Frost Action Predictive Techniques: An Overview of Research Results

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A 6-year research program has materially advanced the state of knowledge regarding frost heave and thaw weakening affecting roads and airfield pavements. The investigations included development and performance of laboratory tests, development of computer models, testing and data collection at field pavement test sites, and validation of the laboratory procedures and computer models against field data. Specific advances include development of a new freezing test to assess the frost susceptibility of soil; development and validation of a mathematical model serving to predict frost heave and thaw consolidation; development of a laboratory test procedure to determine the resilient modulus of frozen, thawed, and recovering granular soils; and conceptualization and testing of a technique for combining the frost heave and thaw consolidation model, the laboratory resilient modulus test, and a pavement response model to predict the nonlinear resilient modulus of granular soils and base course materials as variables in time and space.

Six years of intensive research have materially advanced the state of knowledge of frost action on pavement performance and its application to the prediction of such effects. The two principal adverse effects of frost are ice segregation, causing heave and transient pavement roughness, and thaw weakening of subgrade and unbound base materials, causing accelerated pavement cracking and pavement deformation. It has long been an important goal not only to improve the empirical approaches for management of these problems in designing pavements but also to develop quantitative methods for predicting the surface heave that a given trial pavement section would experience and for evaluating the seasonal changes in supporting capacity of subgrade and base materials that would affect pavement performance under traffic loads *(1, 2)*.

Having a common interest in these goals, three agencies jointly sponsored the research: FHWA, FAA, and the U.S. Army Corps of Engineers *(3)*. The research, which spanned the period from late 1978 through 1984, included equipment development, field and laboratory experiments, and development of mathematical models. The investigations were directed to four principal study areas:

1. Selection and validation of the most effective laboratory index tests to serve as indicators of the susceptibility of soils to detrimental frost action,
2. Development of a soil column device with provisions for nondestructive monitoring of changes in soil moisture content and density during freezing and thawing,
3. Improvement and validation of a mathematical model of frost heave that had been developed earlier and incorporation of processes that take place during and after thawing, and
4. Development of laboratory test methods for the characterization of seasonal changes in resilient modulus of a wide range of types of granular soil and validation of these methods by means of in situ deflection testing of pavements.

The research was performed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Key investigations were conducted by consultants on certain phases of the work, and a board of general consultants who provided guidance and periodic review of the accomplished work was also assembled. The laboratory testing and analysis were conducted at CRREL's facilities in Hanover, New Hampshire, and field sites at Winchendon, Massachusetts, and Albany County Airport, New York, were used for in situ testing and data collection.

The research findings are summarized for each of the four study areas, and reference is made to other reports for details of the investigations.

FIELD TEST SITES

Field test sites were needed to serve as a source of samples of subgrade soils and base materials for roads and airfield pavements and as test beds where the performance of these soils and materials in pavement sections could be monitored and tested under varied conditions of temperature, moisture, and freeze-thaw action and under applied loads. Two sites were used for these purposes.

The first site is the Winchendon, Massachusetts, test site, constructed in 1978 by the Massachusetts Department of Public Works (MDPW) and consisting of 24 soil test sections. The six test sections used in this research consist of about 50 to 90 mm of asphalt concrete and 1.5 m of one of six test soils overlying the natural subgrade, a clean gravelly sand (see grain-size curves, Figure 1). The water table is at a depth of about 1.4 m below the pavement surface. Data were collected from each of the six test sections *(4, 5)* during the freeze-thaw-recovery seasons of 1978–1979 and 1979–1980. The data included temperatures at various depths, depth of frost, state of stress in soil moisture monitored by means of tensiometers at various depths, vertical displacement of paved surface caused by freezing and thawing, and vertical displacement of paved surface under load measured by repeated-load plate-bearing (RPB) tests and by falling weight deflectometer (FWD) tests.

The second test site is at Albany County Airport, located 9.6 km (6 mi) north of the city of Albany, New York, where two pavements were selected for field testing. Taxiway A is a new

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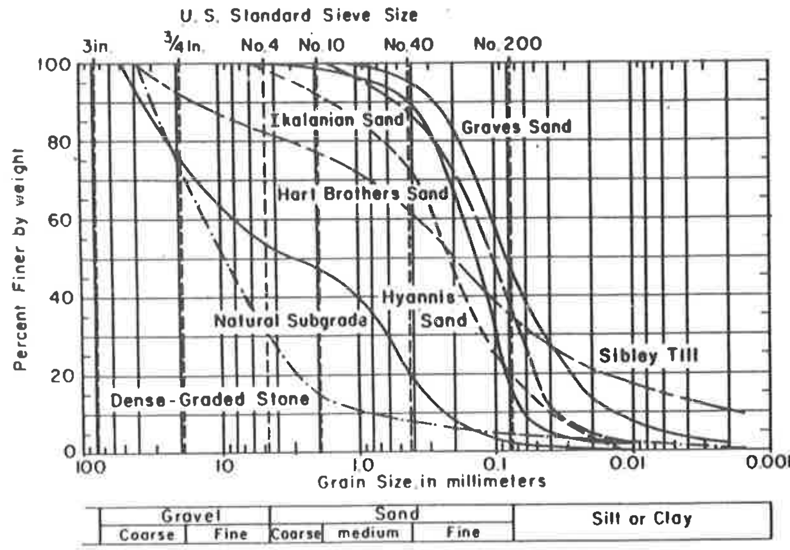

FIGURE 1 Grain-size distributions of Winchendon test soils and natural subgrade.

pavement for which the cross section consists of 330 mm of asphalt concrete, 584 mm of crushed-stone base, and 914 mm of gravelly sand subbase over a subgrade of silty fine sand (Figure 2).

Taxiway B, constructed many years ago (possibly in the 1940s), is no longer in use. The surface is uneven and the asphalt concrete is aged and severely cracked. The asphalt concrete is 76 mm thick and overlies about 102 mm of deteriorated asphalt penetration macadam stone base and 127 mm of gravel subbase. The subgrade is silty fine sand. Samples of the subbase whose composite grain-size distribution is shown in Figure 2 were taken to represent a single 229-mm base-subbase layer.

Data were collected at Albany County Airport from 1979 to 1983 of the same types noted previously for the Winchendon site. The Winchendon and Albany County Airport sites were also used as sources of samples for related laboratory tests. Core samples of the asphalt concrete of 102-mm diameter were taken, and 57-mm diameter undisturbed samples of the finer soils were obtained in the fall before freeze-up. Once frost had advanced to sufficient depth in the sections, core samples of the frozen soil were taken, except for those materials containing numerous gravel-size fragments, in which case specimens of appropriate size were frozen in the laboratory. Bulk samples of about 40 to 50 kg also were obtained from each soil and base material.

FROST SUSCEPTIBILITY INDEX TESTING

Frost susceptibility index tests allow geotechnical engineers to assess the potential for frost heave and thaw weakening of subgrade soils and unbound base and subbase materials in roads and airfields. In a survey of transportation departments throughout the world (*6–8*,pp.105–142), it was found that most agencies have developed their own unique frost susceptibility index criteria based on laboratory tests, that these criteria fail to discriminate marginally frost-susceptible material from material that is frost susceptible, and that there is little documentation of the efficacy of the adopted standards. Furthermore, most of the various tests consider only frost heave or thaw weakening rather than both, and most of those that employ laboratory freezing tests require excessive time and impose poor control of test conditions.

