Prediction of Damage to Flexible Pavements in Seasonal Frost Areas

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The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) is developing a mechanistic pavement design method for use in seasonal frost areas by the Corps of Engineers and the Air Force. The mechanistic method will employ results from a series of five computer programs that compute soil and pavement moisture and temperature conditions (FROST1), resilient modulus and Poisson's ratio (TRANSFORM), stresses and strains in the pavement system (JULEA and NELAPAV), and cumulative damage (CUMDAM). The model has been calibrated for the properties of six soils. Five fatigue equations, three based on horizontal strain at the bottom of the asphalt layer and two based on vertical strain at the top of the subgrade, are used to determine the cumulative damage for two-, three-, and four-layer pavement sections at Springfield, Missouri, and Rochester, Minnesota. Although all of the equations predicted failure during the design life for each pavement section modeled, significant jumps occurred during the spring, indicating that the thaw period is crucial in the fatigue life of a pavement.

In the development of a mechanistic design method for pavements subjected to annual freezing and thawing, seasonal variations must be considered. Seasonal variation in pavement strength manifests by (a) large increases in base and subgrade strengths when frozen, (b) loss in base and subgrade strengths during the spring when thaw weakens the layers, and (c) change in asphaltic concrete strength and modulus with temperatures.

The model in development at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, N.H., is composed of a series of computer programs that are combined to provide a method for predicting the variation in the strength of flexible pavement structures throughout an annual temperature cycle. Variation in soil moisture content does not include an infiltration component and is based only on changing ground water levels. The emphasis of the work in this paper is on the spring thaw period.

The series of programs results in the computation of cumulative damage to the pavement structure attributable to vehicular loadings so that the remaining life of existing pavement systems can be evaluated. Results can also aid in the design of new pavements and overlays.

COMPUTER MODEL

The model includes five programs: FROST1, which computes frost heave and thaw settlement of the pavement structure and soil conditions throughout the depth of the structure (temperature, water content, ice content, density, etc.) at a given time increment; TRANSFORM, which uses FROST1 output files as input and produces files with layered or sublayered pavement systems with a resilient modulus, Poisson's ratio, and density assigned to each layer or sublayer; JULEA or NELAPAV, which calculates stress, strain, and deflection at given points within the pavement profile; and CUMDAM, which calculates incremental and cumulative damage to the pavement structure. Graphs are produced using commercially available plotting programs. The five programs do not work in a consistent system of units. FROST1 is metric, TRANSFORM converts from metric to English, and JULEA and CUMDAM work in English units. NELAPAV can work in either system. In this paper equations are in the units in which they were developed and used in a particular program. Conversion factors used are given in Table 1.

Soil constants and properties of six soils previously studied at a Winchendon, Massachusetts, test site were used for this study (*1*,*2*; E. Chamberlain, unpublished data, 1986). Some of the physical properties of these soils are given in Table 2; grain size distribution curves are shown in Figure 1. Additional properties and information required by each program are discussed later. Special laboratory tests on these soils were conducted at CRREL; test procedures are discussed in Ingersoll (*3*), Chamberlain (*4*), Cole et al. (*1*), and Tice et al. (*5*). Similar data from other soils will be added to the data base in the future.

FROST1

FROST1 was developed by the University of California, Irvine, for CRREL (*6*,*7*). The model assumes one-dimensional vertical heat and moisture flux and is based on a numerical solution technique termed the nodal domain integration method, which allows use of the same computer program to solve a problem by either the finite element method or the integrated finite difference method, or any other mass lumping numerical method. The program was developed for use on problems of seasonal freezing and thawing of nonplastic soils.

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TABLE 1 UNIT CONVERSION FACTORS

Multiply	*By*	*To obtain*
inch	25.4	millimeter
lbf/in.^{2} (psi)	6894.757	pascal
degrees Fahrenheit	t °C = (t °F-32)/1.8	degrees Celsius
lb/ft^3	16.01846	kg/m^3

TABLE 2 PHYSICAL PROPERTIES OF WINCHENDON TEST SOILS

	*Coefficients**		*Atterberg limits*		*Specific*
Soil	*Cu*	*Cc*	*LL*	*PI*	*gravity*
Dense Graded Stone	32.8	7.1	23	3	2.81
Graves sand	39.1	1.6	0	0	2.70
Hart Brothers sand	8.0	0.92	0	0	2.76
Hyannis sand	4.7	1.2	0	0	2.67
Ikalanian sand	4.5	0.96	0	0	2.70
Sibley till	235	4.1	19	4	2.74

* Cu—coefficient of uniformity, Cc—coefficient of curvature.

The program is based on the following assumptions:

1. Darcy's law applies to moisture movement in both saturated and unsaturated conditions.
2. The porous media are nondeformable as far as moisture flux is concerned; that is, consolidation is negligible.
3. All processes are single valued; that is, hysteresis is not present in relationships such as the soil water characteristic curve.
4. Water flux is primarily as liquid; that is, vapor flux is negligible. Additional assumptions are reported by Berg et al. (*6*).

FROST1 requires the following input for initial and boundary conditions:

1. Upper and lower boundary temperatures,
2. Upper and lower boundary pore water pressures,
3. Initial temperature and moisture stress or moisture content, and
4. Surcharge pressure.

For each soil layer FROST1 requires

5. Gardner's coefficients for soil moisture characteristics,
6. Gardner's coefficients for hydraulic conductivity characteristics,
7. Porosity and density,
8. Coefficient of volume compressibility,
9. Freezing point depression,
10. Thermal conductivity and volumetric heat capacity of the dry soil, and
11. A hydraulic conductivity adjustment factor for the freezing zone.

From these inputs, FROST1 calculates frost heave and thaw settlement throughout a given period. In addition, the temperature, water content, ice content, moisture stress, density, and porosity in each element are determined for each time increment of the simulation.

The nodes are points that divide the column of material into vertical elements, as shown in Figure 2. In general, a 2-cm nodal spacing is used within the frost zone, whereas 5- to 20-cm spacings are used below. The water table is adjusted by assigning an appropriate pore water pressure to the bottom node.

