Layer Moduli Determination During Freeze-Thaw Periods

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In seasonal frost areas, a frozen pavement structure undergoes a complex change in its ability to support traffic as the subgrade and base thaw. In an attempt to quantify this change, several test sections of various cross sections were built in the Frost Effects Research Facility at the Cold Regions Research and Engineering Laboratory. These test sections were subjected to freeze-thaw cycles, and changes in their structural capacity were monitored. The performance of only one of these, TS1, is discussed. The structural capacity during the thaw cycles was characterized nondestructively using a falling weight deflectometer (FWD). Other measurements, such as frost and thaw depths, were obtained from subsurface temperature and resistivity gauges. The Corps of Engineers computer program WESDEF was used to backcalculate layer moduli from the FWD data. On the basis of temperature and resistivity gauge measurements, the pavement layers were appropriately subdivided to reflect the thawed and frozen layers. The backcalculated moduli were used to calculate the horizontal strains at the bottom of the asphalt concrete layer and the vertical strain at the top of the subgrade. These results were compared with those of similar strains obtained when the thawed and frozen layers were combined into a single composite layer. It was found that the thicknesses of the frozen and thawed layers were critical in backcalculating layer moduli and damage to pavement structures. Larger errors were introduced between measured and theoretical deflection basins when the frozen and thawed layers were considered as a single composite layer. The horizontal strains at the bottom of the asphalt layer were not greatly affected by ignoring the thawed layer. The damage to pavements with respect to vertical strains was grossly underestimated when the thawed and frozen layers were not considered separately.

Surface deflections obtained with a falling weight deflectometer (FWD) are now routinely used in evaluating the load-bearing capacity of highway and airport pavements. It has become an integral part of many "remaining life" and overlay design procedures. The modulus of the various layers are "backed out" using the measured FWD deflections and theory of elasticity. This procedure of backing out the layer moduli is referred to as backcalculation. Current backcalculation procedures are characterized in one of the following groups: (a) multilayered (e.g., WESDEF, MODCOMP3, EVERCALC, ELSDEF, and MODULUS) and (b) equivalent thickness (e.g., ELMOD, SEARCH, and BOUSDEF). The pavement materials in most of the models are characterized as linear elastic, although it is generally recognized that most materials in a pavement system do not behave in this fashion.

In this study, the pavement structure was divided into multilayers. The materials in these layers were then characterized by two elastic constants: the layer stiffness (E_i) and Poisson's ratio (υ_i). The idealization is shown in Figure 1. The backcalculation procedure officially used by the U.S. Army Corps of Engineers is WESDEF. The maximum number of layers that can be modeled by WESDEF is five, with the fifth layer automatically set as a rigid layer. Best backcalculated moduli results are obtained if the number of unknown layers is limited to three. WESDEF uses the WESLEA layered elastic programs for calculating stresses and strains and deflections in the pavement system. WESLEA was developed by Van Cauwelaert et al. (*1*) for the U.S. Army Corps of Engineers.

The backcalculation of the various layer moduli is an iterative procedure. The solution from WESDEF is a set of layer moduli (E_i) values that will minimize the error between the measured and computed surface deflections. WESDEF is terminated when the absolute sum of the errors between the measured and calculated deflections is less than 10 percent or when the change in modulus is within the specified tolerance of 10 percent. This limit was developed by the Waterways Experiment Station (WES) on the basis of their experience with the 71-kN Road Rater. The Road Rater measured only four deflections, and it was judged that if the individual deflection error was less than 2.5 percent, the computed deflection basin was good. We used this 2.5 percent error for all the seven FWD sensors. Our criterion for a good fit was when the absolute sum of the errors was $\leq$ 17.5 percent. Past experience by WES found that the best fits between measured and calculated deflections were obtained when an artificial rigid layer was placed at a depth of 9.5 m from the surface. In WESDEF, the location of the rigid layer can be changed by the user.

WESDEF has been used quite successfully in nonfrost areas, where the number of layers in a pavement structure remains

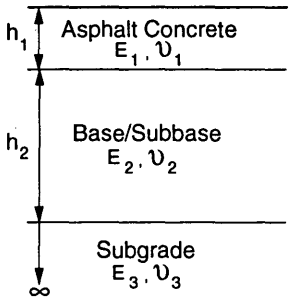

FIGURE 1 Idealization of pavement structure in backcalculation analysis.

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fairly constant throughout the year. The pavement structures in these areas could be idealized as three and, at most, four layers without much loss of accuracy in the results. The situation is much more complex in seasonal frost areas where pavement structures are subjected to freezing and thawing. During thaw, the pavement foundation can become saturated with water from the thawing ice lenses, thus creating weak layers in the base or subgrade. It is possible that a subgrade modeled as a single layer before freeze-thaw needs to be subdivided into three layers or more during thaw. Figure 2 shows the annual possible changes in a pavement structure in a seasonal frost area. Most of the pavement damage in seasonal frost areas occurs during the winter or the spring thaw. The failure will manifest itself on the surface in the form of cracking or rutting (caused by deformation in the base or subgrade). The period and severity of thaw weakening varies, depending on the soil type, degree of saturation, drainage conditions and pavement surface temperatures. Therefore, it is important that any backcalculation procedure used for modeling pavement behavior in seasonal frost areas has the flexibility to manage the complex layer changes.