The objective of this study was to identify the best index test methods for fully characterizing the frost susceptibility of soils. To accomplish this task, a thorough review of frost susceptibility index tests and practices of transportation agencies was made. The index tests were categorized into three types or levels of complexity. One test from each of three types was selected for further evaluation, including the U.S. Army Corps of Engineers frost design soil classification system *(9)*, a moisture-tension–hydraulic-conductivity test, and a new freeze test including both frost heave and thaw weakening elements. For evaluation purposes these tests were conducted on the materials from the Winchendon and Albany test sites. Early results of moisture-tension–hydraulic-conductivity tests were inconclusive, however *(10)*, which led to the conclusion that this test was not suitable for routinely determining the frost susceptibility of soils. The results of the other tests were compared with field observations of frost heave and thaw weakening at the test sites and the validity of each test was determined. The procedures for the selected tests and the analysis of the data are given by Chamberlain *(10)*.

Development of New Freezing Test

From the literature review it was concluded that all freezing tests currently in use have serious faults. It was decided to develop an improved test, for which the following objectives were established:

1. The test should be as simple as possible, of short duration, and provide reliable results.
2. The test conditions must bear a relation to freezing conditions in the field and to thaw weakening.

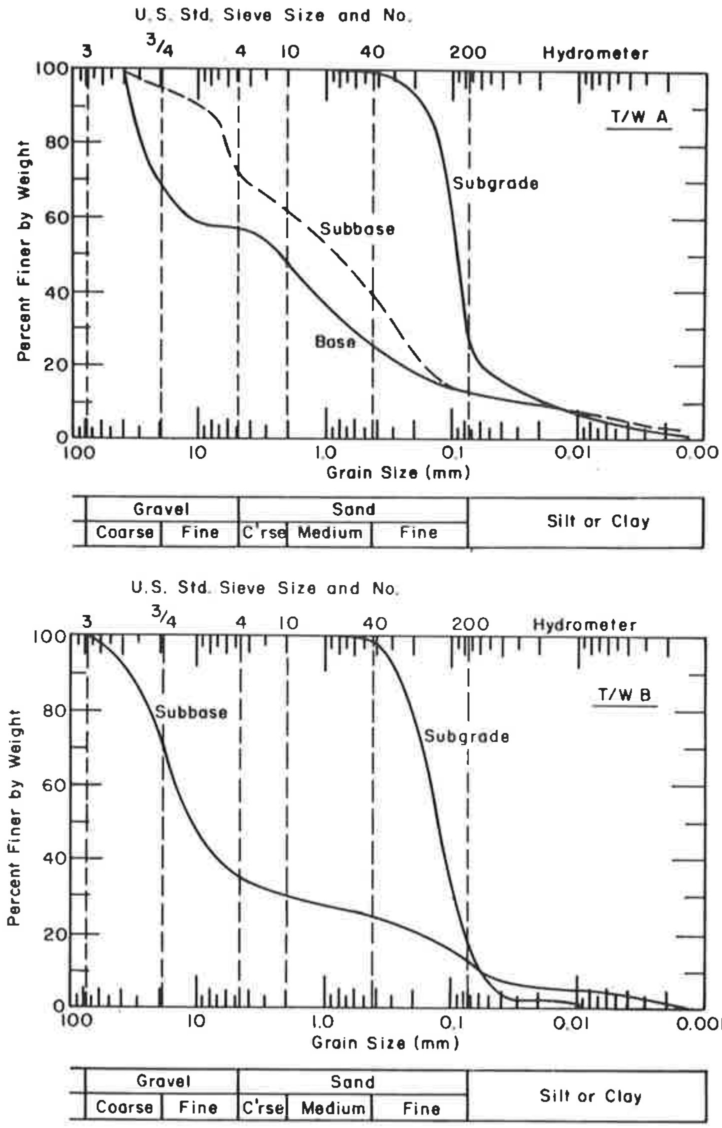

FIGURE 2 Grain-size distribution, materials from Taxiways A *(top)* and B *(bottom)*.

3. The test must accommodate the complete range of material types from granular base and subbase materials to fine-grained subgrade materials.
4. The apparatus should be inexpensive to construct and operate.

The equipment developed under these guidelines (Figure 3) includes a rubber-membrane-lined, multiring freezing cell to minimize side friction, liquid-cooled cold plates for precise top and bottom boundary temperature control, and a data acquisition and control system for automated temperature control and data processing. The test imposes two freeze-thaw cycles to account for the changes in susceptibility to frost heave caused by a prior freeze-thaw cycle, and a California bearing ratio (CBR) test is conducted after the second thaw to provide an index of thaw weakening. The test duration is 5 days. The heave rate at the end of 8 hr of freezing is used as an index of frost heave susceptibility. As will be seen, both indexes must be used to determine the frost susceptibility of a soil. Details of the test and the procedures are provided by Chamberlain *(11)*.

Results by Existing Methods

The frost susceptibility ratings according to three existing methods are shown in Table 1, ranging from *N* (negligible) to *VH* (very high). The range of frost susceptibility ratings varies widely and does not appear to be strongly related to either heave rate or pavement deflection observed in the field.

Results of New Freezing Test

Four freezing tests were conducted on each of the Winchendon soils and two on each of the Albany materials. The frost heave rates for three of the soils were significantly greater during the

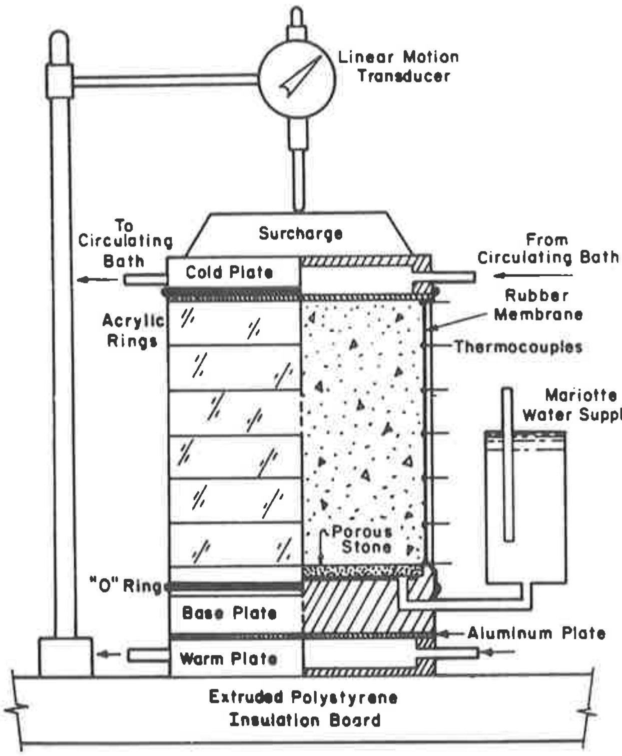

FIGURE 3 Schematic of new freezing test apparatus.

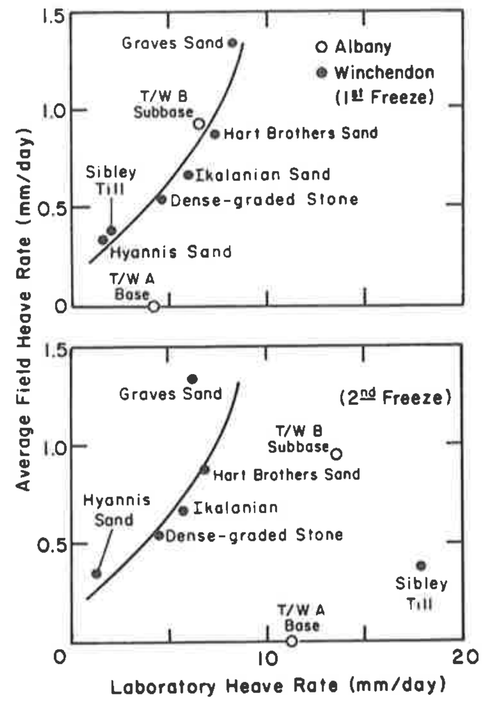

FIGURE 4 Comparison of laboratory and field heave rates during first and second freeze.

second freeze. For two of the soils [Taxiway (T/W) A base and T/W B subbase] the heave rate increased by factors of 2 to 3, whereas for Sibley till it increased by a factor of 9 from one of the lowest heave rates observed (2 mm/day) to the highest (18 mm/day). This illustrates the importance of including the second freeze-thaw cycle in this test.

