SETTING HIGHWAY LOAD LIMITS:
A New Technique

by Richard N. Stubstad and Billy Connor

INTRODUCTION

In interior Alaska, asphalt-surfaced pavements are typically frozen more than 10 feet deep for some five months of the year. The thawing process can be relatively long, lasting weeks or even months. In areas with these freeze-thaw conditions, it is important to determine the structural integrity of flexible pavements during the "thaw weakening" period which generally occurs between initiation of thaw in upper pavement layers and the time the thaw has progressed 5–10 feet deep.

It has been generally concluded that no significant load-associated pavement deterioration takes place when pavements are frozen. Indeed, deflection measurements taken on pavements in a completely frozen state show very minute deflections.

Traditionally, pavement deflections have been monitored in Alaska during the "spring thaw." Load restrictions were applied when Benkelman Beam measurements indicated a significant increase in deflection and continuing until after the deflections reached their peak value. It was strongly felt, however, that a more accurate method of assessing the need for load restrictions should be sought, since each day of load limits on Alaska state roads is costly for the trucking industry (approximately $140,000 per day in 1980). It was therefore important to find a non-destructive test method which would more accurately pinpoint: a) whether a given section of roadway is, in fact, weakened during periods of thawing; b) if so, during what period load limits are necessary; and c) the level of load restriction required.

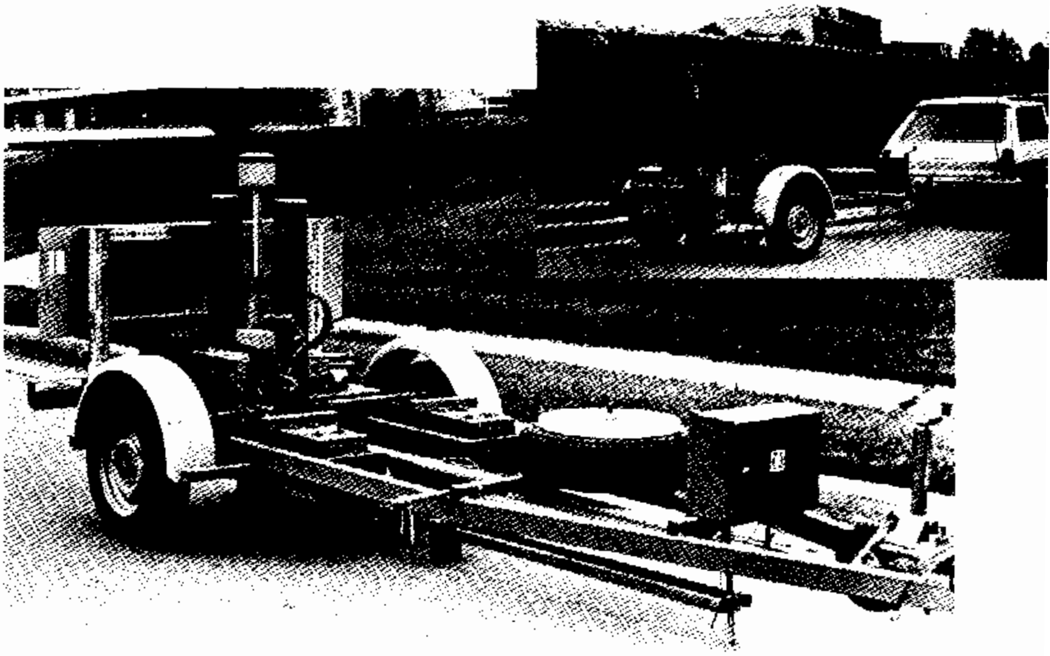

Figure 1. Falling Weight Deflectometer.

THE FWD METHOD

A method was developed using the Dynatest Model 8000 Falling Weight Deflectometer (FWD) Test System which can ascertain the extent of structural weakening of the pavement system for any thaw depth from a few inches to over ten feet.

The Alaska Department of Transportation and Public Facilities Research Section has recently purchased a Falling Weight Deflectometer to inventory the structural strength of Alaskan roadways (Fig. 1). The FWD simulates the load imposed on the roadway by a moving truck by dropping weight on the surface with a force of 9000 pounds. The force can be increased to 27,000 pounds so that aircraft landing loads can also be simulated. The deflection or bending of the roadway is measured and reported in much the same manner as the well-known Benkelman Beam Technique. However, the FWD also measures pavement

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movements at five points at various distances away from the point of loading, providing much more information about soil strengths at various depths.

