Use of the Falling Weight Deflectometer to Predict Damage Potential on Alaskan Highways During Spring Thaw

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Benkelman beam data have been widely used to design overlays and establish load restrictions. However, research carried out in Alaska has shown that their use can result in gross errors in areas where freeze-thaw conditions prevail. It has long been known that the shape of the deflection basin is related to the life of the pavement. As a result, a method has been developed to determine damage potential and thaw depth based on tests with the falling weight deflectometer (FWD). This method adjusts the measured center deflection to the deflection that would have been obtained had no frozen materials been present in the pavement structure. Because this adjusted FWD deflection is essentially equivalent to the traditional Benkelman beam deflection (for relatively thin asphalt-surfaced pavements at the same test load), conventional methods can be used to design overlays and establish load restrictions.

In areas where cyclic freeze-thaw conditions prevail, it is important to establish the structural integrity of flexible pavements during periods of thaw weakening. In Alaska these periods generally occur between the initiation of thaw in the upper pavement layers and when the thaw depth has progressed to some 5 to 10 ft. In Alaska the depth of frost penetration can be appreciable and the thawing process relatively long. This period of time can thus extend into weeks or even months.

Based on experience, it has been found that load limits as large as 50 percent are necessary on many primary state routes in Alaska at any time from initial thawing until the thaw depth has reached several feet. Because this can place extensive and costly restraints on the transportation industry in particular, and therefore on society in general, it was important to find a nondestructive test method that 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 of time load limits are necessary; and (c) the level of load restriction required.

Pavement damage has been regularly observed before Benkelman beam deflections indicate significantly large deflections. This suggests that total deflection alone may be inadequate to establish load restrictions. It is reasonable to assume that even small deflections over a weak base and a frozen subgrade are more damaging than large deflections over a stronger base and thawed subgrade because the conditions for dramatic or total failure in the base are indicated by, for example, the excessively high vertical base strains under the load. An example of such a failure can be seen in Figure 1.

A method has been developed that uses the Dynatest model 8000 falling weight deflectometer (FWD) test system to determine the extent of structural weakening of a pavement system for any thaw depth from a few inches to more than 10 ft. The method involves collecting FWD data and processing these data through a computer program called FROST. The program uses the load and seven deflection (basin) values measured at each test point with the FWD to determine

1. The approximate thaw depth;
2. The corrected center deflection for a 9,000-lb equivalent half-axle 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 9,000-lb load.

The proposed method allows the engineer to monitor the structural adequacy of the pavement at any time during the spring thaw period. Through the rehabilitation of candidate pavements, this is expected to reduce and possibly eliminate the need for load limits in Alaska, which are costly to the Alaskan economy.

NEED FOR LOAD RESTRICTIONS

In interior Alaska, asphalt-surfaced pavements are typically frozen to a depth in excess of 10 ft for about 5 months each year. It has been generally concluded that no significant load-associated pavement deterioration takes place during this period of time. Indeed, deflection measurements taken in the completely frozen state show only minute deflections (<<0.001 in. for either a standard Benkelman beam test or a comparable 9,000-lb FWD test).

Traditionally, pavement deflections have been monitored in Alaska throughout the spring thaw period. Based on these deflection measurements, load restrictions have been applied for periods of time starting when Benkelman beam or FWD measurements reflect a significant increase in deflection until after the deflections have reached their peak value (1). This procedure has been helpful in preventing unacceptably rapid pavement deterioration due to

Figure 1. Pavement failure.

heavy loads. But it is strongly felt that a more accurate method of assessing the need for load restrictions should be sought because it has been shown that each day of load restrictions on the Alaska statewide road network costs the trucking industry approximately $100,000 (1980 dollars) (1).

THAWING PAVEMENT SECTIONS

Completely Thawed Condition

A pavement section in an unfrozen state can be modeled as shown in Figure 2. Under load, the pavement will deflect according to the theory of elasticity, the magnitude of each deflection along the deflection basin being dependent on the elastic properties of the materials in the section.

The deflections measured farthest from the load roughly reflect the condition of the subgrade because the compression of the pavement layers above the subgrade is negligible compared with the vertical movement of the subgrade itself (2, p. 724). The center deflection, on the other hand, can be thought of as the sum of the vertical strains throughout each layer from the top downward and is therefore affected by all layers.