The backcalculation procedure, being iterative, leads to a number of combinations of layer moduli producing the same deflection basin. Therefore, the user must have a reasonable idea of the modulus of the various layers. Other critical information required for backcalculation are layer material and thicknesses. Therefore, even though the FWD test is advertised as nondestructive, a carefully planned boring program should be a standard part of FWD testing. The results from the boring program should include (a) layer thicknesses; (b) material samples for resilient modulus testing; and (c) location of rigid layers, if any.

As part of the development of a design-evaluation method for pavements in cold regions, several test sections were built in the Frost Effects Research Facility (FERF) at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and subjected to freeze-thaw cycles. During the thawing period, deflection measurements were conducted every day with an FWD. The use of FWD deflection data to characterize the thaw weakening of pavements in seasonal frost areas has been previously presented (*2–5*). The deflection measurements obtained during the first and second thaw period were also used to mechanistically characterize (i.e., in terms of layer moduli and strains) the effect of the thawed layer on pavement performance.

Initially we had planned to backcalculate the layer moduli from all the test sections. The test sections ranged from full depth to conventional pavements. Preliminary results showed large errors in the backcalculated moduli during the thaw period. This was especially true for the conventional pavement cross sections. We decided to use a simple full-depth pavement structure to study how WESDEF, or for that matter any of the other backcalculation procedures (multilayered), would work with thawed and frozen layers.

DESCRIPTION OF TEST SECTION

A test section (TS-1) was constructed in FERF; information on FERF can be found in Janoo and Berg (*2*) and Eaton (*6*). A detailed description of the test section can be found in Janoo and Berg (*2*). The test section was 610 cm^2 and 160 cm deep with full-depth asphalt concrete pavements. TS-1 consisted of 15 cm of asphalt concrete over 145 cm of compacted clay soil. The natural foundation under TS-1 was a fine sand (SM) subgrade. Information from drill logs showed no rigid layers to a depth of approximately 20 m.

The compacted clay soil was classified as an inorganic clay of high plasticity (CH) using the Unified Soil Classification System. On the basis of grain size analysis and Atterberg limits, the clay was classified as an F3 soil with respect to frost susceptibility. The compacted clay soil California bearing ratio (CBR) values ranged from 18 percent to 27 percent.

The test section was instrumented with thermocouples, CRREL resistivity gauges and psychrometers. A detailed description of the instrumentation can be found in Janoo and Berg (*2*). Frost and thaw locations were determined from the position of the 0°C isotherm. Frost penetration depths were also determined using the CRREL electrical resistivity gauges. These gauges were especially useful in locating thaw depths when the subsurface temperatures became nearly isothermal at 0.0°C.

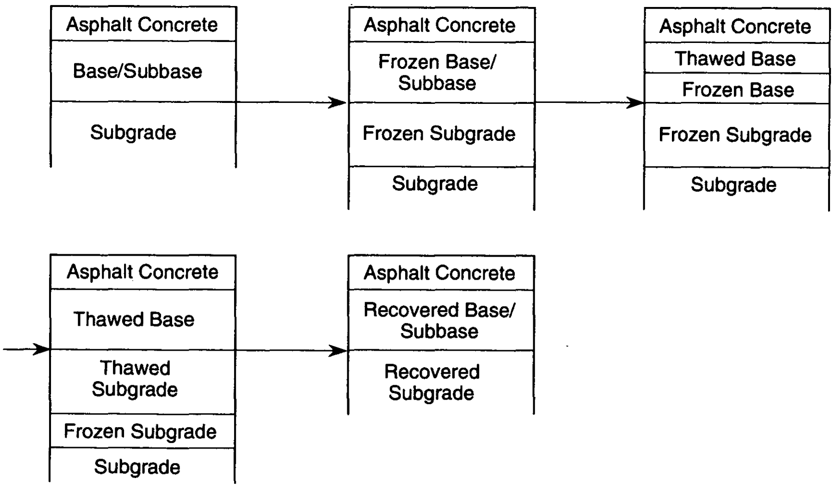

FIGURE 2 Change in pavement structure during freeze-thaw cycling.

TESTING PROGRAM

The test section was frozen from the top down by placing cooling panels on the surface of the pavements. The 0°C isotherms in the test section during the first and second freeze-thaw cycle are presented in Figure 3. The temperature measurements were taken at a single point and were assumed to be representative throughout the respective test sections. The test section was frozen to a depth of 122 cm for the first cycle and 152 cm for the second cycle. Thawing of the test section was done by removing the cooling panels, and the pavement sections were heated by the ambient FERF temperature.

Surface deflection measurements were taken once a day during the thaw periods using a Dynatest 8000 falling weight deflectometer. FWD measurements were taken at four locations on the test section. These locations are illustrated in Figure 4. The FWD measurements were conducted using a 30-cm-diameter plate. The geophones were located at 0, 17.5, 30, 70, 110, 150, and 245 cm from the center of the loading plate. The tests were conducted using four load levels, which ranged from 20 to 67 kN.