TRANSFORM

TRANSFORM was developed at CRREL by Chamberlain (unpublished data, 1986) and Allen. Using the output file produced by the FROST1 program, TRANSFORM computes the moduli of homogeneous soil layers within the pavement profile. TRANSFORM initially divides the pavement structure into homogeneous layers on the basis of material type, ice content (which determines if the layer is frozen or unfrozen), pore water pressure, and temperature. A homogeneous layer consists of a single material type with the temperature, ice content, and pore pressure characteristics shown in Table 3.

The layers are then assigned a modulus value based on regression equations developed from laboratory resilient modulus results for the soils in frozen and thawed states. The equations relate the resilient modulus to temperature, pore water pressure, density, and stress conditions. These equations are shown in Table 4 (*1*). An approximation of the $f(\sigma)$ stress term was used, making this term a constant for each soil and thereby making the equations not dependent on stress. The equation for the resilient modulus of the asphalt layer is

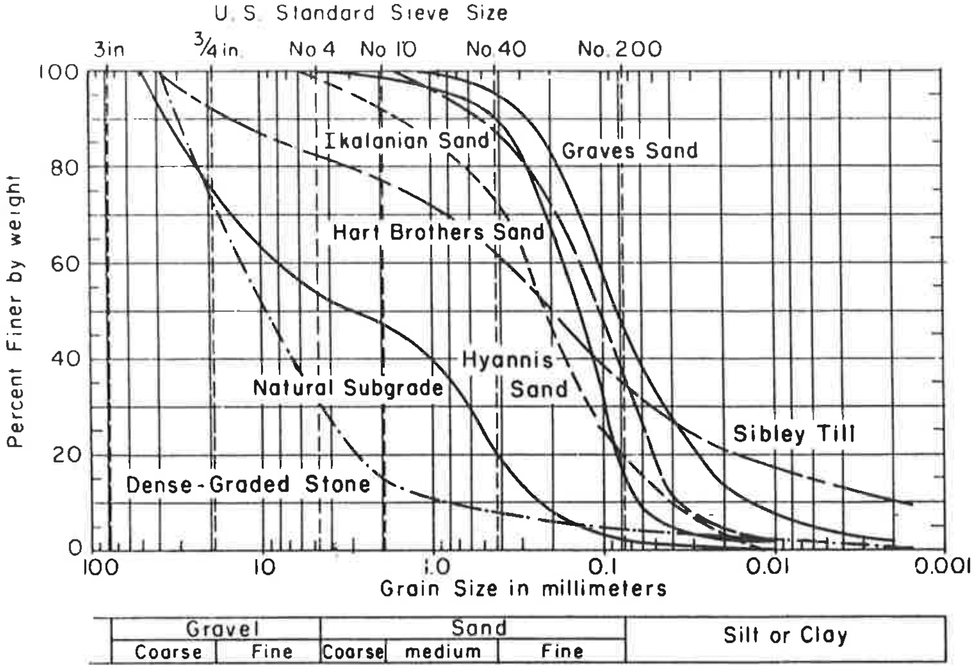

FIGURE 1 Grain size distribution of Winchendon test soils and natural subgrade.

based on a regression of data obtained by Schmidt (*8*) and is as follows:

$$E(\text{MPa}) = [10^{(6.285 - 1.931\times10^{-2}\,T - 3.275\times10^{-4}\,T^2 - 1.888\times10^{-5}\,T^3 + 1.175\times10^{-7}\,T^4 + 1.502\times10^{-8}\,T^5 - 2.022\times10^{-10}\,T^6)}] * 145$$

where T is the temperature of the top FROST1 node in degrees centigrade.

For pavement temperatures greater than 50°C, the asphalt modulus was set to 173 MPa; for temperatures less than −29°C, it was chosen at 33 389 MPa.

To reduce the number of layers, and thus simplify the profile and reduce the computer simulation time, adjoining sublayers were combined if modulus values were within ±20 percent of each other. The resulting modulus of the combined layer is a weighted average of the moduli of the component layers.

Two versions of TRANSFORM produce files appropriate for input into JULEA or NELAPAV. For JULEA this includes one load data file and a structural data file for each day of the simulation. NELAPAV requires a single file containing both load and structural data for each day of the simulation. Both of these programs use layered elastic methods.

JULEA

JULEA was developed by J. Uzan (unpublished data, 1986). Based on Boussinesq theory, JULEA will allow up to 25 layers and will provide a linear elastic solution for determination of stress, strain, and deflection at a point in the given pavement profile using layer modulus, Poisson's ratio, thickness, and area and magnitude of the load. JULEA allows multiple wheel loads.

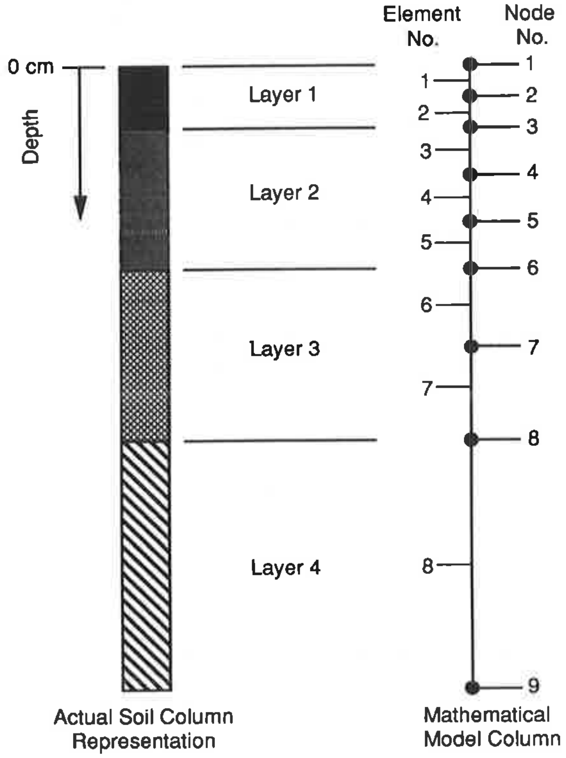

FIGURE 2 Example soil profile divided into finite elements.