Partly Thawed Condition

The same pavement section shown in Figure 2 is shown in a partly frozen state in Figure 3, after the thaw has progressed to a depth of some 6 in. below the asphalt layer. It can be seen that the center deflection is only about one-third the corresponding center deflection of the unfrozen system. Nevertheless, a comparative analysis of these two companion pavement sections performed with the Chevron N-layer computer program reveals that the horizontal strain at the underside of the asphalt and the vertical strain at the top of the base are approximately equal despite the dramatic difference in deflection. Thus, the center deflection alone is a poor indicator of the potential for pavement distress.

However, the asphalt strain (in the present example, some 400 to 500 μin./in.) is still not critical due to the thin surface involved (approximately 1.5 in.), whereas the magnitude of vertical strain in the base, just below the asphalt-base interface, is high (∿0.0026). A good indicator, therefore, of the structural integrity of an asphalt pavement section during spring-thaw-weakened periods is the vertical strain in the granular base. This is because the large resillient strains in the base

Figure 2. Unfrozen asphalt-surfaced pavement under 9,000-lb load.

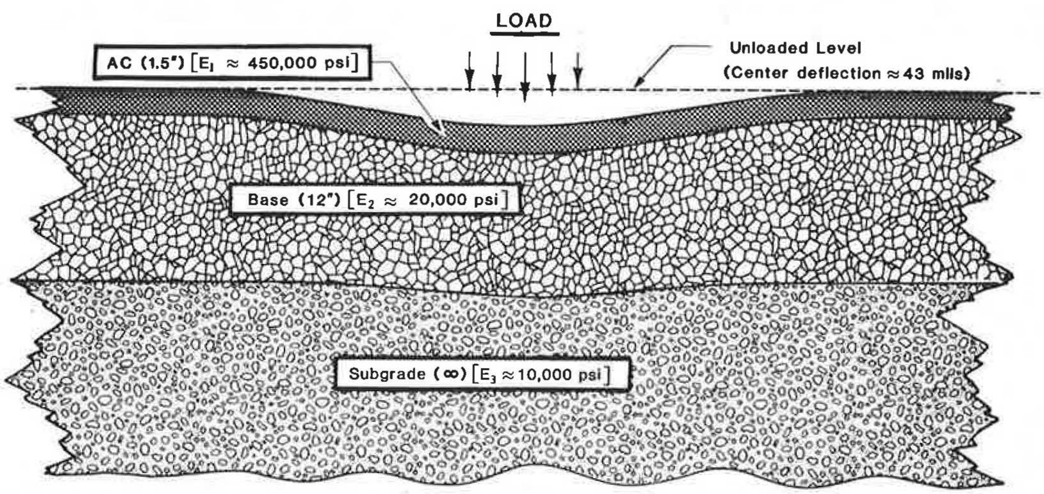


Figure 3. Pavement section from Figure 2 in partly frozen state (thaw depth = 6 in.) under 9,000-lb load.

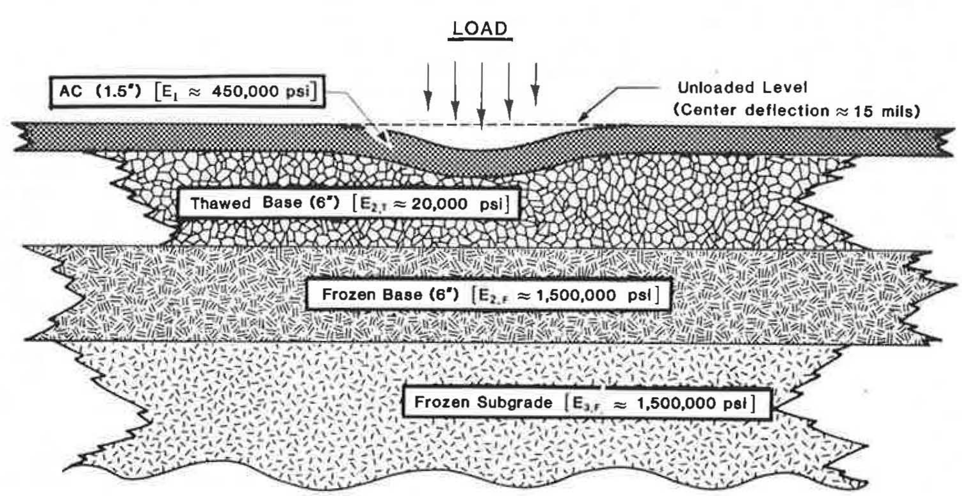
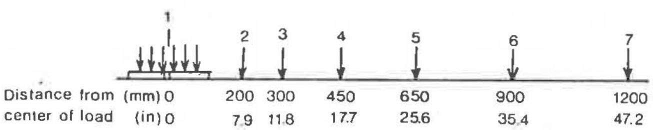