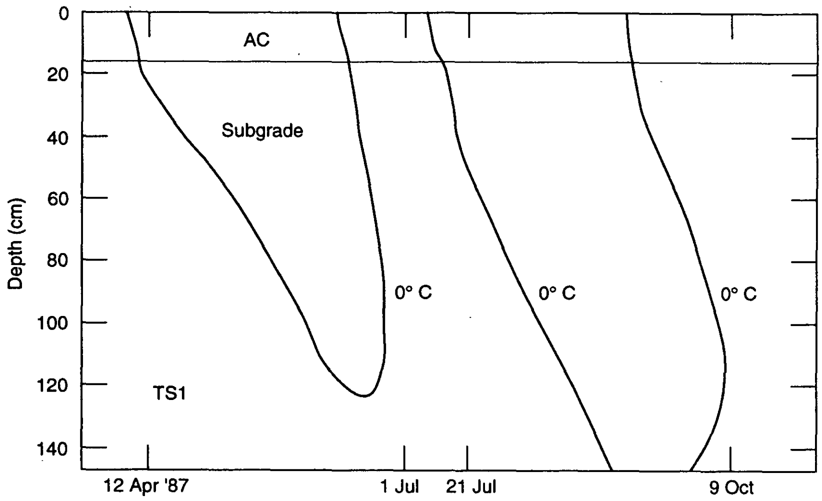

FIGURE 3 Zero degree isotherm in test section.

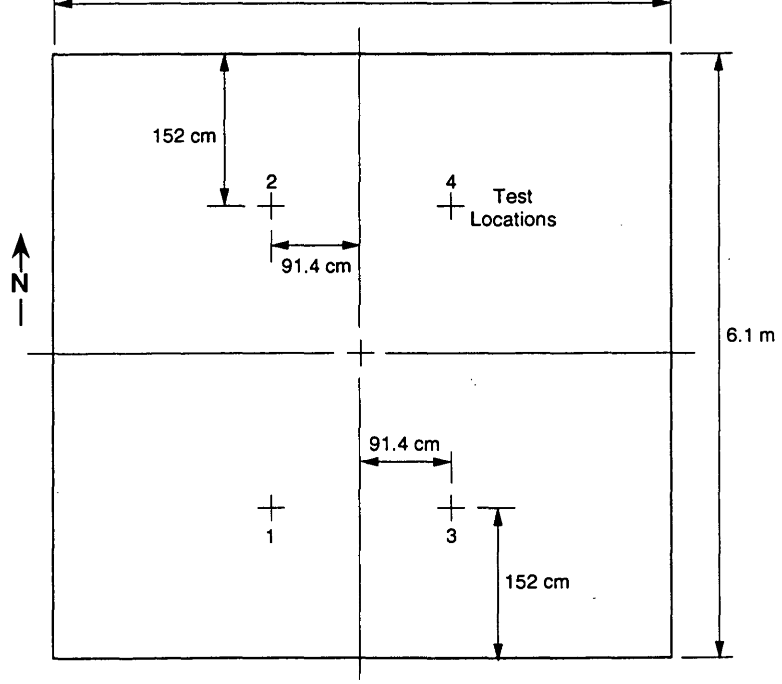

FIGURE 4 Typical FWD location points in test sections.

BACKCALCULATION OF LAYER MODULI

The layer moduli were backcalculated from a normalized 40-kN deflection basin at the four locations in the test section (Figure 4). The normalization was done by plotting the load-deflection data from the first three load levels and applying a linear regression to the data. The representative deflection basin for each test section was obtained using BASIN and the normalized deflection basins from the four FWD points. BASIN, a computer program developed at WES, averages the deflections at each sensor location for a given load level and calculates an average deflection basin area. It then chooses a measured deflection basin that is closest to the averaged basin deflections and area as the representative basin.

Before the application of the first freeze-thaw cycle, FWD measurements were conducted on the newly constructed test sections. The following are seed moduli and Poisson's ratios used in WESDEF for the various layers:

Material Type	*Elastic Modulus (MPa)*	*Poisson's Ratio*
Asphalt concrete	2413.25	0.35
Clay subgrade	03.43	0.40
Natural sand subgrade	206.85	0.40

These were the suggested values in WESDEF. This feature of suggested modulus values of the various pavement materials and their possible range is a useful tool for the new user.

In the initial attempt, prior to freezing, TS-1 was idealized as a three-layer system. The layers were the asphalt concrete (AC) layer (15 cm), the compacted clay layer (145 cm), and an infinite sandy subgrade. The backcalculated values were as follows: AC, 3,292 ± 127 MPa; clay, 140 ± 17 MPa; sand, 114 ± 23 MPa. The mean absolute error was 18.63 ± 11.8, which was greater than the 17.5 percent desired. In the second attempt, the clay layer was divided into two layers. The top and bottom layers were 74 and 71 cm thick. The backcalculated values were as follows: AC, 3,445 ± 540 MPa; top clay, 132 ± 40 MPa; bottom clay, 159 ± 14 MPa; and sand, 110 ± 20 MPa. The mean absolute error was 9.53 ± 6 percent, which was well within the specified requirement of 17.5 percent. Although the error was reduced by half, the changes in the mean modulus were only 5 percent and 3 percent, respectively, for the AC and the sand subgrade. The average of the two-clay layer moduli (145 MPa) was similar to the value of the single clay layer modulus calculated when the system was modeled as a three-layer system. With respect to the calculated strains using either the three- or four-layer system, the difference in the vertical strain at top of the subgrade was approximately 0.3 percent and less for the horizontal strain at the bottom of the AC layer. Because WESDEF is able to accommodate only up to four layers, the mean of the composite clay moduli was used as the baseline. The following are the moduli that were used as the prefrozen (baseline) moduli in TS-1:

