

The coefficients of determination using the 0.075-mm and 0.02-mm grain-size indexes (Table 5) are all significantly less than 0.5 and are of the same order of magnitude. The coefficients for heave rate correlations are all numerically smaller than the corresponding values for maximum heave. This suggests, as discussed earlier, that correlations of heave rates with grain-size criteria provide no statistical advantage over correlations with maximum amounts of heave. Finally, the coefficients of determination for the 0.02-mm correlations are not significantly higher, and in some cases are lower, than the corresponding values for the 0.075-mm correlations. This suggests that the 0.02-mm criterion, which requires the additional expense of a hydrometer test, provides no statistical advantage over the simpler 0.075-mm criterion for predicting field performance.

The regression analyses performed with the tabulated Corps of Engineers laboratory freeze test data show regression coefficients of 0.61 to 0.75 (Table 5). Thus, the method seems to provide better overall statistical fit with the Winchendon field data than do the simple grain-size indexes. However, unlike the simple grain-size indexes, this method does not provide a useful minimum performance requirement, because, as Figure 12 shows, low values of laboratory heave or heave rate from the Corps of Engineers tabulation do not necessarily correspond to excellent performance in the Winchendon field test. Thus, the method cannot identify soils that performed well in the field.

The regression analyses performed with data from the MDPW heave stress test (10 nonplastic soils only) and the new CRREL freeze-thaw test all show high coefficients of determination (except for one value) greater than 0.9. This shows excellent correlations between these test data and the Winchendon field performance data.

THAW-WEAKENING COMPARISONS

Bono (*6*) shows that the percentage of fines serves only as a crude indicator of thaw-weakening behavior during the Winchendon field test. Alternatively, the new CRREL freeze-thaw test is unique among freeze tests in that it

TABLE 5 COEFFICIENTS OF DETERMINATION

Index	Upper Road		Lower Road	
	Max Heave	Heave Rate	Max Heave	Heave Rate
0.075 mm (Figures 7 & 8)	0.45	0.41	0.21	0.17
0.02 mm (Figure 9)	0.44	0.36	0.24	0.15
Tabulated Corps of Engineers Data (Figure 12)	0.67	0.61	0.75	0.63
MDPW Heave Stress Test (Figure 13)	0.96	0.98	0.98	0.91
New CRREL Freeze-Thaw Test (Figure 14)	0.92	0.68	0.98	0.97

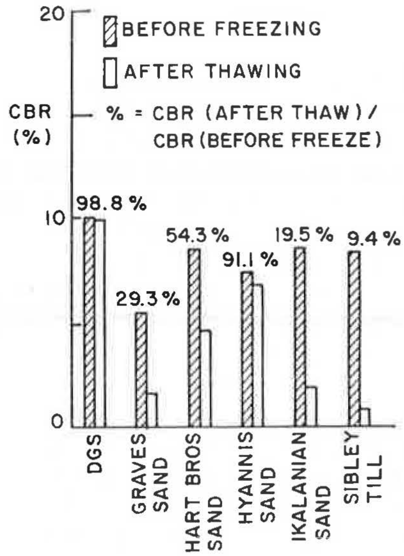

FIGURE 15 CBR before freezing and after thawing in new CRREL freeze-thaw test (*4*).

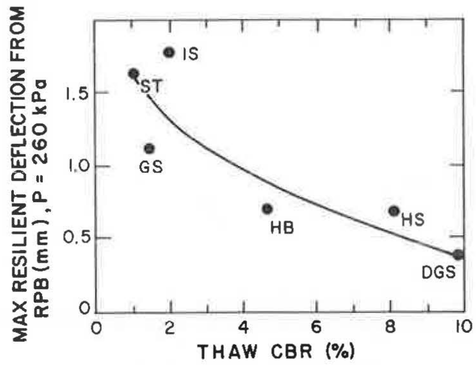

FIGURE 16 Maximum resilient deflection from RPB tests versus thaw CBR.

provides strength data (CBR) on thaw-weakened soil. In this section these CBR data are compared with the maximum vertical resilient displacements measured during the thaw period from the RPB test (Figure 6). Chamberlain (*4*) analyzes these data in more detail than space allows here.