Figure 4. Falling weight deflectometer.

Figure 5. FWD sensor configuration.



apparently give rise to base shear failure, which is, of course, propagated through the thin asphalt surface before asphalt fatigue failure per se.

DEFLECTION MEASUREMENTS

It should be obvious from the preceding discussion that the center deflection reading does not necessarily indicate the potential for load-associated distress in a pavement unless, perhaps, the depth of thaw is known and an adjustment is made in the measured value. Generally, thaw depth will vary greatly from point to point depending on the exposure of the pavement to sunlight, the type of materials present, water content, and so on. Even an approximate thaw depth based on nearby frost tube measurements can be off by several feet and thus by a factor of 2 or more in terms of adjusted (unthawed) center deflection.

The acquisition in the spring of 1982 by the State of Alaska of a heavy-load-capacity Dynatest 8000 FWD (see Figure 4) has now made it possible to make load-deflection measurements rapidly by using a standard equivalent wheel load of 9,000 lb. The requisite deflection basin readings necessary to determine thaw depth and damage potential at any given test point are also obtained. At a test spacing of 0.2 mile, 200 or more test points/day can be covered by a single operator. Thus, at least 40 miles of roadway can be inventoried in a single work day. Generally, each selected roadway is surveyed at least once a week in order to observe the changing structural conditions over the typical spring thaw period of 3 to 6 weeks.

INTERPRETATION OF FWD LOAD-DEFLECTION DATA

FWD Configuration

The FWD load-deflection configuration is variable in terms of load radius, magnitude of the applied load, and deflection measurement positions. The loading plate is circular and has a hole in the center for the measurement of center deflection. Six other available deflection-sensing transducers can be positioned as desired from just outside the loading plate to a distance of some 7 ft along the raise-lower bar. Because of the relatively thin asphalt-surfaced pavements found in Alaska, it was deemed appropriate to use a relatively close sensor configuration (see Figure 5).

A 12-in. loading plate is used, which results in a pressure level of about 82 psi at the design 9,000-lb wheel load. This corresponds with normally encountered truck tire loadings. Other features of the FWD have been described elsewhere (3, p. 464; 4, p. 31).

In accordance with the theoretical effect of frozen materials on the deflection basin, shown in Figures 2 and 3, it was immediately noticed that the same tendency toward 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 high stiffness or modulus of elasticity. It was thus decided to use layered elastic theory to determine the effects of thaw depth and other material characteristics on the seven FWD deflections.

Selection of Input Parameters

Because the FWD is nondestructive, only the load magnitude and seven deflections, and perhaps some information on the likely range of layer thicknesses from construction records, were readily accessible. A series of Chevron N-layer program runs was made for the following range of conditions likely to be present in Alaskan roadways (AC = asphalt concrete and E-value = stiffness):

Item	Value
Thaw depth below asphalt (in.)	2-168
Layer 1 (AC)	
Thickness (in.)	0.75-3
E-value (psi)	430,000-870,000
Layer 2 (granular base)	
Thickness (in.)	12
E-value (thawed portion) (psi)	3,500-65,000
Layer 3 (subbase or embankment)	
Thickness (in.)	59
E-value (thawed portion) (psi)	11,000-22,000
Layer 4 (original soil)	
Thickness	Semi-infinite
E-value (thawed portion) (psi)	7,000-15,000
E-value of all frozen material (psi)	1.5 million

A thaw depth of 14 ft was considered the equivalent of a thawed (or deep permafrost) section because the effect of the modulus of the materials below a depth of 14 ft under a 9,000-lb load is negligible.