Material	*Modulus (MPa)*
Asphalt concrete	3,445 ± 540
Unfrozen clay	145 ± 50
Sand subgrade	110 ± 20

The backcalculated modulus of the natural sand subgrade was found to be lower than expected. However, since the sand subgrade did not undergo any substantial freeze-thaw cycling, we assumed that the modulus of this layer remained the same throughout the two freeze-thaw cycles. The mean layer moduli for TS-1, in conjunction with NELAPAV (*7*), were used to calculate the horizontal strain at the bottom of the asphalt concrete layer ($Z = -152$ mm) and the vertical strain at top of the clay layer ($Z = -153$ mm) where Z is the depth from the surface. The load level used in calculating the strains was 40 kN. The computed strains were 0.00022 and −0.00067 for the horizontal and vertical strains, respectively. These values were used as reference values during the freeze-thaw cycles.

BACKCALCULATION OF LAYER MODULI DURING THAW PERIODS

We selected several days during the first and second thaw period to backcalculate the layer moduli for two cases. The first case involved backcalculating the layer moduli, if we assumed no knowledge of the thicknesses of the frozen or thawed layers. Basically, the frozen, thawed, and unfrozen layers were lumped as a single layer. The scenario is identified as Case 1 in all future discussions. In the second case, backcalculation of the layer moduli was made with the knowledge of the thicknesses of the frozen and thawed layers (Case 2).

Before conducting the backcalculation of the various layer moduli, a literature review was done to obtain any data on the frozen and thawed moduli of base, subbase, subgrade, and asphalt concrete. The results of the review for the base, subbase, and subgrade materials are tabulated in Table 1. These moduli values were used as a guide for selecting the seed modulus for the frozen and thawed clay layer. The data presented in Table 1 are from laboratory resilient modulus tests (*8–13*), with the exception of data furnished by Stubstad and Connors (*12*). The modulus values for frozen soils generally increase with decreasing temperatures. The lowest values are at about −2°C and the highest are at a temperature of about −8°C. Because the lowest resilient modulus values in the table are for temperatures about −2°C, values lower than those shown here are expected to be closer to 0°C.

Resilient modulus values for thawed materials generally increase with decreasing moisture content. The lowest values are near saturation and the highest values in the table are in the range of 50 percent to 80 percent of saturation. It was not possible to conduct laboratory resilient modulus tests on some of the fine-grained soils immediately after thawing because they were unstable. Therefore, the lowest values in the table are not the lowest that these materials may exhibit.

Modulus values in the thawed state are also generally stress dependent. Values for fine-grained materials usually decrease with increasing stress but granular materials generally increase with increasing stress. Modulus values for all materials generally increase with increasing density.

The asphalt concrete modulus can be estimated using the Asphalt Institute (AI) equation

$$\log E = 5.553833 + 0.028829\frac{P_{200}}{f^{0.17033}} - 0.03476(V_v) + 0.07037(n_{70^\circ\mathrm{F},10^6}) + 0.000005(t_p^{(1.3 + 0.49825\log f)}P_{ac}^{0.5}) - 0.00189\left(t_p^{(1.3 + 0.49825\log f)}\frac{P_{ac}^{0.5}}{f^{1.1}}\right) + 0.931757\frac{1}{f^{0.02774}}$$

TABLE 1 **Frozen and Thawed Resilient Modulus Values for Pavement Materials**

Material	USCS Classification	Resilient Modulus	
		Frozen (MPa)	Thawed (MPa)
Winchendon, MA dense graded stone	GM-GP	930 - 56,390	
Albany County Airport TW A, subbase	GW-GM	100 - 34,970	34 - 272
Albany County Airport TW B, subbase	GW-GM	1,520 - 19,280	55 - 366
Minnesota Test Road Class 6 base	GW		74 - 972
Minnesota Test Road Class 3 subbase	SW	1,448 - 46,098	25 - 5,433
Albany County Airport TW A, base course	SW-SM	340 - 24,100	43 - 259
Winchendon, MA Graves sand	SM	650 - 20,590	21 - 158
Winchendon, MA Hart Bros. sand	SM	650 - 20,590	21 - 396
Winchendon, MA Hyannis sand	SM	1,300 - 56,840	27 - 141
Albany County Airport TW A, subgrade	SM		41 - 209
Albany County Airport TW B, subgrade	SM	180 - 39,430	41 - 192
Albany County Airport TW B, subgrade never frozen	SM		42 - 240
Winchendon, MA Ikalanian sand	SM-SP	660 - 22,750	8 - 282
Winchendon, MA Sibley till	SM-SC	1,050 - 45,590	31 - 164
Minnesota Test Road 1206 Subgrade	CL	924 - 10,928	6 - 1,455
Ft. Edward, NY Ft. Edward clay	CL-CH	450 - 6,220	7 - 149
Base Course			(13) 20,685 (12) 1,034
Subbase			(13) 20,685 (12) 1,034
Subgrade			(13) 3,448 (12) 1,034

where

E = dynamic modulus of asphalt concrete,
P_{200} = percent aggregate passing Number 200 sieve,
f = frequency,
V_v = percent air voids,
$h_{70^\circ F,10^6}$ = absolute viscosity at 70°F (poise × 10^6),
P_{ac} = asphalt content (percent by weight of mix), and
t_p = midpavement temperature (°F).