TABLE 3 HOMOGENEOUS SOIL LAYERS PRODUCED BY TRANSFORM PROGRAM

Layer type	*Description*
1	Frozen, volumetric ice content greater than 0.002, with temperature less than -6.0°C.
2	Frozen, volumetric ice content greater than 0.002, with a temperature less than -1.0°C, divided into sublayers with a temperature difference across the layer of less than 1 degree for layers warmer the -6°C.
3	Frozen, with a temperature between -1.0 and -0.5°C.
4	Frozen, with a temperature greater than -0.5 and less than 0°C.
5	Frozen, with a temperature of 0°C.
6	Partially thawed, volumetric ice content greater than 0.002, and positive pore water pressure.
7	Unfrozen, with negative pore water press subdivided into additional layers if the difference in pore water pressure within a single layer is greater than 50 cm of water.
8	Unfrozen, with positive pore water pressure.

NELAPAV

NELAPAV was developed by Irwin and Speck (*9*) at Cornell University under a contract with CRREL. It is an adaptation of the Chevron Layered Elastic Systems program. NELAPAV has the ability to accommodate layers having moduli of elasticity that vary with the level of stress or strain in the layer and to produce both linear and quasi-nonlinear solutions with seven modulus models given in Table 5 (*10*). (Model 7 is not currently incorporated into the CRREL version of NELAPAV.) It will allow up to 25 layers in its present form. Initially, NELAPAV was run using the linear model 0 to compare its output with the linear JULEA solution. To investigate the nonlinear aspects of thawing soils, NELAPAV was then run using the linear model 0 for frozen layers, unfrozen layers with negative pore pressure and the asphalt layers, and model 3, which is dependent on the J_2/τ_{oct} stress term, for the thawed and partially thawed layers.

The solution computed by NELAPAV is an approximation to the exact solution. In reality, the stress state changes from point to point. Therefore, the modulus of a nonlinear material varies both vertically and horizontally. Whereas NELAPAV recomputes the set of compatible moduli to determine the states of points at various radii, it is bound by the assumption that the moduli are constant everywhere in the layers. A more exact theory for nonlinear materials would allow the modulus to vary horizontally within the layer in accordance with the nonlinear model.

CUMDAM

The program CUMDAM was developed at CRREL. It uses five fatigue equations—three based on horizontal strain at the bottom of the asphalt layer and two based on the vertical strain at the top of the subgrade. The equations are as follows.

Asphalt Strain

The Asphalt Institute (*11*):

$$N_a = 18.4\ C\ (4.325 \times 10^{-2})\ |\varepsilon_t|^{-3.291}\ (E_a{}^{-0.854})$$

where

N_a = number of load applications for cracking,
C = a function of the volume of the voids and the volume of asphalt (10^z),
$z = 4.84\ [(V_b/V_v + V_b) - 0.69]$,
V_b = volume of asphalt (%),
V_v = volume of voids (%),
ε_t = tensile strain at the bottom of the asphalt layer (in./in.), and
E_a = modulus of the asphalt layer (psi).

TABLE 4 RESULTS OF REGRESSION ANALYSIS

Material	*Regression equation*	n	R^2	*Std. error*
Natural subgrade				
Frozen	$M_r\text{(MPa)} = 20.74\ f\ (\sigma)^{0.352}$	65	0.76	0.201
Graves sand				
Frozen	$M_r\text{(MPa)} = 39.1(w_u/w_t)^{-1.79}$	95	0.91	0.502
Thawed	$M_r\text{(MPa)} = 6.68\times10^4\ f\ (\psi)^{-2.2948} f\ (\sigma)^{0.414}$	186	0.89	0.144
Ikalanian sand				
Frozen	$M_r\text{(MPa)} = 86.4(w_u/w_t)^{-1.32}$	87	0.92	0.749
Thawed	$M_r\text{(MPa)} = 3.021\times10^4 f\ (\psi)^{-3.266} f\ (\gamma)^{11.634} f\ (\sigma)^{0.442}$	119	0.89	0.276
Hart Brothers sand				
Frozen	$M_r\text{(MPa)} = 4.085\times10^1\ (w_u/w_t)^{-1.59}$	99	0.92	0.623
Thawed	$M_r\text{(MPa)} = 1.269\times10^5 f\ (\psi)^{-3.089} f\ (\gamma)^{7.023} f\ (\sigma)^{0.453}$	172	0.87	0.185
Hyannis sand				
Frozen	$M_r\text{(MPa)} = 33.45\ (w_u/w_t)^{-2.03}$	69	0.95	0.617
Thawed	$M_r\text{(MPa)} = 7.147\times10^4 f\ (\psi)^{-1.782} f\ (\sigma)^{0.264}$	128	0.71	0.129
Dense Graded Stone				
Frozen	$M_r\text{(MPa)} = 82.27\ (w_u/w_t)^{-2.03}$	32	0.87	0.413
Thawed	$M_r\text{(MPa)} = 1.56\times10^5 f\ (\psi)^{-1.76} f\ (\sigma)^{0.136}$	64	0.65	0.202
Sibley till				
Frozen	$M_r\text{(MPa)} = 1.01\times10^2\ (w_u/w_t)^{-3.446}$	108	0.87	0.71
Thawed	$M_r\text{(MPa)} = 7.47\times10^6 f\ (\psi)^{-2.829} f\ (\sigma)^{0.192}$	118	0.63	0.283

Notes:

RPB = repeated-plate bearing apparatus waveform

n = number of points

M_r = resilient modulus

f = load wave frequency

$f\ (\sigma) = [(J_2/\tau_{oct})/\sigma_o]$

σ = stress (kPa)

J_2 = second stress invariant (kPa^2)

τ_{oct} = octahedral shear stress (kPa)

w_u = unfrozen water content

w_t = total water content

$T = \theta/\theta_o$

θ_o = 1°C

ψ = moisture tension

ψ_o = 1 kPa

$f\ (\gamma) = \gamma/\gamma_o$

γ_o = 1 mg/m^3

$f\ (\psi) = [(101.38-\psi)/\psi_o]$

γ = soil density (mg/m^3)

Witczak (*12*):

$$N_a = ab^{qd}\,(1/\varepsilon_t)^c$$

where

$a = 1.86351 \times 10^{-17}$,
$b = 1.01996$,
$c = 4.995$,
$d = 1.45$, and
q = pavement temperature (°F).