Processing of Input Parameters

By using various combinations within the range of parameters given in the preceding table and eliminating some unlikely combinations, about 350 Chevron computer runs were executed. As a result, a solution table was created, with line entries consisting of (a) the specific combination of input parameters (i.e., layer thicknesses, thaw depth, etc.) associated with the output, (b) the vertical surface deflections (i.e., the deflection basin) for a 9,000-lb FWD applied load, (c) the vertical strain at the surface of the thawed portion of the granular base, and (d) the horizontal strain at the underside of the asphalt-bound surface course.

Two examples of deflection basins are shown in Figures 2 and 3. Figure 3 shows clearly how, for a pavement with a shallow thaw depth, the deflection values rapidly approach zero as the distance from the load increases. The early spring FWD data showed precisely this tendency, which dictated the next step: compare the FWD field-gathered data with the data in the solution table and find the best fit or fits.

FROST PROGRAM

Best Fit

The FROST program was written in BASIC, adaptable both for the HP-85 microcomputer provided with the FWD by the manufacturer and for the mainframe Honeywell computer currently used by the Alaska Department of Transportation and Public Facilities.

The program first scales the FWD-measured deflection basin to the 9,000-lb design load because the measured FWD load varies perhaps between 8,500 and 9,500 lb. It then scans the solution table, comparing the theoretical set of deflection basins with the measured one, and selects the three best-fit theoretical basins from the solution table. The best fit is based on a derived solution index or score. Finally, the three selected basins are 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 difference between each theoretical deflection (i.e., from the solution table) and each measured deflection (in micrometers) and partly from the offset of the measured deflections resulting from lying parallel to the theoretical deflection basin. The two offsets for each deflection position--i.e., the absolute offset and the offset from being parallel--are linearly weighted in proportion to their distance from the center of the loading plate (except the center deflection, which is arbitrarily assigned a weight of 50). This is done in order to weight more heavily the outermost sensors because these deflection readings are affected to the greatest degree by the presence of frozen materials in the pavement structure.

Thus, the lowest score represents the best fit. The three lowest scores from the measured deflection basin versus the solution-table basins are weighted in proportion to the inverse square of their scores. The output parameters are determined by means of this weighted averaging technique.

This can be represented mathematically as follows:

$$\left[\sum_{i=1}^{3} (D_i/I_i^2)\right] / \left[\sum_{i=1}^{3} (1/I_i^2)\right] \qquad (1)$$

where D_i is the unknown parameter (e.g., depth of thaw) for each of the three best-fit solution-table data sets i and I_i is the score of the three respective best-fit data sets i.

For example, if the three best-fit curves had scores of 4,000, 6,500, and 20,100 and their corresponding solution-table thaw depths were 6, 3, and 12 in. in that order, the program would calculate a thaw depth of

$$\left\{[6/(4{,}000)^2] + [3/(6{,}500)^2] + [12/(20{,}100)^2]\right\} / \left\{[1/(4{,}000)^2] + [1/(6{,}500)^2] + [1/(20{,}100)^2]\right\} = 5.37 \text{ in.} \qquad (2)$$

Because this is at best an approximation (as discussed in the following section), the FROST program would print out an approximate frost depth of 3 to 9 in.

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, and so on. Because the solution table does not cover every conceivable solution due to the unmanageably large 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 the following:

1. Approximate thaw depth--Because the FROST program heavily weighs the outermost deflections, thaw depth can be fairly easily determined to within approximately 1 ft at shallow thaw depths and 2 ft or so at greater depths.
2. Adjusted center deflection--The solution table also predicts what the deflection would have been had no frost been present in the upper approximately 14 ft of the materials, all other parameters being equal. This adjusted no-frost deflection value is further adjusted for temperature to a standard 70°F by using the following equation (5):

$$d_{1,adj\ 70°} = d_{1,adj}\,(0.64 + 25.2/t) \qquad (3)$$

where

$d_{1,\ adj\ 70°}$ = deflection adjusted to 70°F,
$d_{1,\ adj}$ = adjusted field measured deflection (i.e., for a thawed section), and
t = pavement temperature (°F).