The following assumptions were used in calculating the modulus of the AC using the preceding equation:

P_{200} = 5 percent,
V_v = 4 percent (the acceptable range was 3 to 5 percent),
$\eta_{70^\circ F,10^6}$ = 2.5-AC 20 asphalt (*14*), and
P_{ac} = 6 percent (the acceptable range was 5 to 7.5 percent).

The frequency (f) used was 20 Hz, which is commonly assigned to FWD loading. Temperature measurements were taken at 5, 10, and 15 cm from the surface of the AC layer. The midpoint temperature was interpolated linearly between the three temperature measurements.

To reiterate, Case 1 is the three-layer system. WESDEF was used to backcalculate the modulus of the asphalt concrete, composite (thawed and frozen and unfrozen) clay and the sand subgrade layers. When the frozen and thawed layers were accounted for in Case 2, there were different structures in the first and second thaw cycles. At the end of the first freeze cycle, the frost front was located at a depth of 122 cm from the asphalt concrete surface. Thaw was basically downward. The pavement structure was divided into five layers. The structure consisted of an asphalt concrete layer, a variable thickness thawed lawyer (h_t), a variable thickness frozen layer (h_f), an unfrozen clay layer (h_{uf}), and the infinite sand subgrade (Figure 5*a*). At the end of the second freeze cycle, the frost depth was down to 152 cm from the asphalt concrete surface. In the early stages of the second thaw cycle, the pavement structure was idealized as that shown in Figure 5*b*. The structure consisted of an asphalt concrete layer, a variable thickness of the thawed (h_t) and frozen layers (h_f), and the sand subgrade. Partially through the second thaw cycle, thawing of the pavement structure was occurring simultaneously from the top and bottom. This pavement structure is shown in Figure 5*c*.

The idealized pavement structures used in WESDEF are shown in Figure 6. In the first thaw cycle (Case 1), the structure shown in Figure 5*a* was modeled by the structure shown in Figure 6*a*. Because of the limitation of four layers in WESDEF, it became necessary to combine the unfrozen clay layer with the sand subgrade. The modulus of this composite (clay/sand subgrade) layer was fixed at an average of the two-layer moduli of 128 MPa. In the early stages of the second thaw cycle, the pavement structure shown in Figure 5*b* was idealized by the structure in Figure 6*b*. The modulus of the layer below the frozen layer (sand subgrade) was fixed at 110 MPa. For the late stages of the second thaw cycle, the limitation of four layers in WESDEF meant that the thawing layer below the frozen layer could not be included in the idealization. It was idealized by the structure shown in Figure 6*c*.

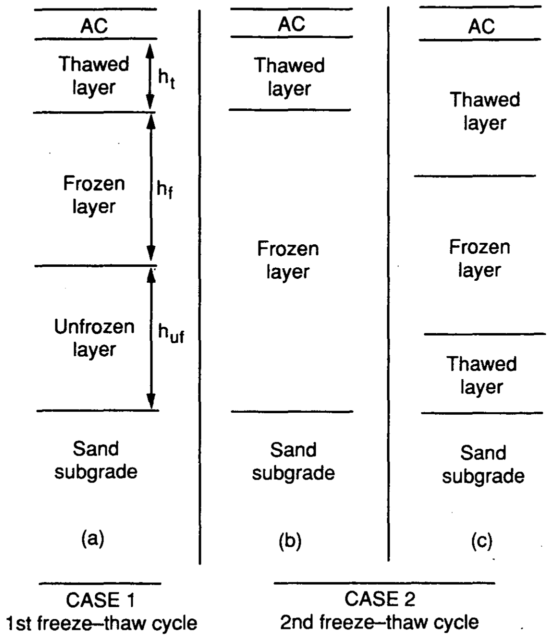

FIGURE 5 Actual pavement structures in TS-1 during thaw cycles.

The results from the backcalculation follow. Every attempt was made to minimize the error between the measured and calculated deflections. The absolute arithmetic (AA) errors in the backcalculation of the layer moduli for both cases are shown in Figure 7. The AA errors for most of the days are larger in the first case than in the second. The error was reduced when the thawed and frozen layers were separated. It was found that the largest deflection errors occurred at the sixth and seventh sensors in Case 2, probably because of the constant values assigned to the composite subgrade in the later stages of thawing. However, in both cases, with an exception of a few days, the AA error exceeded our criterion of 17.5 percent. The data in Figure 7 show the best fit between measured and calculated deflection basins that were attainable with WESDEF.

An attempt was made to isolate the source of the large errors in Case 1 (Figure 7). It was found that the backcalculated sand subgrade modulus in Case 1 was similar to its mean prefrozen value. This value gives confidence to our assumption that the modulus of this layer remains constant during the thaw cycles. The backcalculated modulus of the sand subgrade for the two thaw cycles is shown in Figure 8. We found that most of the values were within one standard deviation of its mean prefrozen value, which suggests that the errors are in the upper layers; it also reinforces the need to separate the frozen and thawed layers in the backcalculation process.