Results of the tests showed that the CBR values for most of the soils were reduced by two cycles of freezing and thawing. Again the detrimental change was greatest for the Sibley till material, the reduction in CBR being by a factor of 8.5.

Discussion of Results

Comparisons of the laboratory and field frost heave rates are shown in Figure 4. With the exception of the T/W A results, there is a strong correlation between these heave rates for the first freeze-thaw cycle. The correlation is not on a line of equality, because the laboratory heave rates exceed the field values by a factor of 10 or more. However, because it was the intent of this study to use the freezing test qualitatively as an index test, not a quantitative predictor of frost heave in the field, the differences are not considered significant. When the results are plotted for the second freeze, the correlation between the laboratory and field results becomes weaker.

The correlation between the CBR after thawing and the maximum resilient pavement deflection during thawing (Figure 5) is better than the correlation between the frost heave parameters. In this case, all the average values of deflection fall close to a straight line showing inverse proportionality with CBR after thawing.

The comparisons shown in Figures 4 and 5 clearly show the

TABLE 1 SUMMARY OF FROST SUSCEPTIBILITY RATINGS ACCORDING TO ALL CRITERIA

Site and Material Type	Existing Methods: Corps of Engineers Grain Size Classification	Existing Methods: Comparison with Tabulated Data	Existing Methods: CRREL Freeze Test	New Freezing Test: 8-hr Heave Rate: First Freeze	New Freezing Test: 8-hr Heave Rate: Second Freeze	New Freezing Test: Thaw CBR	Range of Field Observations: Heave Rate	Range of Field Observations: Pavement Deflection
Winchendon								
Dense graded stone	VL-H	H	M	M	M	M	M	
Graves sand	L-H	H	H	H	M	VH	L-H	H-VH
Hart Brothers sand	VL-H	L	H	M	M	H	VL-M	H
Hyannis sand	N	N	L	VL	VL	M	N-L	M
Ikaianian sand	VL-H	L	M	M	M	H	VL-M	H-VH
Sibley till	VL-H	L-M	L-M	VL	VH	VH	N-VL	H-VH
Albany								
T/W A base	N-H	M-H	M	M	H	L	N	N
T/W B subbase	VL-H	L-M	H	M	H	M	L	H

Note: N = negligible; L = low; VL = very low; M = medium; H = high; VH = very high.

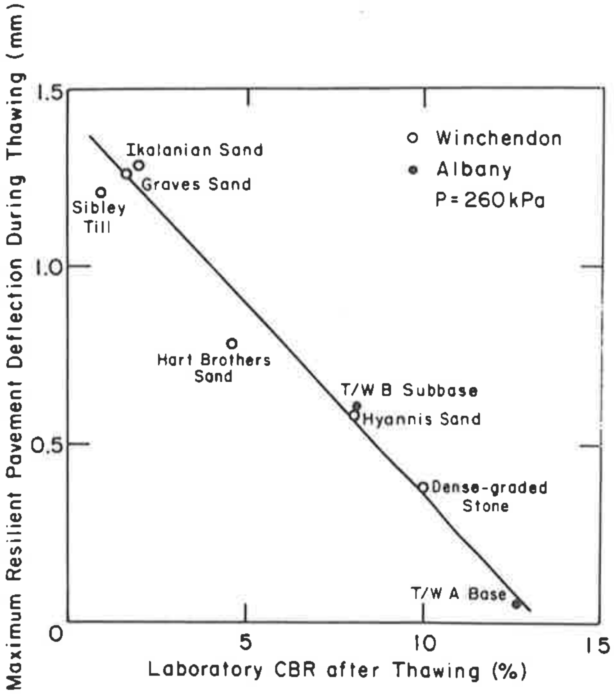

FIGURE 5 Comparison of CBR after thawing with maximum resilient pavement deflection during thawing.

need for including a thaw weakening indicator as a frost susceptibility index in the laboratory freezing test. If the heave rate from the first freeze were used alone to determine the frost susceptibility of the Sibley till soil, it would have been concluded that it was non-frost-susceptible. On the basis of results of the second freeze, the CBR after thawing, and the pavement deflection under load in the field, this soil is clearly frost-susceptible.

Preliminary frost susceptibility classification criteria for the new freezing test, based on the 8-hr frost heave rate during the first freeze and the CBR after two cycles of freezing and thawing, are as follows. Because the criteria were established on the basis of the comparison of a limited number of laboratory and field tests, they are tentative and subject to further confirmation.

Frost Susceptibility Classification	*Heave Rate (mm/day)*	*Thaw CBR (%)*
N	<1	>20
VL	1-2	20-15
L	2-4	15-10
M	4-8	10-5
H	8-16	5-2
VH	>16	<2

Conclusions Regarding Index Tests

It is clear from this study that to determine most accurately the frost susceptibility of a soil, it is necessary to conduct a freezing test. Although the Corps of Engineers soil classification method is useful for separating non-frost-susceptible soils from frost-susceptible soils, it does not discriminate well their degree of frost susceptibility, and it cannot be effectively used to predict the degree of thaw-weakening susceptibility.

The heave rate in the laboratory freezing test can be used to determine the frost heave susceptibility in the field, and the CBR value after freezing and thawing is a strong indicator of field thaw weakening leading to increased resilient pavement deflection under load.

The freezing test proposed is a workable candidate for replacing the Corps of Engineers standard freezing test because it requires much less time to conduct (5 versus 14 days), it provides much better boundary temperature control, it eliminates the side-friction problem prevalent in the current standard test, it provides an indicator of thaw-weakening susceptibility as well as an indicator of frost heaving susceptibility, and it allows the determination of the effects of repeated freezing and thawing.

SOIL COLUMN AND DUAL GAMMA SYSTEM

Design Features

It has long been known that moisture content and density change significantly when soil freezes. Changes in these variables need to be evaluated in time and space because they contain critical parameters in heat and mass transfer during freezing and thawing. A soil column and dual gamma system were constructed to generate such data from laboratory tests. The data were then used to develop, verify, and refine the mathematical model of frost heave and thaw settlement.

Figure 6 is a schematic drawing of the soil column. Three separate devices of this general type were fabricated and used. Their interior dimensions were about 50 mm in diameter, 135 mm in diameter, and 100 mm by 100 mm square, respectively. The columns consisted of segments each 300 mm long, which were stacked one on the other to provide any desired length from 900 to 1500 mm. The upper 300 mm of the column was tapered to reduce side friction that developed as freezing occurred from the top downward *(12)*. Details of the soil column, test procedures, and some early test results were given by Ingersoll and Berg *(13)*.

A dual gamma system was designed to be used with the soil column. Its primary purpose is to nondestructively monitor changes in density and moisture content with time and vertical position during freezing and thawing of soils in the soil column. The system *(14)* consists of two nuclear sources, an electronic detector to monitor gamma radiation from the sources (Figure 7), a tower to position the sources and detector vertically, and electronic equipment to control, monitor, and record data from the system.

Testing

Several tests were run on soils from the Winchendon site and other soils, and results were used as one source of data for validation and refinement of the frost heave model, a mathematical model of coupled heat and moisture flow *(13)*. During late 1984 and 1985, two special tests were conducted using the soil column and dual gamma system whose objectives were to monitor changes occurring during thaw *(15)*.