With the FWD, one person can make approximately 200 measurements in a day. While the Benkelman Beam test method allows approximately the same production rate, it requires three or four people, a dump truck and another vehicle. The operating cost for the FWD is approximately 25% of that for the Benkelman Beam.

The new method involves collecting FWD data and processing this data through a computer program called "FROST." The program uses the load and the deflection basin shape measured at each test point with the FWD to ascertain:

1) the approximate thaw depth;

2) the "corrected" center deflection for a 9000-pound equivalent wheel load, had there been no frozen materials in the pavement structure, adjusted to a surface temperature of 70°F; and

3) a "damage indicator," corresponding to the approximate resilient vertical strain in the granular base material, under the design 9000-pound load.

The latter "damage indicator" was used in the FROST program since, in Alaska, roadways are usually surfaced with a thin asphalt layer. Fatigue cracking in the asphalt is generally preceded by distress in the weaker unbound materials, in particular the granular base, which may be subject to excessive loads during its thaw-weakened state.

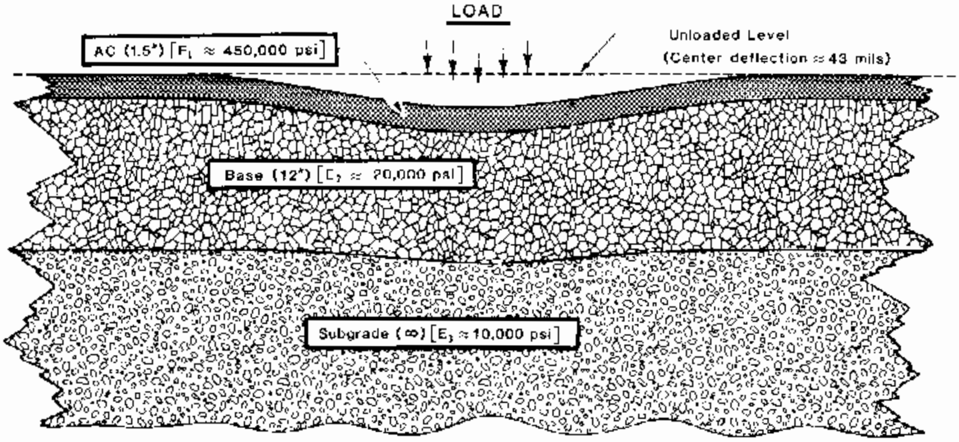

Figure 2A. Schematic representation of an unfrozen asphalt surfaced pavement under a 9000 lb load.

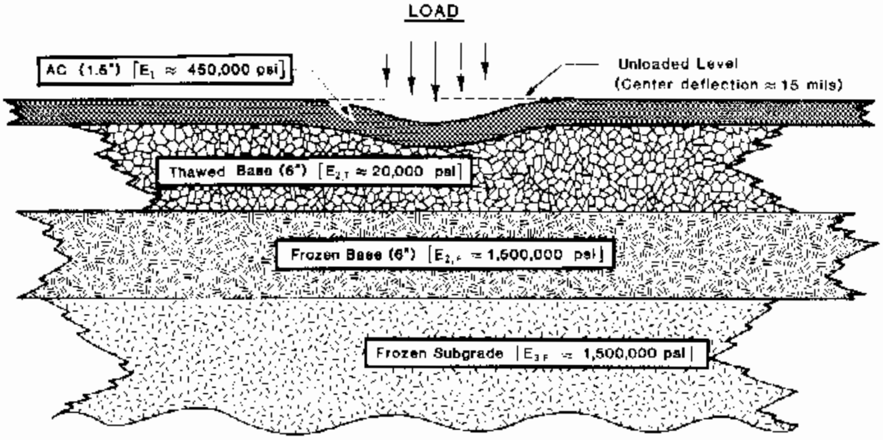

Figure 2B. Schematic representation of a partially frozen asphalt surfaced pavement under a 9000 lb load.

The proposed method allows the engineer to monitor the structural adequacy of the pavement at any time during the spring thaw. Such monitoring is expected to reduce and possibly eliminate, through rehabilitation of problem pavements, the need for the load limits that are so costly to the Alaskan economy.