The Army Corps of Engineers (*13*):

$$N_a = 10^{(5\ \log|\varepsilon_t| + 2.66\ \log E_a - 2.68)}$$

Subgrade Strain

The Asphalt Institute (*11*):

$$N_s = 10^{[1/m(\log l - \log \varepsilon_v)]}$$

where

N_s = allowable traffic based on subgrade strain,
m = a constant (0.25),
l = a constant (2.8×10^{-2}), and
ε_v = vertical strain at the top of the subgrade (in./in.).

The Federal Aviation Administration (Bush) (*14*):

$$N_s = 10^{\left(\frac{\log \varepsilon_v}{-0.17985} - 12.215\right)}$$

TABLE 5 RESILIENT MODULUS: NELAPAV MODELS

	NELAPAV models	
Model no.	Name	Specification
0	Linear	E = constant
1	Bulk stress	$E = k_1\ \theta^{k_2}$
2	Deviator stress	$E = \begin{cases} k_2+k_3(k_1-\sigma_d) & \sigma_d < k_1 \\ k_2+k_4(\sigma_d-k_1) & \sigma_d \geq k_1 \end{cases}$
3	Second stress invariant	$E = k_1\ (J_2/\tau_{oct})^{k_2}$
4	Octahedral shear stress	$E = k_1\ \tau_{oct}{}^{k_2}$
5	Vertical stress	$E = k_1\ \sigma_v{}^{k_2}$
6	Major principal stress	$E = k_1\ \sigma_1{}^{k_2}$
7	First stress invariant octahedral shear stress and anisotropic consolidation ratio	$E = k_1(J_{1o}{}^2 + J_{1P}{}^2)^{k_2}\ (1 + \tau_{oct})^{k_2}\ k_c{}^{k_4}$

Notes:

θ = bulk stress
k_1, k_2, k_3, k_4 = constants
σ_d = deviator stress
σ_v = vertical stress
σ_v = major principal stress
J_{1o} = first stress invariant due to overburden only
J_{1p} = first stress invariant due to overburden and load
k_c = anisotropic consolidation ratio

For these calculations, the design traffic (n) is 685 loadings per day or a total of 5,000,000 passes of the equivalent standard axle load (ESAL) of 18,000 lb in 20 years. N_s or N_a were calculated daily using the above equations. The damage was accumulated as a summation of n/N incremented daily to match the time increment run in FROST1, starting on the first day of the freezing season at that site (Rochester, Day 13; Springfield, Day 69).

Although some of the equations are being applied outside of the original assumptions used in their development, they are representative of cumulative damage models currently available and are used for the initial analysis until more appropriate equations can be determined.

CALIBRATION OF THE MODEL

The model was calibrated by matching heave determined in FROST1 and deflection determined from JULEA and NELAPAV to field data from the Winchendon test site. Each of the six Winchendon pavement test sections contained 8 cm of asphalt over 1 to 1.5 m of a test soil. The sections were built for research only and never received significant vehicular traffic, but were tested using nondestructive equipment.

Data from the test site included temperatures from thermistors placed to a maximum depth of approximately 1.5 m, surface elevations to determine frost heave, and deflections from repeated-load plate bearing (RPB) tests performed during the winter and spring of 1978/1979. The RPB was a nondestructive testing apparatus used by CRREL before obtaining a falling weight deflectometer (*15*). This self-contained trailer-mounted apparatus generated successive load pulses in the 1- to 140-kip range at rates up to 20 repetitions per minute. The loading pulse profile from the RPB is the standard pulse used for laboratory resilient modulus tests at CRREL (Figure 3).

As mentioned, heave predicted by the FROST1 program was compared with the surface elevation data from the Winchendon test site. For each soil, the modifier of the hydraulic conductivity in the freezing zone was adjusted until the predicted heave most closely matched the observed heave, as shown in Figure 4.

Initial calculations by the model produced deflections during spring thaw that were generally much lower than those

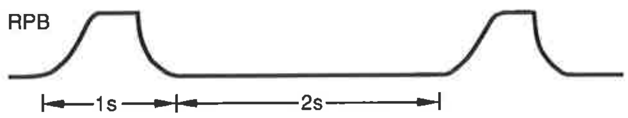

FIGURE 3 Typical RPB load pulse profile.

produced by the RPB for the same input load magnitude. These data indicated that, during spring thaw, the moduli values calculated by the programs were higher than those existing in the field.

An investigation of output from FROST1 during spring thaw indicated the presence of days when layers within the structure exhibited positive pore pressures, denoting saturation of the soil. Since the resilient modulus equations produced from the CRREL laboratory program (Table 3) were not intended for a saturated soil condition, a reduction factor (k) was applied to the modulus of saturated thaw layers, calculated in TRANSFORM, as follows:

$$M_r(\text{saturated}) = \frac{M_r(\text{thawed})}{k}$$

The magnitude of the k factor was determined by extrapolation of laboratory resilient modulus results to a 0 moisture tension case and refined with comparison to the field RPB data for each soil case. Model simulations using various k factors were made until the predicted deflection data closely matched data obtained in the field (e.g., Figure 5).

RESULTS

Pavement Response Models

Calibration of the programs to the Winchendon RPB deflection data indicated the following:

1. NELAPAV, using the linear model, gives approximately the same solution as JULEA (Figure 6).
2. The nonlinear model used in NELAPAV for the thawed layers produces closer agreement to the field data than the linear JULEA (or NELAPAV) solutions (Figure 7).