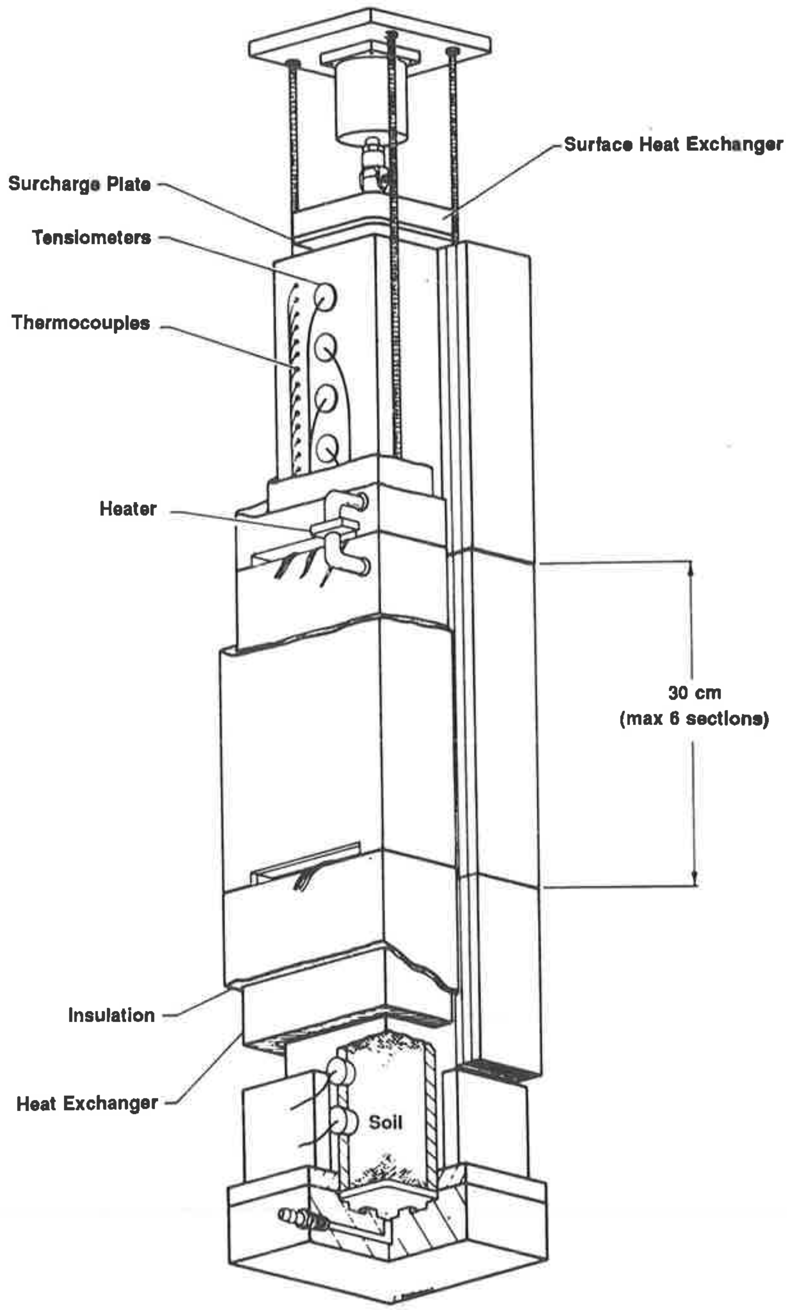

FIGURE 6 Soil column (schematic).

In addition to settlements during thawing (Figure 8), changes in temperature and moisture stress were also monitored. Slight positive pressures were observed in both tests before the entire frozen layer was thawed. When thawing was complete, water drained downward into the underlying soil. The results of the tests were used as a data set for refinement and validation of the thaw settlement portion of the frost heave model. The simulated settlements, temperatures, and moisture stress obtained by use of the model agree reasonably well with the observed values.

MATHEMATICAL MODEL OF FROST HEAVE AND THAW SETTLEMENT

Model Development

The model assumes one-dimensional vertical heat and moisture flux. Its development was reported earlier *(5, 12, 16–21)*. The model is intended for use on problems of seasonal freezing and thawing of nonplastic soils beneath pavements in which frost does not penetrate deeply into soils beneath the water table.

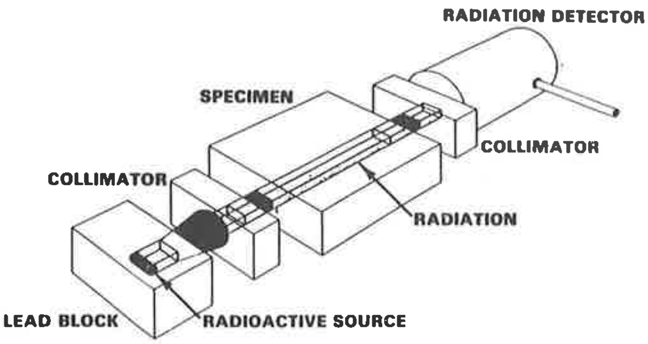

FIGURE 7 Dual gamma system (schematic).

Furthermore, it is intended for use where surcharge effects are not large (usually less than 60 kPa).

The main assumptions embodied, the governing equations, boundary and initial conditions, numerical approach to simulation as a system of finite elements, probabilistic concepts, and interim results of verification trials of the frost heave model have been presented in the reports referenced earlier. The latest version of the model has been summarized by Johnson et al. *(15)* and Guymon et al. *(22)*. The most recent development includes the incorporation of a submodel for thaw settlement. A principal objective of the submodel is the prediction of the generation and dissipation of pore-water pressures during and after thawing and the build-up of moisture tension during subsequent recovery from the thaw-weakened condition.

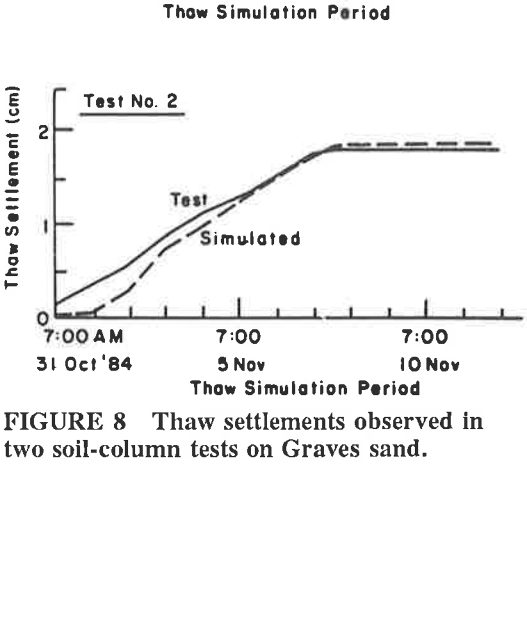

FIGURE 8 Thaw settlements observed in two soil-column tests on Graves sand.

Conceptual Basis for Thaw Settlement Algorithm

The concepts advanced by Morgenstern and Nixon *(23)* provide the framework for the thaw settlement and pore-water pressure algorithm presented here. The Morgenstern and Nixon model is based on well-known theories of heat conduction and of linear consolidation of compressible soils. Terzaghi's one-dimensional consolidation theory was applied to develop a moving boundary solution applicable to permafrost soils that thaw and consolidate under the application of load. A closed-form solution was obtained.

This application of the model is directed to layered systems of well-compacted soil. Consequently the application is restricted to winter heaving of subgrade soils and spring thaw settlement originating in those same soils with no net consolidation or change in pavement elevation occurring over a sequence of several years of freeze-thaw action.

A departure from the Morgenstern and Nixon model is the solution of the linear governing equation of excess pore-water pressure (Terzaghi's equation) numerically rather than exactly. The numerical code for this solution already exists in the frost heave model. This method allows more flexibility in handling the upper surface pore-water pressure boundary condition. A second departure of the method proposed here from that of Morganstern and Nixon is the use of a more general heat transport equation.

The equations composing the basis of the algorithm for estimation of thaw settlement and of pore-water pressure during and after thawing are given by Guyman et al. *(22)*, as are the boundary conditions and other assumptions.