The backcalculated asphalt concrete moduli for both cycles with respect to midpavement temperatures are shown in Figure 9. For comparison, the modulus values obtained from AI (*14*) are also shown in the same figure. The backcalculated AC moduli from both cases were consistently lower than the AI predicted modulus. The exception to this is at low temperatures. Also the backcalculated AC modulus appears to

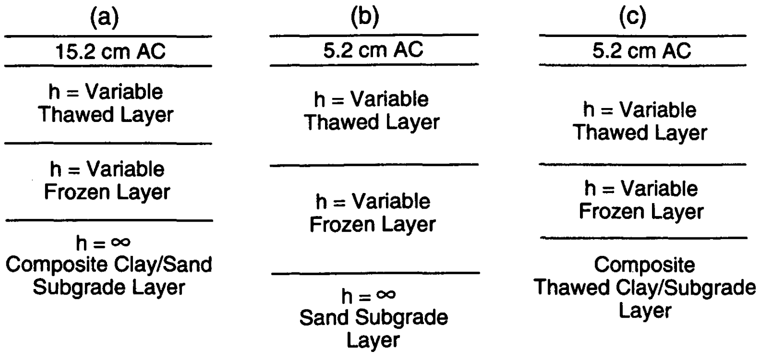

FIGURE 6 Idealized pavement structure used in WESDEF.

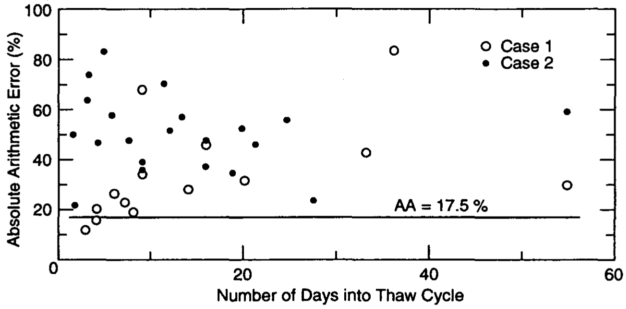

FIGURE 7 Absolute arithmetic error distribution in backcalculation of layer moduli during thaw periods.

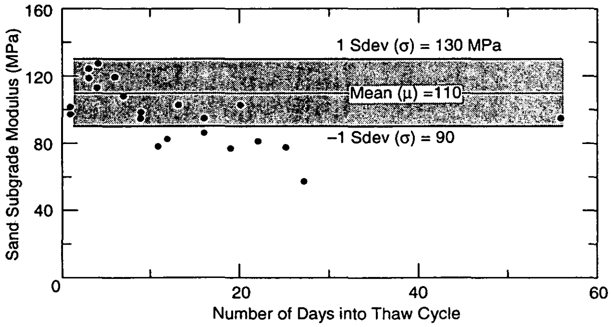

FIGURE 8 Variation of sand subgrade modulus in both thaw cycles.

be unaffected by how the pavement system was modeled. Therefore, we can conclude that the larger errors in Case 1 result from the lumping of the frozen and thawed layers as one single layer. Attempts to fix the asphalt concrete modulus in WESDEF for both thaw cycles for both cases with the predicted AI modulus only increased further the AA error. A regression equation ($r = 0.54$) was developed for the AC modulus in seasonal frost areas (Figure 9*c*):

$$ACMOD = 5{,}944 - 242(T_P)$$

where $ACMOD$ is the AC modulus in megapascals and T_p is the midpavement temperature (°C). This regression can be

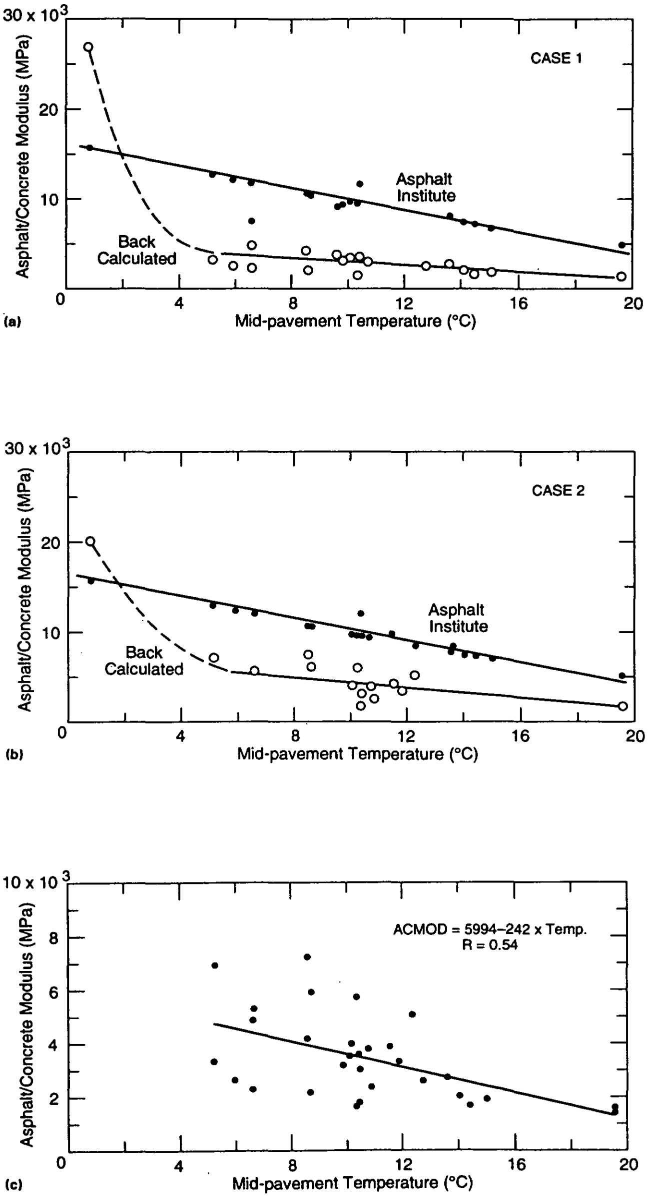

FIGURE 9 Variation of asphalt concrete modulus in both thaw cycles.

used as a guide for selecting asphalt concrete moduli in seasonal frost areas.