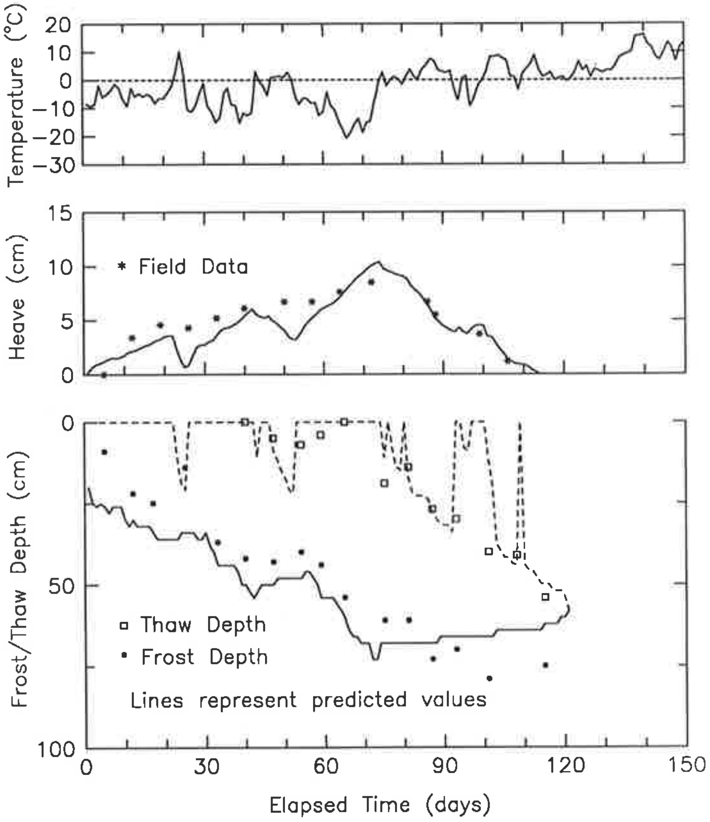

FIGURE 4 Example of comparison between field data and FROST1-predicted heave and frost depths. Case modeled is asphalt over Graves sand at Winchendon, Massachusetts, starting December 10, 1978.

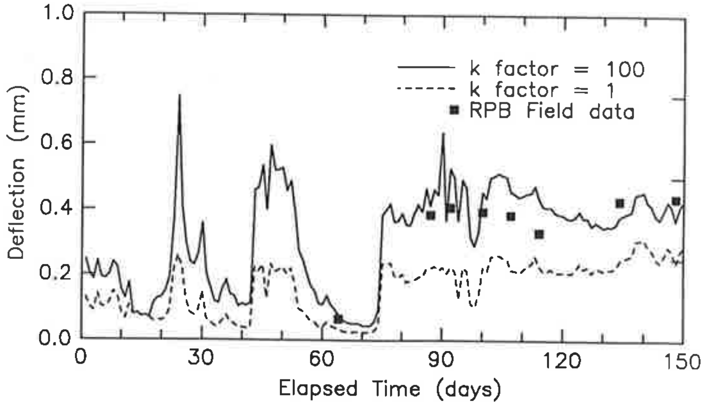

FIGURE 5 Example of *k* factor calibration. Case modeled is asphalt over dense graded stone at Winchendon, Massachusetts, starting December 10, 1978.

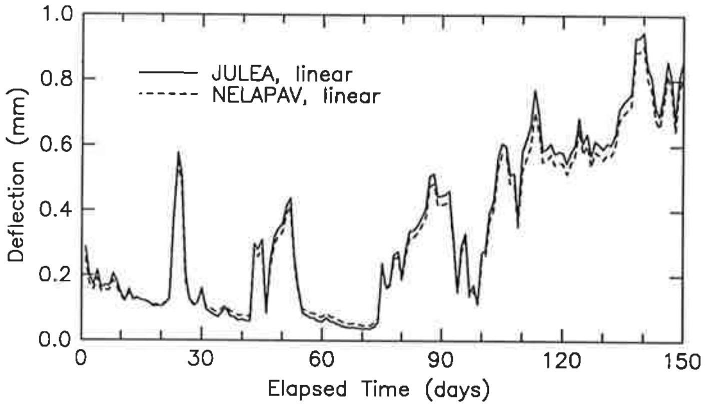

FIGURE 6 Comparison of JULEA and NELAPAV predicted deflections when NELAPAV is run with linear model. Case modeled is asphalt over Graves sand at Winchendon, Massachusetts, starting December 10, 1978.

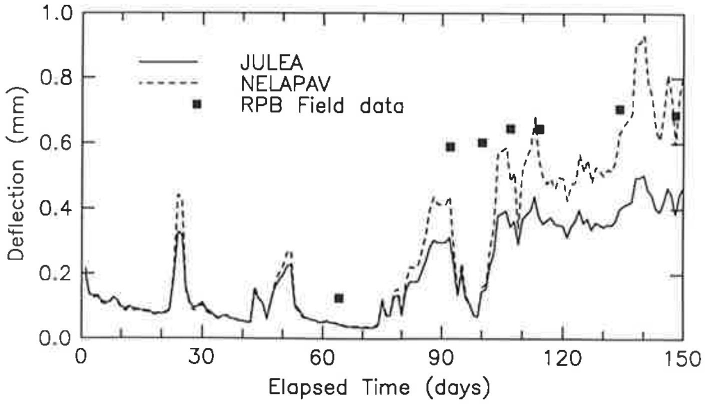

FIGURE 7 Comparison of JULEA and NELAPAV predicted deflections for typical Winchendon test site. Case modeled is asphalt over Ikalanian sand at Winchendon, Massachusetts, starting December 10, 1978.

Cumulative Damage

As part of developing a mechanistic design method for pavements in cold regions, we report the results from three pavement profiles for annual temperature cycles at two geographic locations. The pavement profiles, shown in Figure 8, result from the current Corps of Engineers reduced subgrade strength design method (*16*), except for the two-layer case, which is analogous to the Winchendon test site. The subgrade material, Graves sand, is an especially high-heaving material. The environmental conditions chosen were those at Springfield, Missouri, and Rochester, Minnesota, to represent typically warm and typically cold seasonal frost locations. The freezing indices used for the sites, the coldest in 30 years, were 702 and 2,805 degree Fahrenheit days, respectively. These cases are purely hypothetical and do not represent any existing field site.