Model Verification and Assessment

Model verification has been a continuing process since completion of early work on formulating the model reported elsewhere *(16)*. Details have been presented by Guymon et al. *(5, 18, 19)*, including comparison of simulations with both laboratory and field data.

The results from the model demonstrate that for different soils ranging from silts to relatively coarse-grained and marginally frost-susceptible soils, good results can be obtained with the model. To achieve such results, however, good estimates of hydraulic parameters are required. Judgment is required in assigning appropriate values, because considerable error may occur in the most carefully measured soil parameters, particularly unsaturated hydraulic conductivity.

Also, use of the model requires calibration of the hydraulic conductivity correction factor *(E)*, a phenomenological correction factor for freezing soil. Assuming that sufficient measurements were available for partly frozen soil so that hydraulic conductivity could be related to freezing temperature or ice content, it is conceivable that such data could be used instead of the phenomenological relationship.

The model also requires an estimate of the moisture tension in the freezing zone. This is done indirectly through the selection of a residual (unfrozen) water content for the frozen zone and by calculating the corresponding pore-water tension by the

Gardner *(24)* equation. Generally values of residual water content are selected so that the moisture tension is 75 to 100 kPa. Actual values may be soil-specific and much greater or lower than this range.

It is believed that the model simulates phenomena in the freezing zone adequately for the present engineering purposes, and that it will meet the need of practicing pavement engineers to predict frost heave and some of the parameters influencing thaw weakening of pavement systems. The development of a model more closely linked to accepted concepts of soil physics awaits a more complete understanding and formulation of processes in the freezing zone, as well as justification of the additional computer time and expense required to solve a more complex formulation of the processes, and of the additional time, equipment, and expense for conducting laboratory tests to define additional soil parameters.

Output from the model includes cumulative frost heave at the surface, subsurface temperatures, and pore-water pressures. The predicted frost heave can be used directly to aid in selection of an appropriate pavement design by relating it to pavement roughness criteria. Temperatures are used to determine positions of freezing and thawing zones, and temperatures and pore-water pressures are used in empirical equations developed from laboratory tests to estimate resilient modulus values of layers within the pavement system at various times of the year.

SEASONAL VARIATION IN RESILIENT MODULUS OF GRANULAR SOILS

This phase of the research was directed to a principal underlying cause of premature distress in pavement systems containing soils that are susceptible to frost action, the reduction of the resilient modulus of subgrade soils and unbound base courses during and following spring thaws. In this context the resilient modulus is conventionally defined as deviator stress divided by resilient (i.e., recoverable) strain. The research was concerned with frost-susceptible granular soils exhibiting little or no cohesion and a high degree of nonlinear (i.e., stress dependent) mechanical behavior. The research objective was to develop laboratory methods of characterizing the seasonal changes of resilient modulus of such materials throughout a complete annual cycle. Field in situ tests were conducted to validate the laboratory methods.

Interim results have been given by Cole et al. *(25)* and Johnson et al. *(26)*. Detailed procedures, results, and analyses of repeated-load triaxial tests and of field in situ plate loading tests and the corresponding deflection basin analyses are given in a four-part report series *(4, 27–29)*. The approach developed for prediction and evaluation of resilient modulus has been presented by Cole et al. *(30)*.

Characterization by Laboratory Testing

The techniques developed here have allowed the simulation in the laboratory of the loss of stability upon thawing followed by the gradual recovery of stiffness experienced in the field after thawing as a frost-susceptible soil drains, consolidates, and desaturates.

The experimental approach called for performing repeated-load triaxial tests on all the asphalt-concrete and test soils from both test sites. Starting with samples in the frozen state, load cycles on the soils were applied by using two waveforms to simulate the loading pulses associated with the two field-testing devices used here: FWD and the RPB apparatus. At each level of confining and deviator stress used in the laboratory tests, 200 load cycles were applied, and a resilient modulus and resilient Poisson's ratio were calculated when a nominally steady-state response was achieved. Similar tests were performed on the same samples after thawing and at successive stages of recovery.

The key variable in the recovery process is soil moisture tension. As a soil drains after thawing, it first reconsolidates to a condition of zero pore-water pressure. Following this phase, gradual desaturation occurs, the moisture tension rises, and the material increases in stiffness. A system was developed that used removable triaxial cell bases equipped with tensiometers; this allowed the retesting of a given specimen several times at increasing levels of moisture tension, thus simulating the changes observed in the field work. Each specimen remained mounted on a given base throughout the testing sequence and excessive handling was thus avoided. The use of moisture tension as the primary means to describe the soil state has proven to be very effective because it strongly influences the resilient modulus and is relatively easily monitored in both the field and laboratory.

Standard statistical analysis techniques have been used in this work to generate empirical expressions for resilient modulus in terms of unfrozen water content for the frozen soil and in terms of moisture tension, applied stress, and in some cases dry density for thawed and recovering soil. In some cases, for nonfrozen material, the commonly used bulk stress model for stress dependency of a nonlinear material has been used, which is of the form

$$M_r = K_1 \, \theta_{K_2}$$

where K_1, K_2 are constants and θ is the bulk stress, that is, the sum of the principal stresses, also termed the first stress invariant J_1. A somewhat more complex stress function involving the second stress invariant and the octahedral shear stress has also been used:

$$M_r = K_1 \, (J_2/\tau_{oct})_{K_2}$$

where

K_1, K_2 = constants,
J_2 = second stress invariant = $\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3$, and
τ_{oct} = octahedral shear stress.

This later function is unique in that it accounts for the effects on the modulus of both confining pressure and principal stress ratio in a manner appropriate for many granular materials. Figure 9 shows a plot of resilient modulus versus bulk stress for a Winchendon test soil (Hyannis sand). The bulk stress model does not account for the fact that, for certain types of soil, the

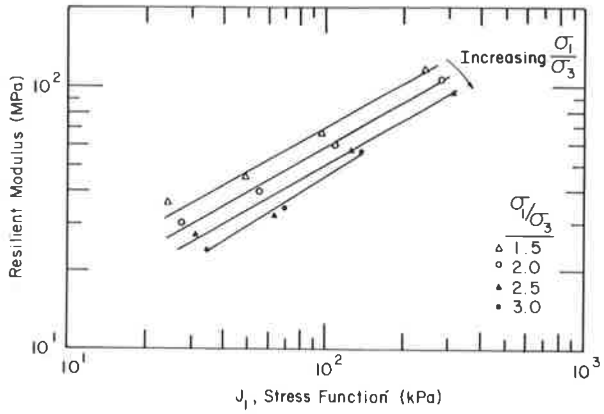

FIGURE 9 Resilient modulus of Hyannis sand versus J_1.

modulus decreases with increasing principal stress ratio. The stress function J_2/τ_{oct}, however, accounts for the influence of the stress ratio and thus linearizes the data more efficiently (Figure 10).

The laboratory testing sequence mentioned earlier generates data that allows the modeling of the post-thaw recovery process

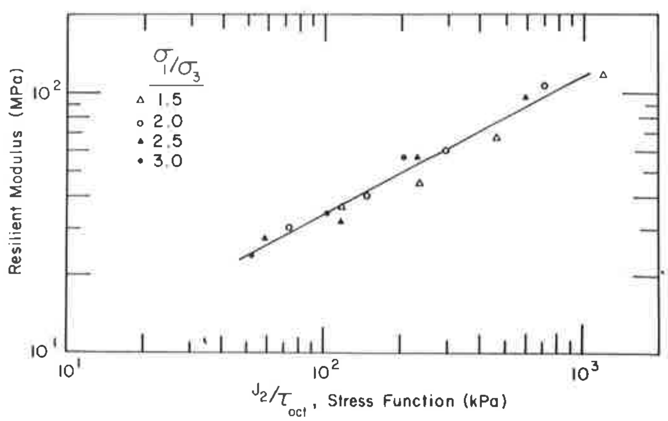

FIGURE 10 Resilient modulus versus J_2/τ_{oct} for the test data given in Figure 9.

with a single equation. The increasing stiffness associated with the recovery phase is predicted through the moisture tension term, which is a component of the coefficient K_1.