THAWING PAVEMENT SECTIONS

A pavement section in an unfrozen state is shown in Figure 2A. Under load, the pavement will deflect according to the theory of elasticity with the magnitude of each deflection (from a point directly under the load outwards to a distance of, e.g., 4 feet) being dependent on the elastic properties of the materials in the section.

The deflections measured furthest from the load roughly reflect the condition of the lower layers in the pavement system as depicted in Figure 2A. The center deflection at the pavement surface is the sum of the change in thickness at the base and the deflection at the top of the subbase. The deflection at the surface of the subbase is the sum of the change in thickness and the deflection at the top of the underlying layer. In general, the deflection at the top of each layer is the sum of the change in thickness of that layer and all layers beneath it.[1]

The same pavement section is shown in a partially frozen state in Figure 2B, after the thaw has progressed 6" below the asphalt layer. All other parameters being equal, the center deflection is only about 1/3 of the value of the corresponding unfrozen system center deflection. Nevertheless, a comparative analysis of these two companion pavement sections reveals that the horizontal strain at the underside of the asphalt and the vertical strain at the top of the base are approximately equal. Thus center deflection alone is a poor indicator of the potential for pavement distress.

The asphalt strain, though, is still not critical due to the thin surface involved (approximately 1½"), while the magnitude of vertical strain in the base is around 2600×10^{-6} just below the asphalt-base interface.

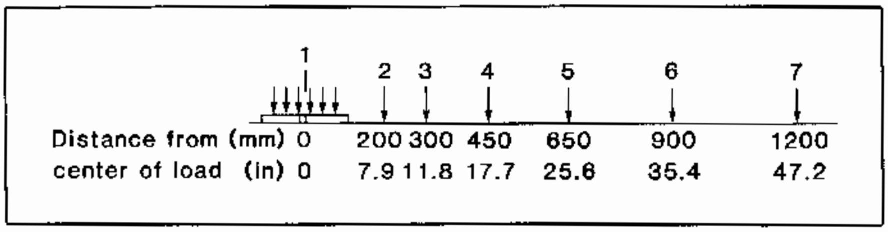

Figure 3.

INTERPRETATION OF FWD LOAD-DEFLECTION DATA

The FWD Configuration

The FWD load-deflection configuration is variable in terms of the load radius, the magnitude of the applied load and the deflection measurement positions. The loading plate is circular, with a hole in its center for measuring the center deflection. The six other available deflection-sensing transducers may be positioned as desired from just outside the loading plate to a distance of some 2.25 meters (approximately 7′) along the raise/lower bar. Due to the relatively thin asphalt-surfaced pavements prevalent in Alaska, it was deemed appropriate to use a relatively close sensor configuration (Fig. 3).

A 300 mm (12″) loading plate is used, corresponding to an equivalent 82 psi, 9000-pound wheel load. Other features of the FWD have been described elsewhere.[2,3]

In accordance with the theoretical effect of frozen materials on the deflection basin as shown in Figure 2B, it was immediately noticed that the same tendency towards virtually no deflection at large distances from the FWD load was occurring during the early spring of 1982. Such a phenomenon can only occur if the underlying layers have a very high stiffness or modulus of elasticity. It was therefore decided to utilize layered elastic theory to ascertain what the effects of thaw depth and other material characteristics would have on the shape of the deflection basin.

Selection of Input Parameters

Since the FWD is non-destructive, only the load and deflections, and perhaps some information of the likely range of layer thicknesses from construction or other records, are available. The following likely range of conditions present in Alaskan roadways were assumed to be appropriate:

Thaw depth (below asphalt):
50 mm–4200 mm (2″–14′)

Thickness of layer 1 (AC):
20 mm–75 mm (¾″–3″)

E-value (stiffness)[1] of layer 1:
3000–6000 MPa (430,000–870,000 psi)

Thickness of layer 2 (granular base):
300 mm (12″)

E-value of layer 2 (thawed portion):
25–450 MPa (3500–65,000 psi)

Thickness of layer 3 (subbase/embankment):
1500 mm (5′)

E-value of layer 3 (thawed portion):
75–150 MPa (11,000–22,000 psi)

Thickness of layer 4 (original soil):
semi-infinite

E-value of layer 4 (thawed portion):
50–100 MPa (7000–15,000 psi)

E-value of all frozen material:
10,000 MPa (1,500,000 psi)

A thaw depth of 4200 mm (14′) was considered the equivalent of thawed or deep permafrost sections since the effect of the modulus of the materials below a depth of 14′ under a 9000-pound load is negligible.