Figures 9 and 10 show the mean daily temperatures, frost heave, frost penetration, and thaw penetration at the Springfield, Missouri, and Rochester, Minnesota, sites for the design years (1977–1978 and 1978–1979, respectively) for the two-

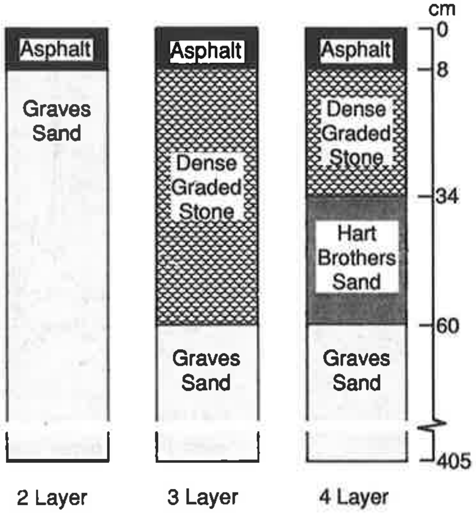

FIGURE 8 Pavement profiles.

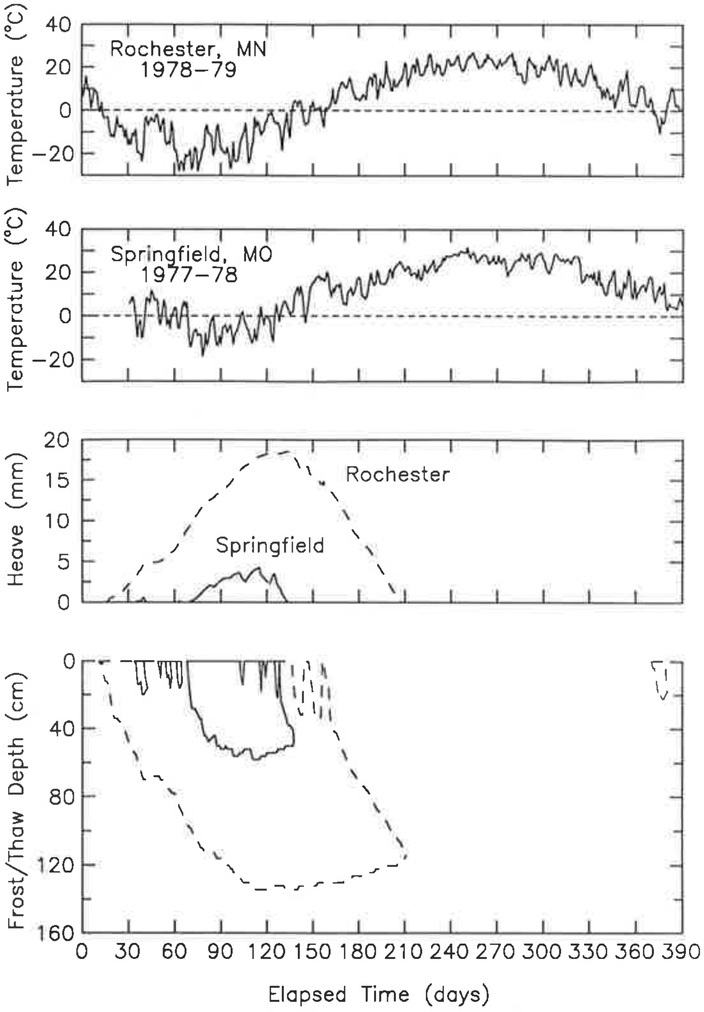

FIGURE 9 Predicted heave and thaw depths at Springfield, Missouri, and Rochester, Minnesota, during design cold year: two-layer pavement structure.

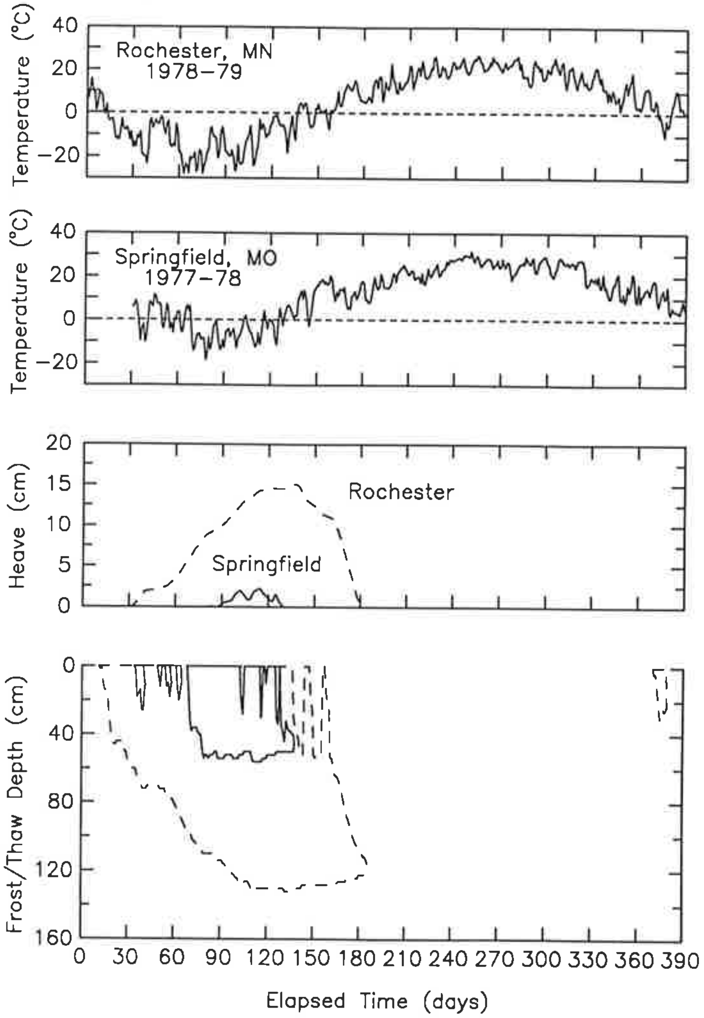

FIGURE 10 Predicted heave and thaw depths at Springfield and Rochester during design cold year: four-layer pavement structure.

and four-layer cases as depicted in Figure 8. The time plotted begins on November 1 of the design year; however, because Springfield has such a mild season, its simulation started on December 1.