Six soils from the Winchendon test site and five from the Albany County Airport were tested in this manner and analyzed to characterize the moisture-tension-dependent nonlinear resilient modulus. For example, the results for a dense-graded crushed stone base at Albany County Airport yielded the following expression:

$$Mr \text{ (MPa)} = 1.10 \times 10^6 (101.36 - \psi)^{-2.40}(J_2/\tau_{oct})^{0.30}$$

where Mr is the resilient modulus and ψ is moisture tension in kilopascals.

Field Verification

For validation purposes, field tests were used to determine the surface deflection response of paved soil test sections under loads imposed by an RPB apparatus and an FWD. The tests were performed at critical times between late fall and late spring to characterize the variation in load response throughout the freeze-thaw-recovery cycle.

The validity of the laboratory results was then examined by comparing the measured deflection basins with deflection basins calculated for the test section by using the expressions for resilient modulus developed from the laboratory tests. In using these expressions, temperatures and moisture tensions measured at the time of each field loading test were applied to evaluate the resilient modulus.

Procedures for the in situ tests and for analysis of deflection basins have been given elsewhere *(25, 26)*. Measured deflections varied substantially through successive stages of the freeze-thaw cycle (Figure 11). Deflections were calculated for the same states by means of a nonlinear elastic-layer analysis for pavements (NELAPAV) (Irwin and Johnson, unpublished data). The calculated deflections generally agreed well with those measured by in situ testing (Figure 12).

The calculated resilient moduli and other results from the analysis of the test sections have been summarized elsewhere *(4, 28)*. The calculated resilient moduli of the test soils show the expected seasonal variation; extremely high values are found in the frozen condition, which decrease dramatically upon thawing and increase somewhat during the late spring, summer, and fall. An interpretation of the variation in modulus of the upper layer of each test soil is given in Figure 13 for the Winchendon test sections.

The agreement of the calculated deflections with the deflections measured under plate loading is strong evidence that the equations for nonlinear resilient modulus developed from laboratory triaxial tests represent valid characterizations of the materials in the layered pavement system. The procedures for the laboratory repeated-load triaxial tests, including testing at successive levels of moisture tension to track the recovery process in thaw-weakened soils, yield acceptable results, and such tests should provide a useful basis for structural evaluation and design of pavements affected by freezing and thawing.

This investigation has demonstrated a strong dependence of the resilient modulus on the seasonally varying environmental parameters of temperature and moisture tension. Evaluation of these environmental variables can be made by installing sensors at various depths below a paved surface and collecting data over a complete annual cycle. Alternatively, the frost heave model *(5)* can be used to predict both temperature and moisture tension as variables in time and space.

SIMULATING FROST HEAVE AND PAVEMENT DEFLECTION

Approach

In addition to its primary use for the calculation of frost heave, the mathematical model also serves the essential function of predicting the time-dependent dissipation of excess pore pres-

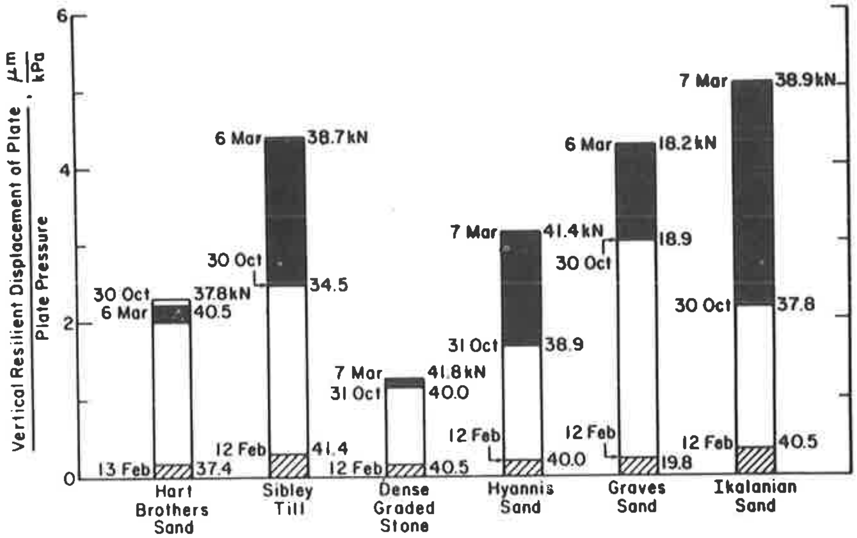

FIGURE 11 Vertical resilient displacement observed on six test sections before freezing, while frozen, and during thawing.

sure during thaw and buildup of moisture tension during recovery. To test these capabilities, the mathematical model for frost heave and thaw consolidation and the NELAPAV response model were used in concert with the results of laboratory resilient-modulus tests to simulate frost heave and pavement deflection in the field. Comparison with field observations provided the ultimate test of the modeling and laboratory testing procedures.

Calculations were made with the mathematical model to simulate the frost heave and thaw consolidation at the field test sites. The time-dependent temperature and pore pressures calculated for nodal points within the pavement profile were used to determine unique layers within the freezing or thawing system and to select equations characterizing the resilient modulus of each layer. The appropriate equations for resilient modulus were then input into the NELAPAV program along with temperatures and pore pressures (moisture tension), and the deformations and stresses at each point of interest were

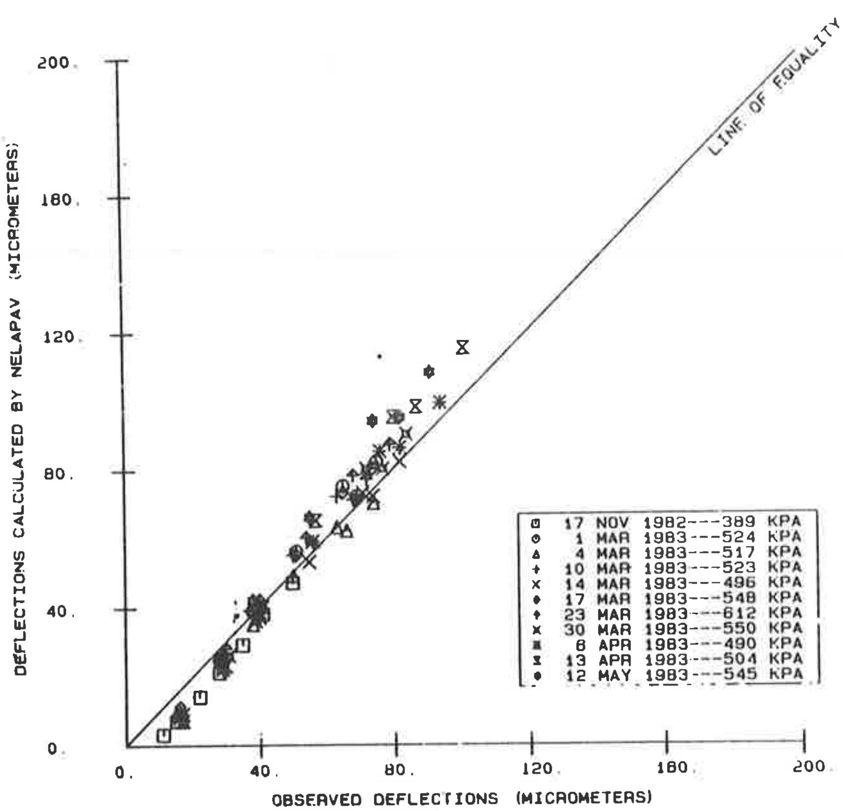

FIGURE 12 Measured surface deflections compared with deflections calculated by NELAPAV, Taxiway A, test point N2, 1982–1983.