Processing of Input Parameters

Using various combinations within the range of parameters listed above, while eliminating some very unlikely combinations, about 350 computer runs of the Chevron N-Layer program were executed to predict the deflection basin as well as stresses and strains within the embankment. A kind of "solution table" was created, each line consisting of:

1) The specific combination of input parameters associated with the output.

2) The theoretical deflection basin for a 9000-pound FWD-applied load.

3) The vertical strain at the surface of the thawed portion of the granular base.

4) The horizontal strain at the underside of the asphalt-bound surface.

Two examples from the Chevron runs were figuratively shown in Figures 2A and 2B. In Figure 2B, it can clearly be seen how the deflection values rapidly approach zero as the distance from the load increases, for a pavement having a shallow thaw depth. The FWD data gathered in early spring showed precisely the same tendency, so the next step became clear: compare the FWD data with the solution table data and find the best fit, or fits.

THE FROST PROGRAM

The FROST program was written in BASIC, adaptable for the HP-85 micro-computer provided with the FWD by the manufacturer. The program first scales the FWD-measured deflection basin to the 9000-pound design load, since the measured FWD load varies perhaps between 8500 and 9500 pounds. It then scans and compares the measured deflection basin with the three "best fit" theoretical basins from the solution table. The best fit is based on a derived solution index or "score" as described in the following paragraph. Each of the three are finally weighted in proportion to their "goodness of fit" to determine the required output parameters.

The score is determined partly on the basis of the *absolute* value of the offsets between each theoretical and measured deflection (in μm) and partly from the offset of the measured deflections from lying *parallel* to the theoretical curve. Additionally, the two offsets for each deflection position, i.e. the absolute offset and offset from being parallel, are weighted linearly in proportion to their distance from the center of the loading plate (in mm).

This is done in order to weigh more heavily the outermost sensors, since these deflection readings are affected to the greatest degree by the presence of frozen materials in the pavement structure.

According to the above algorithm, the center deflection would receive a weight of zero. Therefore, it was arbitrarily assigned a weight of 50 (mm). The other six sensor positions have weights of 200, 300, 450, 650, 900, and 1200 (mm) respectively.

Thus the lowest score represents the best fit. The three lowest scores from the measured deflection basin vs. the solution table basins are weighted proportional to the inverse square of their scores. The output parameters are determined through this weighted averaging technique. This may be mathematically represented as:

$$\frac{\sum_{i=1}^{3} \frac{D_i}{(I_i)^2}}{\sum_{i=1}^{3} \frac{1}{(I_i)^2}}$$

where D_i = the depth of thaw for each of the three "best fits" in the solution table, and I_i = the "score" of the three "best fit" data sets. For example, if the three best fit curves had indices of 4000, 6500 and 20,100 respectively, and their corresponding solution table thaw depths were 6", 3" and 12" in that order, the program would calculate a thaw depth of:

$$\frac{\frac{6}{(4{,}000)^2} + \frac{3}{(6{,}500)^2} + \frac{12}{(20{,}000)^2}}{\frac{1}{(4{,}000)^2} + \frac{1}{(6{,}500)^2} + \frac{1}{(20{,}000)^2}} = 5.37$$

It is recognized that this is at best an approximation, so the FROST program would print out an approximate frost depth of between 3" and 9".

The FROST Output

The three theoretical deflection basins selected by the FROST program are associated with their own unique values of thaw depth, E values, layer thicknesses, etc. Since the solution table does not cover every conceivable solution, given the unmanageably huge matrix of possible solutions, only an approximation of the results can be expected for each individual output parameter.

It was therefore decided that the most indicative and direct parameters in the FROST output would be:

1) *The approximate thaw depth.* Since the FROST program heavily weighs the outermost deflections, this parameter can be fairly easily determined to within approximately one foot at shallow thaw depths and two feet at greater depths.