This equation was found to be sufficiently accurate for the 3 in. or less of asphalt thicknesses involved.

3. Damage indicator--The damage indicator 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.

Example

An example of the FROST program output is shown in Figure 6. The example was drawn from springtime measurements taken along the Parks Highway connecting Anchorage and Fairbanks, Alaska. Note that the input quantities are in metric units derived from the FWD tests, whereas the output has been converted to standard American units for the user's convenience.

The data in Figure 7 compare the actual measured deflection with the adjusted deflection at a typical FWD test point as a function of test data. The vertical strain on the base is also plotted for the same test point in Figure 8. A plot of horizontal asphalt strain also shows the same tendency--namely, that the largest strains (and therefore damage potential) often occur prior to the peak, unadjusted deflection. In addition, the peak adjusted deflection follows both the horizontal asphalt strain and the vertical base strain; thus, any of these parameters can be used as an indicator of damage potential.

In the example shown, the greatest damage potential actually occurred on the same data as the lowest center deflection, which would result in gross errors in the establishment of load restrictions. Figure 9 shows how the FROST program calculates the increase in thaw depth as a function of time.

APPLICATION OF THE FROST PROGRAM

The establishment of load restrictions has traditionally been based on the judgment of the maintenance foreman and the Benkelman beam deflection measurements. In 1980 a method of establishing load restrictions was adopted that attempted to limit damage during spring thaw to that expected during the summer months (1). Analysis of the data collected with the FWD showed that this objective was not being accomplished. This was further supported by maintenance personnel, who felt that the adopted method imposed load restrictions too late. However, it proved to indicate correctly the point at which load restrictions should be removed.

The method developed in 1980 was based on Figure 10. By knowing the normal summer deflection and the deflection measured in the spring, the load restriction could be found. By using Figures 6 and 9 and assuming the normal summer deflection to be 0.015 in., a 75 percent load limit was placed about April 26 under the current method. However, based on the adjusted deflection from Figures 6 and 9, 50 percent load restrictions should have been enforced before March 23. Field investigations showed that the 75 percent load restrictions were inadequate for this section because much of the pavement was severely fatigue-cracked within the first week of spring thaw.

By using the adjusted FWD center deflection from the FROST program, load restrictions may be imposed