Figure 15 shows a comparison of the CBR values obtained from the new CRREL freeze-thaw test after two freeze-thaw cycles with before-freezing CBRs for the six soils tested. This comparison provides an index measure of the effects of thaw weakening and identifies Sibley till and Ikalanian silt-sand as highly thaw-weakening soils.

Figure 16 is a plot of the maximum pavement deflection from RPB tests versus the thaw CBR for each of the six soils tested. These data show a well-defined relationship between the RPB deflection and thaw CBR, suggesting that the new CRREL freeze-thaw test shows promise of quantifying thaw weakening of soils in the field. Chamberlain (*4*) has recently proposed tentative frost susceptibility criteria for the new CRREL test (Table 6) that include both heave and thaw-weakening behavior.

It is interesting to note that Sibley till showed little to moderate field heave (Table 2) yet very high thaw weakening (Figure 15). The plasticity of this soil may be an indicator of its high thaw weakening. Also, Sibley till developed very high heave stresses in the MDPW heave stress test. Thus, this test may also serve as an indicator of thaw-weakening behavior of plastic soils, although the reasons for this are not understood.

FROST PENETRATION DEPTHS

Table 7 shows the maximum measured frost penetration depth in inches for each of the 12 soils averaged for the three seasons. The 3-year average freeze index (FI) is about 977 °F-days. For eight of the soils the frost penetration values of Table 7 are about 3 to 10 in. deeper for the upper roadway. For the remaining four soils the frost penetration values are slightly deeper (by less than 3 in.) for the lower roadway than for the upper roadway. Thus, frost penetration beneath the lower roadway has been somewhat limited by the higher water-table conditions. This occurs because water has high volumetric heat (62.4 Btu/ft^3/°F), about

TABLE 6 TENTATIVE FROST-SUSCEPTIBILITY CRITERIA FOR NEW FREEZE TEST (*4*)

Frost susceptibility classification	Heave rate (mm/day)	Thaw CBR (%)
Negligible	<1	>20
Very low	1-2	20-15
Low	2-4	15-10
Medium	4-8	10-5
High	8-16	5-2
Very high	>16	<2

TABLE 7 FROST PENETRATION DEPTHS

Soil	Frost Penetration Depth (inches)		
	Measured		Calculated
	Upper Road	Lower Road	
Moulton Pit Silt	15.4	15.9	24.3
Graves Silt Sand	19.7	15.2	25.6
Morin Clay	19.1	21.7	25.9
Ikalanian Silt Sand	28.0	21.8	31.9
Worcester Till	35.0	37.8	38.8
Keating Stone Dust	34.0	27.3	38.8
Hart Brothers Sand	34.3	24.0	35.8
Sibley Till	42.2	32.6	38.8
Mason Pit Sand	32.4	26.9	35.8
Hyannis Sand	30.3	31.3	33.4
Keating Dense Graded Stone	38.6	28.3	40.9
Corbosiero Sand	30.7	27.8	33.4
Average	30.0	25.9	33.6

twice that of soil, relinquishing large amounts of thermal energy as it cools. The measured frost depths are all less than the design frost depth of 52 in. given by MDPW criteria.

The measured frost penetration depths were compared with calculations by the modified Berggren formula:

$$FP = \lambda[(48 * K_s * FI/L)]^{1/2} \quad (1)$$

where

FP = depth of frost penetration,
K_s = thermal conductivity,
FI = surface freezing index,
L = latent heat, and
λ = dimensionless correction coefficient, given as a function of mean annual temperature, mean freezing temperature, volumetric heat (C_s), and L.

The thermal parameters K_s, L, and C_s were calculated from estimated in situ densities and water contents using correlations provided by Aldrich (*14*). The surface freezing index was estimated from the air freezing index, using the Corps of Engineers *n*-factor approach (*15*). The calculations for a surface FI of 600 °F-days (n = 0.6) are summarized in Table 7. Figure 17 shows a comparison of the frost penetration depths measured for the upper roadway with values computed by Equation 1.