2) *The adjusted center deflection.* The solution table also predicts what the deflection would have been had no frost been present in the upper approximately 14" of materials, all other parameters being equal. This adjusted, no-frost deflection value is further adjusted for temperature to a standard 70°F, using the following equation:[4]

$$d_{1,\,adj.70^{\circ}} = d_{1,\,adj.}\,(0.64 + 25.2/t^{\circ}F)$$

which was found to be sufficiently accurate for the 3" or less of asphalt thicknesses involved.

3) *The "damage indicator."* This value is really tantamount to the theoretical vertical strain at the top of the granular base (under the load). This was deemed at the outset to be the most indicative measure of load-damage potential for springtime thawing conditions. It was found that this "damage indicator" or vertical base strain, no matter what the frost depth, was merely a function of the adjusted center deflection value (see output parameter # 2 above), regardless of the input parameters associated with the given answer found in the solution table. However, this is under the constraint that the asphalt does not appreciably exceed 3" nor is it less than ½" thick.

The derived $d_{1,\,adj.\,70^{\circ}F}$ vs. vertical base strain (ξ_2) relationship is given as:

$$\xi_2 = 84.9 \times d_{1,\,adj.70^{\circ}F}^{\ .858}$$

where d_1 is in mils (in. x 10^{-3}). The r^2-value for the whole solution table is 0.97. The valid range of ξ_2-values is between 400 and 10,000 microstrains, though the equation is naturally limited to the input parameter range covered by the solution table. Figure 4 shows how well the adjusted deflection predicts the ξ_2-value, or the damage potential.

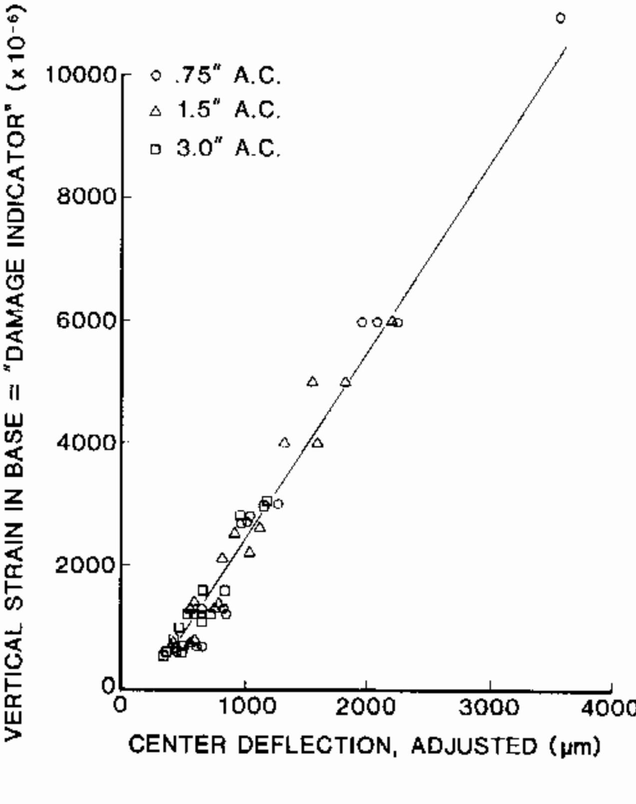

Figure 4.
Comparison of adjusted center deflection and vertical strain in the base.

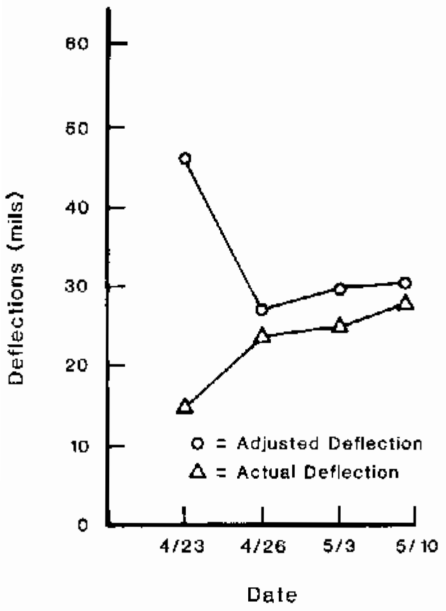

Figure 6. Comparison of actual and adjusted deflections.