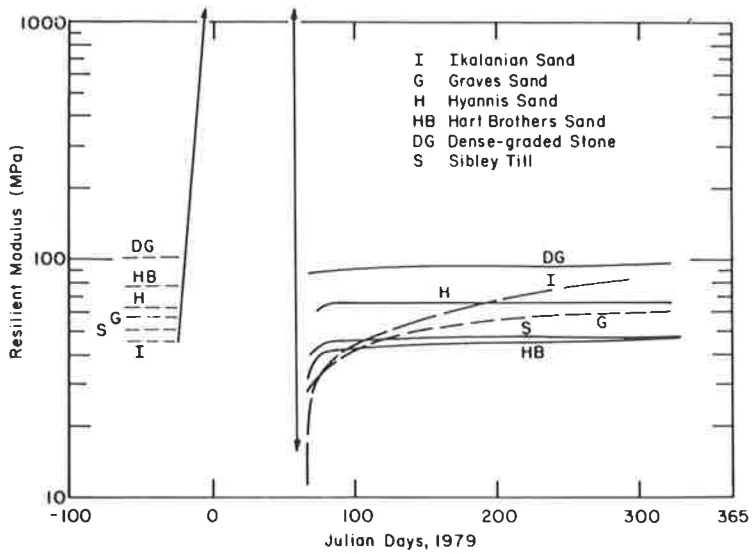

FIGURE 13 Interpretation of seasonal variation in resilient modulus of six test soils directly beneath asphalt pavement under 200 to 300 kPa plate pressure.

calculated. The test of the efficacy of the procedure required a comparison of the calculated seasonal variation of frost heave and pavement deflection under repeated loading with the observed values.

Results and Discussion

Figure 14 shows an example of the results for the Graves sand test section at the Winchendon test site. The calculated pavement deflections agree well with the measured values. The predictions made to date with this procedure demonstrate the efficacy of using the frost-heave–thaw-consolidation model and the NELAPAV response model to calculate seasonal frost heave and pavement deflection under load. The model thus provides an instrument for implementing much of the work performed under this multiphase research project.

IMPLEMENTATION OF RESEARCH FINDINGS

The investigations have produced results that can be advantageously implemented into current practice of design and evaluation of pavements in frost areas. The results of the examination of frost susceptibility index tests *(10)* have identified the Corps of Engineers frost design soil classification system and a new laboratory freeze-thaw test as two levels of testing that should be put into practice. The frost heave model can be implemented beneficially in any system for pavement design or evaluation. And finally, the laboratory repeated-load triaxial test on thawed and recovering soil can not only be implemented in mechanistic design and evaluation systems, but when used with either the frost-heave–thaw-consolidation model or with in situ measurements of moisture tension can be implemented in systems employing a cumulative damage approach.

The scope and extent of the implementation of each of the research findings and their potential impact on pavement design and evaluation depend on the type of system used for pavement analysis. The approach to implementation of each finding is shown in the form of flow charts (Figures 15 through 19).

Corps of Engineers Frost Design Soil Classification System

This frost susceptibility classification system *(9)*, based on simple classification type tests, leads to assignment of a corresponding frost group number to each soil. Its implementation (Figure 15) is limited to those pavement design and evaluation systems that are based on the frost group number.

New Laboratory Freeze-Thaw Test

This improved freezing test (Figure 16) also incorporates a CBR test on the thawed specimen. Outputs are heave rate from the freezing phase, and CBR in the thawed state; from these outputs, scales of susceptibility to frost heave and thaw weakening may be derived, as shown earlier. Frost heave susceptibility can be applied effectively to any mechanistic or empirical design and evaluation system as an indication of potential roughness. The classification of susceptibility to thaw weakening can be used as an indicator of spring loss of support for application under any empirical design and evaluation system. It is expected that the application of these indicators in developing a pavement design would be accomplished as appropriate adjustments to design thicknesses determined by other types of analyses.

Frost Heave Model

The frost heave model provides for the first time an ability to calculate with reasonable confidence the magnitude of the

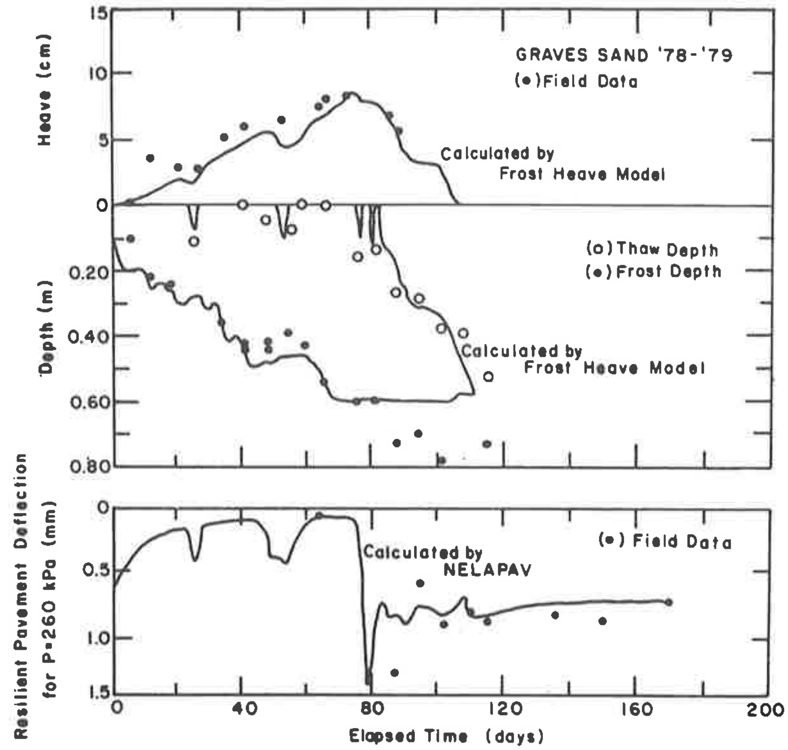

FIGURE 14 Comparison of simulated frost heave, frost and thaw depth, and pavement deflection with field observations.

heave that can be expected in a given pavement cross section under prescribed climatic, geotechnical, and hydraulic conditions. Because the outputs of depth of frost and magnitude of heave (Figure 17) are referenced to a particular point on the pavement where conditions are known, the model does not predict pavement roughness. Heave at a point can be used as an indicator of potential roughness, however, and can be implemented as an adjunct to any pavement design and evaluation system. For example, the calculated frost heave might serve as a basis for adjusting a trial design thickness if necessary to reduce the expected winter pavement roughness. The second principal output from the model, the predicted depth of frost beneath a pavement having a certain trial cross section, can be used as direct input for those design systems incorporating a dependence of the total thickness of the pavement section on the depth of frost. It can also be used as an adjunct to any design system.

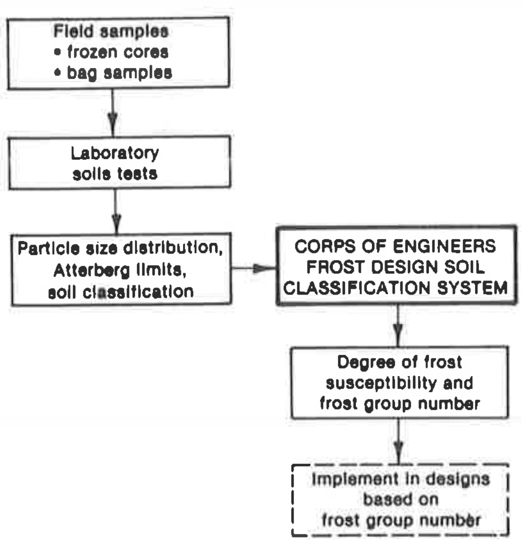

FIGURE 15 Implementation of Corps of Engineers frost design soil classification system.