Strains produced by JULEA for the four-layer case at each site are shown in Figures 11 and 12. Output from the fatigue equations for Rochester two-, three-, and four-layer cases is shown in Figures 13–15. A cumulative damage equal to 1.0 indicates pavement failure. Therefore, for a pavement system to last its design life, the amount of cumulative damage must be less than 1.0 for that period. For a 20-year design life, this indicates that the yearly cumulative damage should be less than 0.05 if the damage is assumed to be evenly distributed throughout the pavement life.

The figures produced during the simulations indicate the following:

1. For the two-layer case, failure of the pavement in less than 1 year was predicted by all five fatigue equations (Figure 13). For all cases, failure occurred during the thawing season, with a significant jump in the cumulative damage.

2. For the three-layer case, all the fatigue equations again predicted failure within the 20-year life span (Figure 14). Witczak and the Corps horizontal strain equations and the FAA vertical strain equation showed abrupt increases in the cumulative damage during the thawing period, resulting in failure within the first year. However, the Asphalt Institute equations for horizontal and vertical strain both showed a more gradual increase in cumulative damage, beginning in the spring and continuing through the rest of the period modeled. The Asphalt Institute horizontal and vertical equations predicted failure in approximately 2 and 6 years, respectively.

3. For the four-layer case, the pavement also failed, based on the horizontal strain criteria, with the Witczak equation predicting the earliest failure (Figure 15). Again, significant jumps in the cumulative damage were predicted during the thawing season by Witczak's and the Corps' horizontal strain equations and the FAA vertical strain equations. As in the

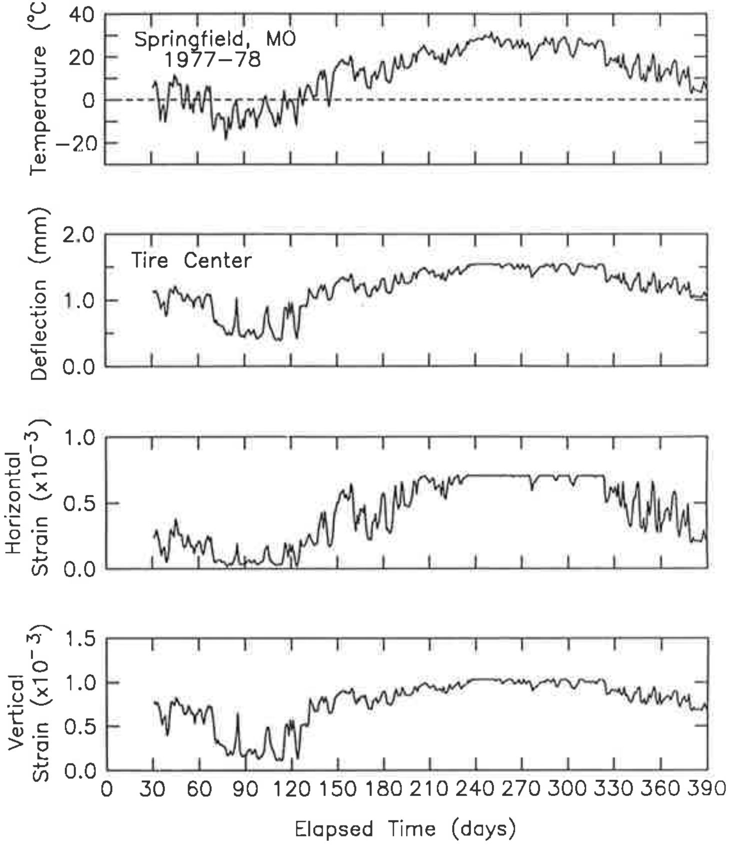

FIGURE 11 Engineering properties calculated by JULEA: surface deflections and strains at base of pavement and top of subgrade with four-layer pavement structure, Springfield.

three-layer case, the Asphalt Institute equations predicted more gradual failure in approximately the same time.

CONCLUSIONS

1. From the calibration effort, it was concluded that a nonlinear solution produces better correlation with observed repeated plate bearing test deflection data, especially during periods of thaw, than a linear elastic solution. Therefore, further simulations should concentrate on the nonlinear models with the addition of model 7 in NELAPAV.
2. The cumulative damage predictions produced the following preliminary conclusions:

- For the two-layer pavement structure, all of the cumulative damage equations predicted failure within the first thawing period. Failure was expected since the pavement modeled was designed for research and not for traffic.
- For the three- and four-layer cases, fatigue equations that use only one strain value for the entire subgrade layer may be misleading. FROST1 and TRANSFORM produce layered systems containing thin layers that may have substantially different moduli than the bulk of the subgrade. The current CRREL procedure uses the strain value at the point under investigation, typically less than 1 cm under the subgrade interface. If this layer has a particularly high or low modulus value, fatigue predictions will be affected accordingly. However, the significant rapid increases in the values for cumulative damage during the spring thaw period illustrate the amount of damage that the pavement may sustain in the thaw-weakened state.
- The cumulative damage equations are being applied outside the bounds of the original assumptions on which they are based, or beyond the data used in their development. For this preliminary study, several equations were incorporated into the CUMDAM program for comparison and evaluation. Further study on suitable damage equations is warranted.