Figure 6. Example of FROST program output.

```
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 stain 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 stain in base]

Station: 292.4b
Load-adjusted deflections [µm]:
 933  531  241   66    4    1    1
Approx.thaw depth: 2 - 3 ft
Thawed, adj.center deflection
  = 42.3 mils [@ 70 F]
Damage factor = 2700 µ in/in
 [Approx.vertical stain in base]

Station: 292.6b
Load-adjusted deflections [µm]:
 854  551  338  121   51   17    7
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection
  = 37.3 mils [@ 70 F]
Damage factor = 2300 µ in/in
 [Approx.vertical stain in base]

Station: 292.8b
Load-adjusted deflections [µm]:
 636  386  223  101   39   17    9
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection
  = 28.4 mils [@ 70 F]
Damage factor = 1600 µ in/in
 [Approx.vertical stain in base]

Station: 293b
Load-adjusted deflections [µm]:
 604  376  216   92   33   13    8
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection
  = 27.1 mils [@ 70 F]
Damage factor = 1400 µ in/in
 [Approx.vertical stain in base]
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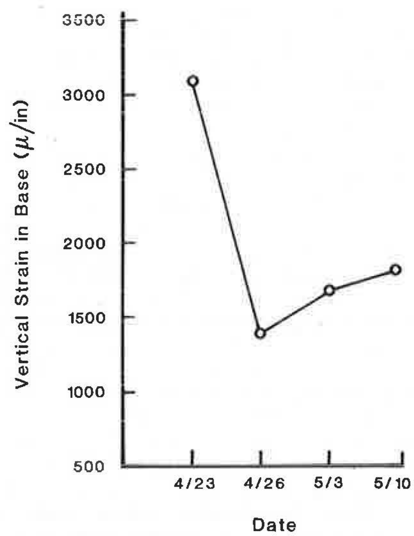


Figure 8. Vertical strain in base.

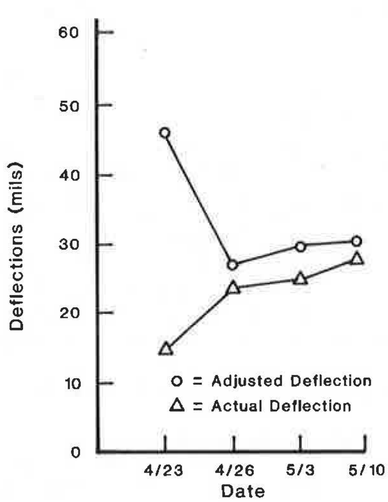


Figure 7. Actual versus adjusted deflections.

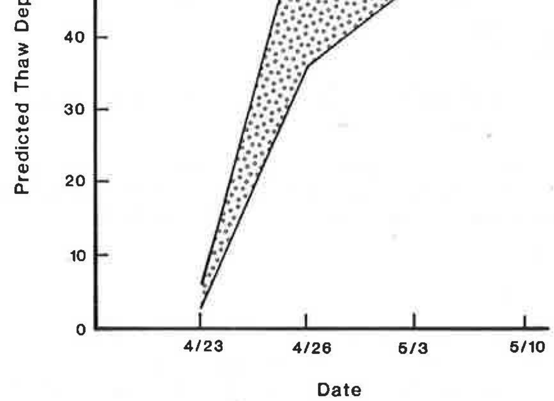
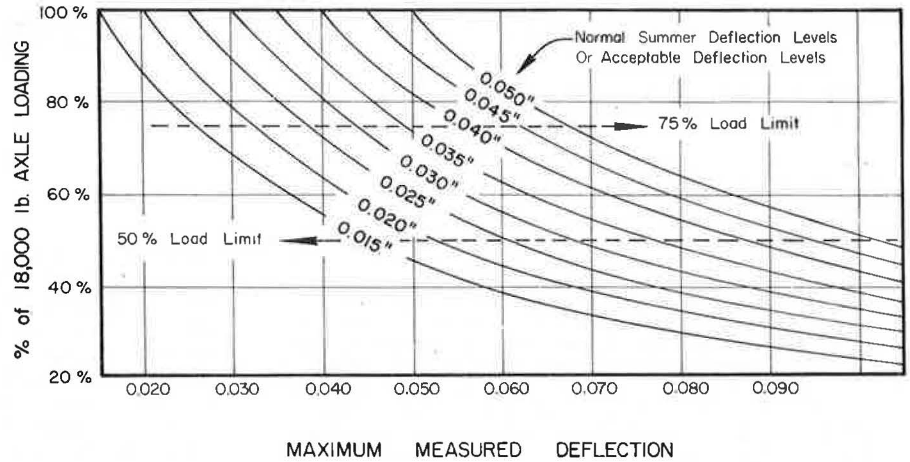


Figure 9. Predicted thaw depth.

Figure 10. Load limit percentages for measured deflections and normal summer deflection levels or acceptable levels.



from the time the greatest damage potential along a section of roadway approaches the limiting value of the curves in Figure 10 (1). After the adjusted deflections fall below the threshold value, load restrictions can once again be lifted.

Perhaps the greatest value of this method, however, is the ability of the FWD and the FROST program to delineate quickly and accurately the sections of roadway most in need of structural rehabilitation. In many cases, it appears that only short lengths of roadway over long distances need imminent repair, so it is hoped that some well-placed maintenance and rehabilitation funds will eventually eliminate the need for load restrictions on all primary state routes.

LIMITATIONS OF THE PROGRAM

The range of solution-table parameters used in the FROST program was solely geared for Alaskan roadways. It is recognized that other cold-climate applications of the method described here will require an additional range of parameters (e.g., larger asphalt thicknesses) to enhance the limited range covered by the existing solution table.

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 FWD and the Chevron 5-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 center deflection is adjusted by using the shape of the deflection basin to determine the deflection that would have occurred in a completely thawed embankment. It is felt that this adjusted deflection is a better indicator of the damage potential to highway surfaces in areas where thaw weakening occurs.

ACKNOWLEDGMENT

This study was sponsored by the Alaska Department of Transportation and Public Facilities with the assistance of personnel from Dynatest Consulting, Inc., of California.

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Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.