Repeated-Load Triaxial Test on Frozen and Thawed Soil

The repeated-load triaxial test on frozen and thawed specimens provides a means of evaluating the resilient modulus of sub-

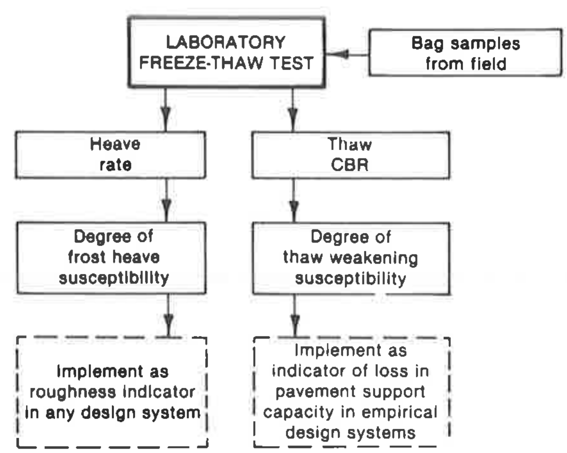

FIGURE 16 Implementation of new freeze test.

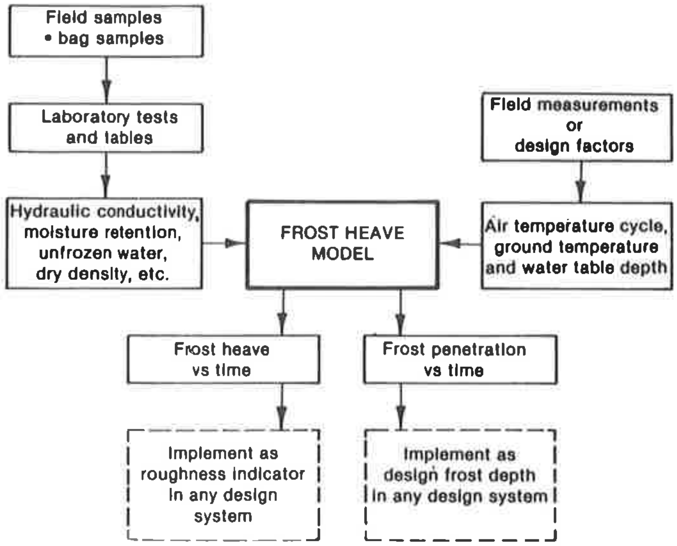

FIGURE 17 Implementation of frost heave model.

grade and base soils at various stages during the freeze-thaw-recovery cycle. The regression equations for soil in the thawed state (Figure 18) are of the greatest interest, because in many cases they represent the most critical condition showing the lowest resilient modulus and consequently the greatest potential for pavement distress. The expressions for resilient modulus can be implemented directly in any mechanistic design and evaluation system that employs a multilayered or finite-element simulation model formulated to analyze nonlinear materials.

Evaluation of Seasonal Variation of Resilient Modulus

It is unrealistic to base the design or evaluation of a pavement on only the lowest value of resilient modulus reached during the year (usually during thawing), and there is no reasonable basis for selecting any other single value to serve as an annual average representative of all the seasons. Rather, methods currently coming into greater use that include a cumulative damage approach offer the advantage of assessing in a more rigorous way the effect of the complete annual cycle of freezing, thawing, and recovery. Application of these methods requires that the resilient modulus be expressed as a function of time to make it possible to analyze the pavement performance by dividing the year into discrete intervals during which the modulus may be assumed to be constant. The evaluation of seasonal variation of the resilient modulus requires that the modulus be characterized in terms of the moisture tension and that the seasonal variation of the moisture tension be monitored or predicted. Figure 19 shows that repeated-load triaxial tests can be used to measure the resilient modulus as a function of temperature, soil stress, and moisture tension. The frost heave model and its associated thaw settlement model are used to predict the key parameters of temperature and moisture tension as variables in time and space. With this linkage, the resilient modulus at various depths is defined as a continuous function of time, facilitating the application of mechanistic analyses for pavement design and evaluation by using a cumulative damage approach.

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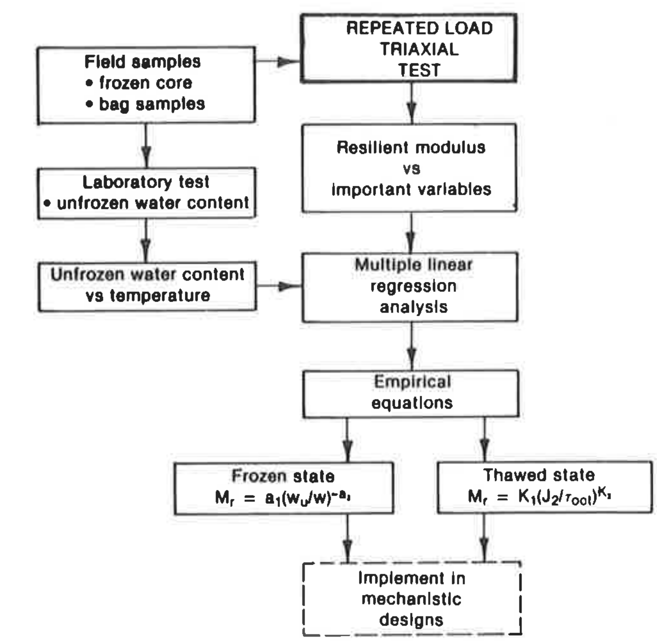

FIGURE 18 Implementation of repeated-load triaxial test for stress-strain-deflection analysis.

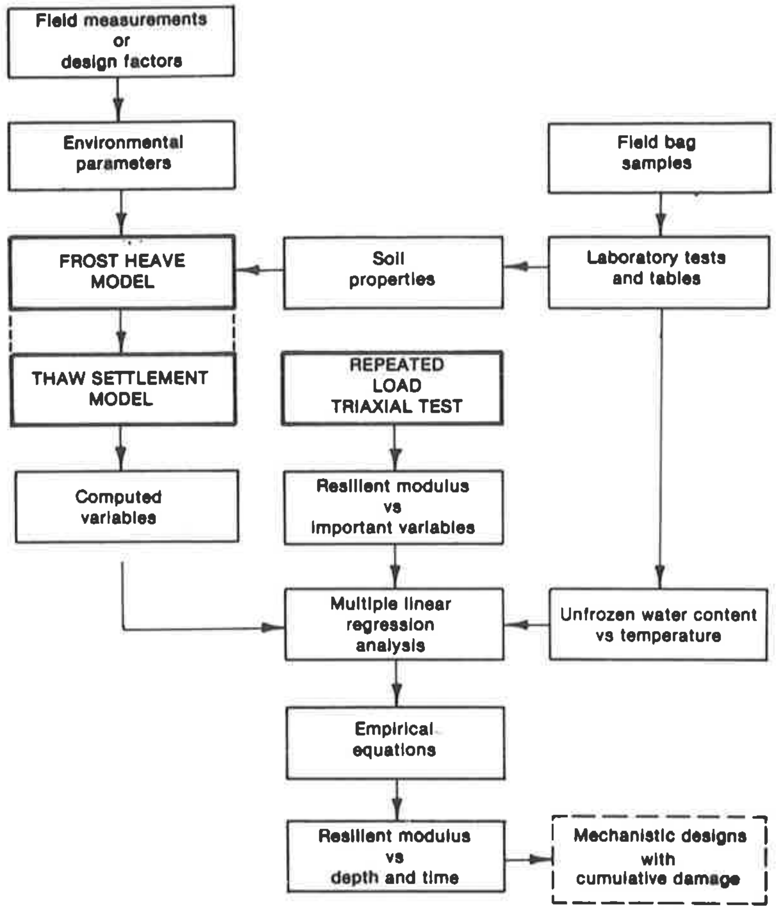

FIGURE 19 Implementation of seasonally varying resilient modulus for stress-strain-deflection analysis with cumulative damage approach.

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