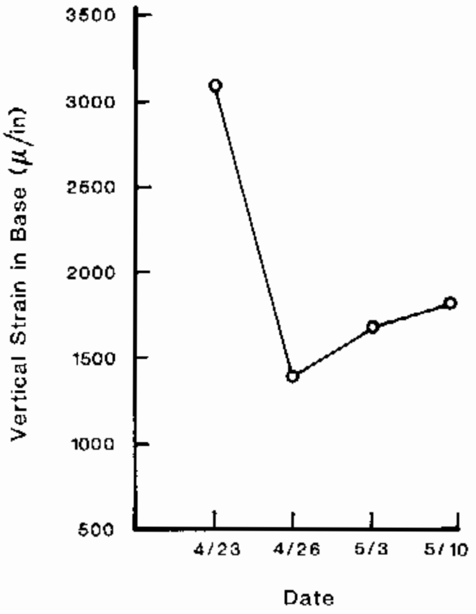

Figure 7. Vertical strain in base.

Example

An example of the FROST program output is shown in Figure 5. The example was taken from springtime measurements along the Parks Highway connecting Anchorage and Fairbanks. Note that the input quantities are in metric units derived from the FWD tests, while the output has been converted to standard American units for the user's convenience.

Figure 5. Typical FWD stations.

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Input File: PH#2
Date: 82 04 26 Temp: 66 F
Roadway: PARKS HIGHWAY; RUN#2
Load Radius (mm): 150
Sensor Positions (mm):
  0  200  300  450  650  900  1200

Station: 292b
Load-adjusted deflections [μm]:
  632  433  306  178  74    16    0
Approx. thaw depth: 3 – 5 ft
Thawed, adj. center deflection
   = 29.0 mils [@ 70 F]
Damage factor    1600 μ in/in
   [Approx. vertical strain in base]

Station: 292.2b
Load-adjusted deflections [μm]:
1174    717   429   159    1     1     1
Approx. thaw depth: 2 – 3 ft
Thawed, adj. center deflection
   = 56.4 mils [@ 70 F]
Damage factor = 3900 μ in/in
   [Approx. vertical strain in base]
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Figures 6 and 7 compare the actual measured deflections at one test point with the vertical strain in the base and the adjusted deflection measurement. It can be seen that the adjusted deflection is indicative of the vertical strain, and therefore the damage potential. The highest damage potential occurred on the same date as the lowest center deflection, indicating that there have been gross errors in establishing load restrictions. Figure 8 clearly shows how the thaw depth increased with time.

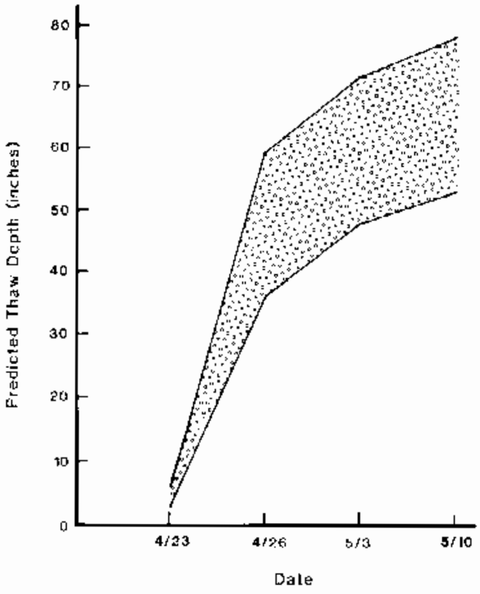

Figure 8. Predicted thaw depth.

SUMMARY AND CONCLUSIONS

Load restrictions have traditionally been based on Benkelman Beam data collected during the spring thaw period. However, it has been shown that the shape of the deflection basin significantly affects pavement life. Use of the Falling Weight Deflectometer and the Chevron N-Layer computer program model has shown that the maximum damage potential may occur long before the peak deflection occurs.

A method has been developed to adjust the measured center FWD deflection so that the adjusted deflection can be used to design overlays and establish load restrictions in a conventional manner. The method uses the vertical strain in the base course as a damage indicator. The center deflection is then adjusted using the shape of the deflection basin to determine the deflection that would cause the same vertical strain in a completely thawed embankment. This adjusted deflection seems to be a better indicator of the damage potential to highway surfaces in areas where thaw-weakening occurs.

REFERENCES

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[4] The Asphalt Institute. 1969. Asphalt Overlays and Pavement Rehabilitation. Manual Series 17. College Park, MD 20740.

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