Several interesting trends were noticed between the clay layer modulus for the two cases. For discussion purposes, the composite clay modulus in Case 1 is designated as E_c, and the thawed clay layer modulus in Case 2 as E_t. In Figure 10, Case 1 is identified as composite and Case 2 as thawed layer. It becomes apparent in Figure 10 that as soon as thawing of the subgrade commences $E_t \ll E_c$. The difference is approximately 96 percent when $E_t \approx 10$ MPa; this compares with $E_c \approx 280$ MPa at the beginning of thaw (76-mm-thick thawed layer). At the same time, with respect to its prefrozen strength, E_c was about two times greater, and E_t was approximately a quarter of its prefrozen strength. E_c decreases rapidly to a thaw depth of 800 mm from the top of the clay layer, after which it starts to increase (Figure 10). E_t shows a gradual increase with thaw depth. E_c and E_t have approximately the same value when the thaw depth is greater than 1 m ($\approx$80 MPa). However, this value is still less than the prefrozen value of 145 MPa.

The effect of neglecting the thawed layer (Case 1) on pavement performance can be shown by the calculated horizontal and vertical strains at the bottom of the asphalt concrete and at the top of the clay layer, respectively. The horizontal and vertical strains were calculated using NELAPAV (linear). The horizontal strains were calculated at a depth of 152 mm and the vertical strain at 153 mm depth from the surface. The horizontal strains were also calculated with Jung's (*15*) method of using the center and first FWD deflection measurements. The horizontal strain (H_s) is calculated from

$$H_s = \frac{h(d_0 - d_1)}{r^2}$$

where

H_S = horizontal strain at the bottom of the asphaltic layer,
h = thickness of asphalt concrete layer (mm),
d_0 = surface deflection under center of load (mm),
d_1 = surface deflection at edge of plate (mm), and
r = radius of loaded plate (mm).

Jung found that the horizontal strains obtained from this equation compared well with those calculated using linear elasticity. The horizontal strains with respect to thaw depth for both freeze-thaw cycles are shown in Figure 11. Also shown in this figure are the horizontal strains calculated from Jung's equation. The horizontal strains calculated from Jung's method were higher than those from NELAPAV. Similar results were reported by Jung (*15*) for non-frost conditions. However, this equation can be used to estimate reasonably well the horizontal strains. Because it is larger than those

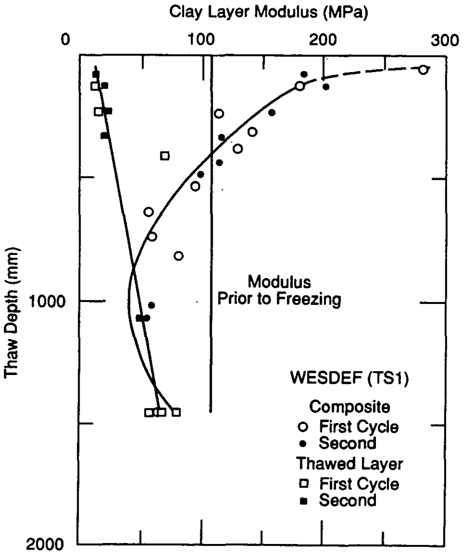

FIGURE 10 Change in clay layer modulus with thaw depth for both cycles.

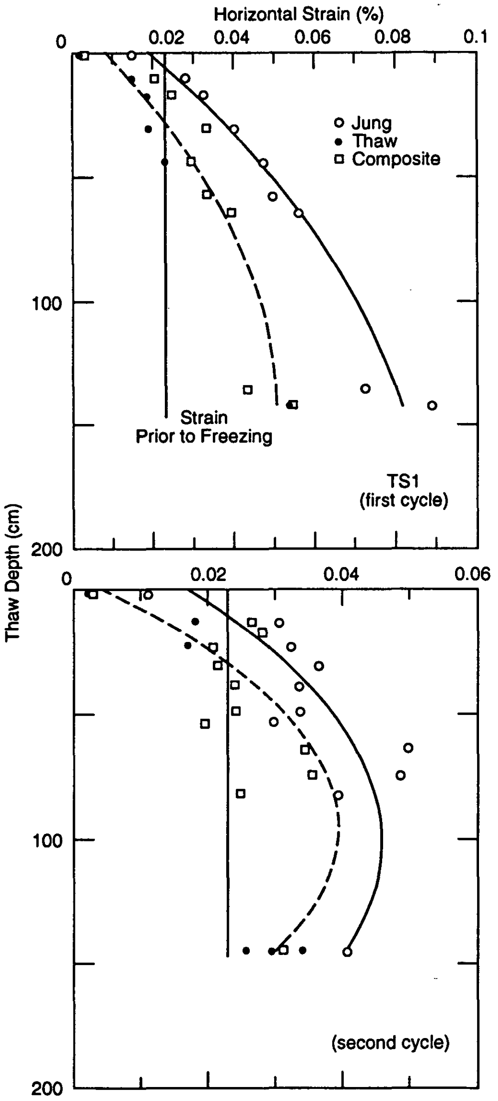

FIGURE 11 Change in horizontal strain with thaw depth for both cycles.