The calculated frost penetration depths agree generally with the measured frost penetration depths. The average calculated frost depth, 33.6 in., is about 10 percent larger than the average frost depth measured beneath the upper roadway and 25 percent larger than the average frost depth measured beneath the lower roadway (Table 7). Aldrich (*14*) points out that Equation 1 may overestimate frost penetration depths because of freezing-point depressions of soil moisture (neglected in these calculations). The freezing-point depression of soil moisture is greatest in fine-grained soils (*16*), and this may account for the particularly large differences between calculated and measured frost penetration depths for Moulton pit silt, Graves

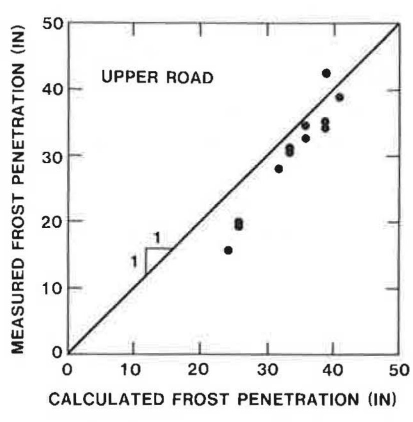

FIGURE 17 Measured frost penetration versus frost penetration calculated by modified Berggren formula; FI = 600 °F-days.

silt sand, and Morin clay. Also, the Winchendon test cells (Figure 1) did not include a base or subbase, did not experience traffic loadings, and were narrower (8 ft) than real highways. Frost penetration depths might have been larger if these features had been modeled in the field test.

SUMMARY AND CONCLUSIONS

This paper presents an analysis of 3 years' worth of field data acquired at the Winchendon field test site to further the understanding of the mechanics of frost action in soils and to improve existing highway frost design criteria. It analyzes and interprets in detail the Winchendon field test data on frost heave, thaw weakening, and frost penetration. A number of frost index tests and classification methods are evaluated. The following conclusions were obtained from these analyses.

Grain-Size Criteria

Simple grain-size criteria such as the percent of particles smaller than 0.075 or 0.02 mm correlate weakly with the Winchendon field performance data. These data show that all soils having few fines (particles smaller than 0.075 mm) performed well in the field test. Of the soils with intermediate and many fines, some performed well and some poorly, with a great deal of scatter. Inevitably these simple criteria reject some soils that heaved small amounts in the field test and hence are not useful for predicting the frost heave susceptibility of soils that fail these criteria.

U.S. Army Corps of Engineers Frost Design Classification System and Tabulated Freeze Test Data

The U.S. Army Corps of Engineers Frost Design Classification System and tabulated freeze test data provided very wide ranges of frost susceptibility compared with the field performance of the 12 test soils. Although most of the field data fall within the ranges of frost susceptibility given by the Corps of Engineers system, the ranges are too broad for accurate predictions of field performance. In addition, a low value of tabulated laboratory heave or heave rate corresponded to a wide range of field observations and not necessarily to negligible to low frost heave in the field. Thus, these methods may reject many satisfactory soils.

Freezing Tests

Comparisons of the field frost heave data with freezing data from the MDPW heave stress test on nonplastic soils and with freezing data from the new CRREL freeze-thaw test show excellent correlations. All soils that developed small heave stresses with time (R less than 18) in the MDPW test performed satisfactorily in the field. Heave stresses for the two plastic soils, Morin clay and Sibley till, were much higher than would be expected from the measured field heaves. However, the large resilient deflections of Sibley till show that the high heave stresses for plastic soils may be a useful indicator of large thaw weakening in the field.

The thaw-weakening CBR data from the CRREL freeze-thaw test correlated well with the resilient deflections from RPB tests in the field. Thus, this test shows promise of quantifying the thaw-weakening behavior of soils in the field. Data from the CRREL test have been used to develop tentative frost susceptibility criteria, which include the factors of both frost heave and thaw weakening (Table 6).

Both the MDPW and CRREL freezing tests require more elaborate test equipment than the simple index measures described earlier. However, they provided the best agreement with the Winchendon field performance data on frost heave and thaw weakening and show great promise.

Frost Penetration Depths

Frost penetration depths calculated by the modified Berggren formula are in general agreement with frost penetrations measured at the Winchendon field test. The average calculated frost penetration is about 10 percent larger than the average frost depth measured beneath the upper roadway and about 25 percent larger than the average frost depth measured beneath the lower roadway. This may possibly be due to the effects of freezing-point depressions of soil moisture, approximations inherent in the n-factor adjustment of air to ground surface temperatures, and other factors not accounted for in the field test. In comparison with the design frost depth for Winchendon of 52 in. given by MDPW design criteria, these data show that it may be possible to achieve savings from the use of reduced base and subbase thicknesses in frost protection of subgrades.

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