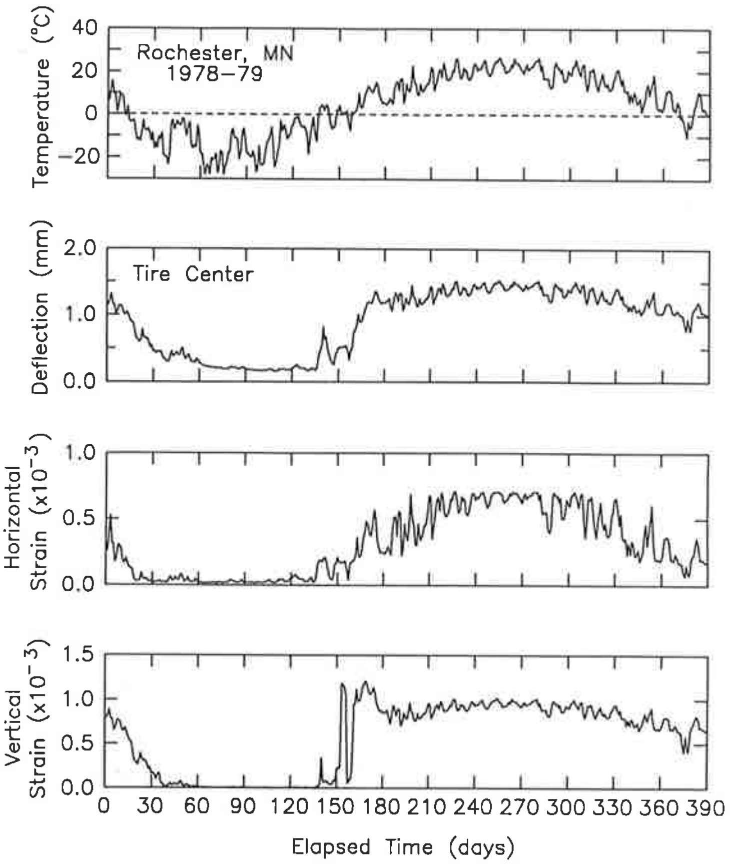

FIGURE 12 Engineering properties calculated by JULEA: surface deflections and strains at base of pavement and top of subgrade with four-layer pavement structure, Rochester.

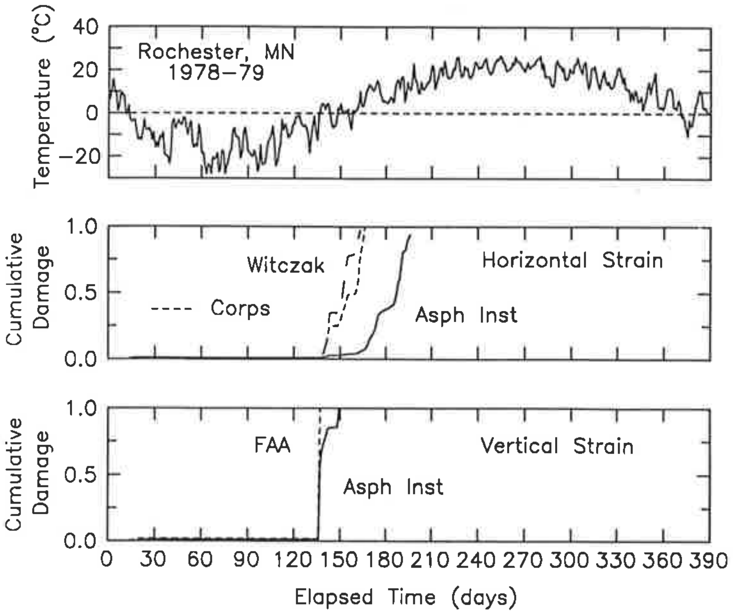

FIGURE 13 Cumulative damage through time during design year at Rochester: two-layer pavement structure.

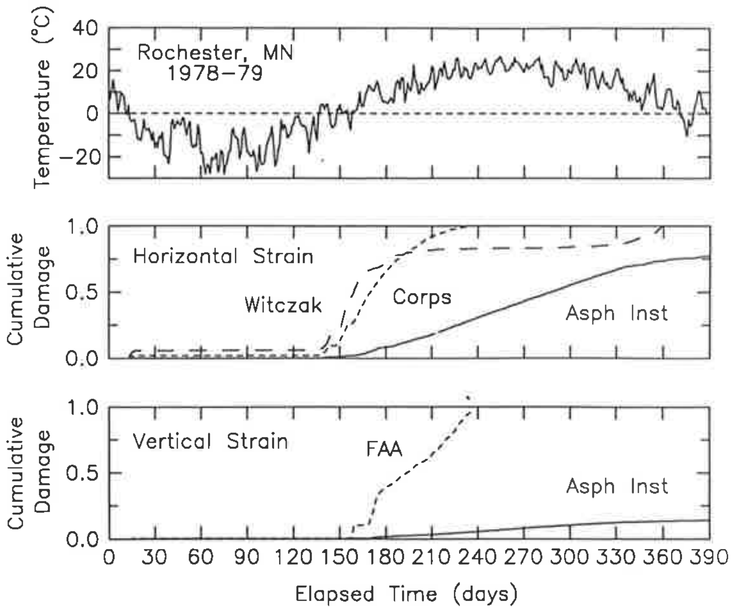

FIGURE 14 **Cumulative damage through time during design year at Rochester: three-layer pavement structure.**

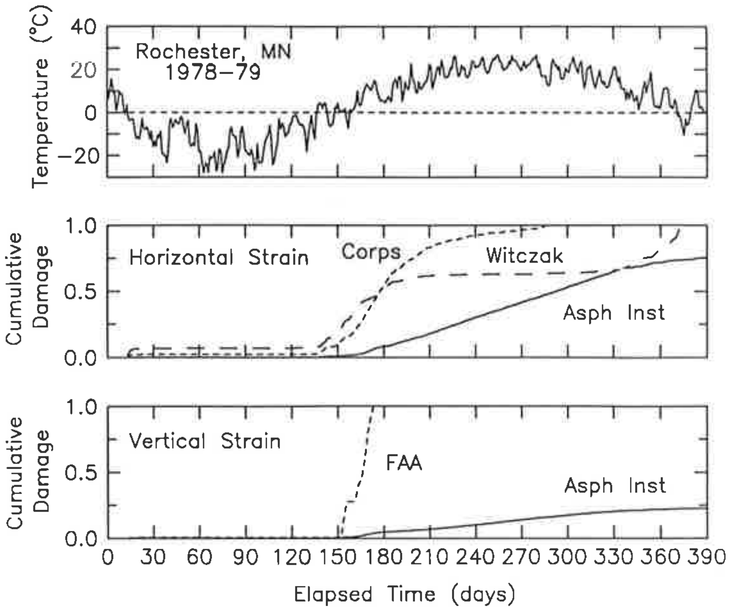

FIGURE 15 **Cumulative damage through time during design year at Rochester: four-layer pavement structure.**

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