calculated from layer elastic theory, the damage calculated from these strains will be larger and therefore conservative. The calculated strains were as high as 1.5 times their prefrozen values during thaw. Another interesting observation in the horizontal strains in Figure 11 is the negligible difference between the two cases. This suggests that the condition of the subgrade has only a small effect on the horizontal strain at the bottom of the AC layer, 0.00022 and −0.00067 for Cases 1 and 2.

The calculated vertical strains with thaw depth for Case 1 (ε_{vc}) and Case 2 (ε_{vt}) for the two cycles are shown in Figure 12. At the beginning of thaw, there was a dramatic increase in (ε_{vt}). It was found to be about four times larger than ε_{vc}. With respect to its prefrozen value, ε_{vt} was approximately 3.5 times larger at the beginning of the thaw period. With time, as thaw progressed downward, ε_{vc} increased rapidly, whereas after the initial rapid increase, ε_{vt} started to recover. This was substantiated later during trafficking of the test sections, when the change in rut depth with traffic was large soon after the beginning of loading. At a depth of about 1 m, the strains ε_{vc} and ε_{vt} become the same.

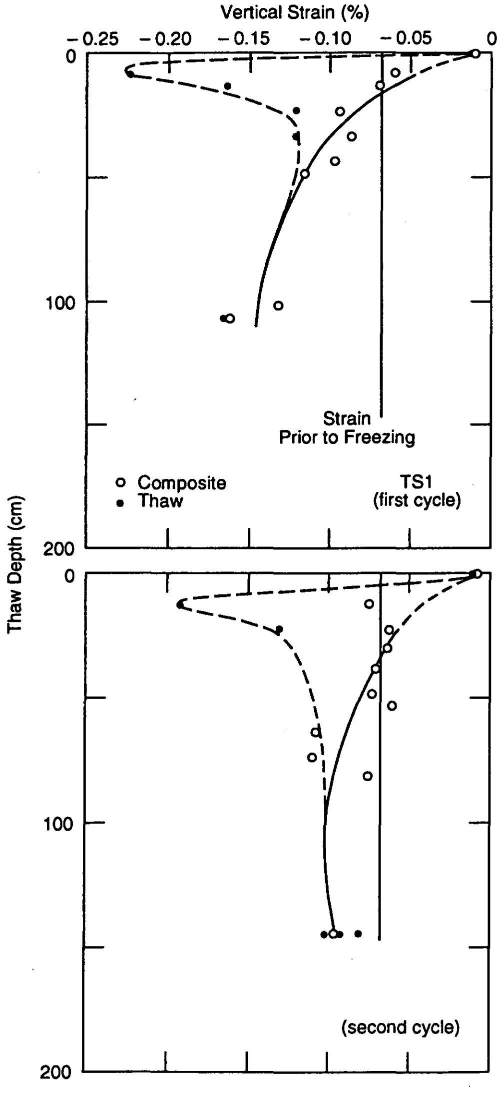

FIGURE 12 Variation of the vertical strain with thaw depth for both cycles.

CONCLUSIONS

From the results of this study, the following conclusions can be drawn regarding the effect of the frozen and thawed layers when backcalculating pavement layer moduli from FWD data:

1. The study showed that the thicknesses of the frozen and thawed layers are critical in backcalculating layer moduli and damage to pavement structures.
2. Larger errors are introduced between measured and theoretical deflection basins when the frozen and thawed layers are considered as a single composite layer. The errors can be attributed to the frozen and thawed layers being lumped together as one layer. These errors were reduced when the thawed and frozen layers were considered as separate layers. However, there were times, even when the deflections were within a specified tolerance, that the backcalculated moduli were unreasonably low or high. At other times, the backcalculated moduli of the thawed and frozen layers were inverse to what was expected. It was also found that it is possible to reduce the AA error by 50 percent and not change the horizontal or vertical strains significantly.
3. The backcalculated asphalt concrete modulus was lower than that predicted by the Asphalt Institute empirical equation. A regression equation was developed to help in selecting seed moduli in seasonal frost areas. It was also found that the asphalt modulus was independent of the modeled support.
4. The horizontal strains at the bottom of the asphalt layer were not greatly affected by ignoring the thawed layer. The horizontal strains as calculated by the Jung method using FWD deflections directly showed a trend similar to that calculated from layer elasticity during thaw periods. The strains from the Jung method were found to be slightly high but will produce conservative results.
5. The damage to pavements with respect to vertical strains was grossly underestimated when the thawed and frozen layers were not considered separately. The difference in the calculated vertical strain could vary by a factor of 4.
6. Finally, the backcalculated moduli for the two cases are the product of the mathematical linear elastic model used and may not truly represent the actual field conditions. Partial verification has been done, but additional research is needed to verify the reductions in the moduli and strains seen in this study during thaw periods in the field.

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