Evaluation of Variables Affecting Flexible Pavement Thawing for Timing Spring Load Restrictions

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A finite element analysis of pavement freezing and thawing was performed on four flexible pavement structures developed to represent typical pavements that receive spring load restrictions because of thaw weakening. The pavement structures consisted of 2- and 4-in.-thick asphalt concrete surface courses, 6- and 12-in.-thick granular base courses and fine- and coarse-grained subgrade materials. TDHC, a two-dimensional finite element heat transfer model, was used for the analysis. Air temperatures, short- and longwave radiation, and convection were included as the external variables driving the pavement thermal response. Latent heat, caused by the phase change of water during freezing and thawing, is included in the model. The results suggest that average daily pavement surface-air temperature differences vary from 2°F in February to 11°F in May. These data suggest that pavement thawing will be initiated during this time for average daily air temperatures of 30°F or less. In addition, it was found for the pavements analyzed that thawing reached the top of the subgrade, after pavement surface temperatures reached 32°F, in 1 to 4 days in thin pavements and in 4 to 9 days in thick pavements. The duration of thawing for total thawing to occur was correlated with the freezing index for all subgrade types combined with satisfactory results.

During spring thawing, the strength of the ground may be measurably weakened compared with its summer-fall state for one or both of the following reasons:

1. Moisture migration into the soil during the preceding freezing period and
2. Development of excess hydrostatic pressure in base and subgrade materials as moisture is liberated during thawing.

Recognition of seasonal variation in material properties is necessary for realistic estimates of pavement performance. For primary road facilities, it is necessary to minimize the detrimental effects of substantial thaw weakening because it is anticipated that these roads will perform at a high level of serviceability throughout the year under high traffic volumes. However, for many secondary roads with lower traffic volumes it is not economically feasible to provide adequate frost protection throughout for spring thawing. Agencies faced with secondary road maintenance in frost areas often choose to restrict vehicle or axle loads, or both, during some of the spring thaw period to reduce damage that may occur at this time.

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Studies performed in Alaska, Minnesota, and Washington (*1–3*) have shown that flexible pavements that were susceptible to spring thaw damage were weakened relative to summer stiffness levels when thawing had reached the bottom of the base course layer. Analytical studies of hypothetical pavement sections by Rutherford (*4,5*) resulted in similar findings. These field and analytical studies indicated that the time for base thawing to occur is short. However, because of radiation and the absorptive properties of the pavement surface, base thawing occurs before air temperatures warm to 32°F. The duration of the weakened period has been found to be variable and is a function of depth of freezing, soil type, lateral drainage potential, and surface thermal conditions. The end of ground thawing is important since it represents the end of the generation of excess moisture. However, there is not always enough time for sufficient recovery of stiffness of the unbound materials to warrant the removal of load restrictions.

The purpose of this study was to evaluate analytically when flexible pavement thawing occurs to gather information for use in timing spring load restrictions. Previous work (*4*) suggested that the following were of interest: (a) the start of pavement thawing, (b) the time for thawing to reach the top of the subgrade material, (c) the time for a small amount of subgrade thawing (4 in.) to occur, and (d) the time to total thaw. The analysis was performed on pavement cross-sections that were developed to represent "typical" pavement sections currently being restricted in the United States (*5*). In addition, it was desirable to develop pavement sections that represented a range of material types so that a range of performance could be observed.

ANALYSIS APPROACH

Two broad categories of variables required consideration to perform the analysis of pavement thawing: (a) climatic conditions or external variables and (b) layer material types and associated index and thermal properties. The choice of pavement cross-sections, climatic variables, and model selection will be discussed in this section.

Model Selection

The primary mode of heat transfer in pavement structures is conduction. However, two aspects of the ground thermal regime warrant particular consideration for realistic results when modeling ground freezing and thawing. These include (a) consideration of ground surface effects, including radiation and convection and (b) the inclusion of latent heat effects caused by the phase change of the water in a pavement structure when it freezes and thaws. To adequately consider these effects, TDHC, a two-dimensional heat conduction finite element model developed by Goering and Zarling (*6*), was selected for the analysis.

Pavement Cross Sections

Hypothetical pavement cross sections were developed to represent to the best extent possible the types of road construction and subgrade materials existing in pavements currently being restricted. Data obtained from a survey of spring load restriction practices (*5*) were weighed heavily in the development of these sections. The data suggested that pavement cross sections on which load restrictions are currently being applied have the following ranges:

	Range	*Normal*
Asphalt surface (in.)	1½–6	2–4
Aggregate base (in.)	4–18	6–12

On the basis of this information, 2- and 4-in. asphalt surface courses and 6- and 12-in. unbound aggregate base courses were selected for the cross-sections for the analysis.

The predominant subgrade material present was clay, where load restrictions have reportedly been applied. Silts, gravels, granular materials, and tills were also mentioned as subgrade types requiring restrictions in the survey of current practice (*5*). Based on this information, both fine and coarse subgrade materials were modeled in the analysis. The pavement sections chosen for analysis are shown in Figure 1.

Material Thermal Properties

The thermal properties required for the analysis are the frozen and unfrozen thermal conductivity, the frozen and unfrozen volumetric specific heat capacity, and the latent heat. The values for the various materials are shown in Table 1. These properties are a function of the dry density of the material (γ_d) and the moisture content (w). Values for the thermal conductivity of the unbound materials were estimated using Kersten's equations (*7*) and assuming that all of the moisture is frozen at temperatures below 32°F, a reasonable assumption for granular materials. Fine-grained materials may contain unfrozen moisture at temperatures below 32°F; however, it was assumed for this analysis that all of the moisture was frozen during the freezing season. The amount of unfrozen water affects the volumetric latent heat, which is a significant variable in the rate of advancement of the thawing plane.

CLIMATIC VARIABLES

Previous work in pavement thermal analyses (*8–10*) has shown that the following surface thermal effects warrant consideration for realistic predictions of pavement thermal response:

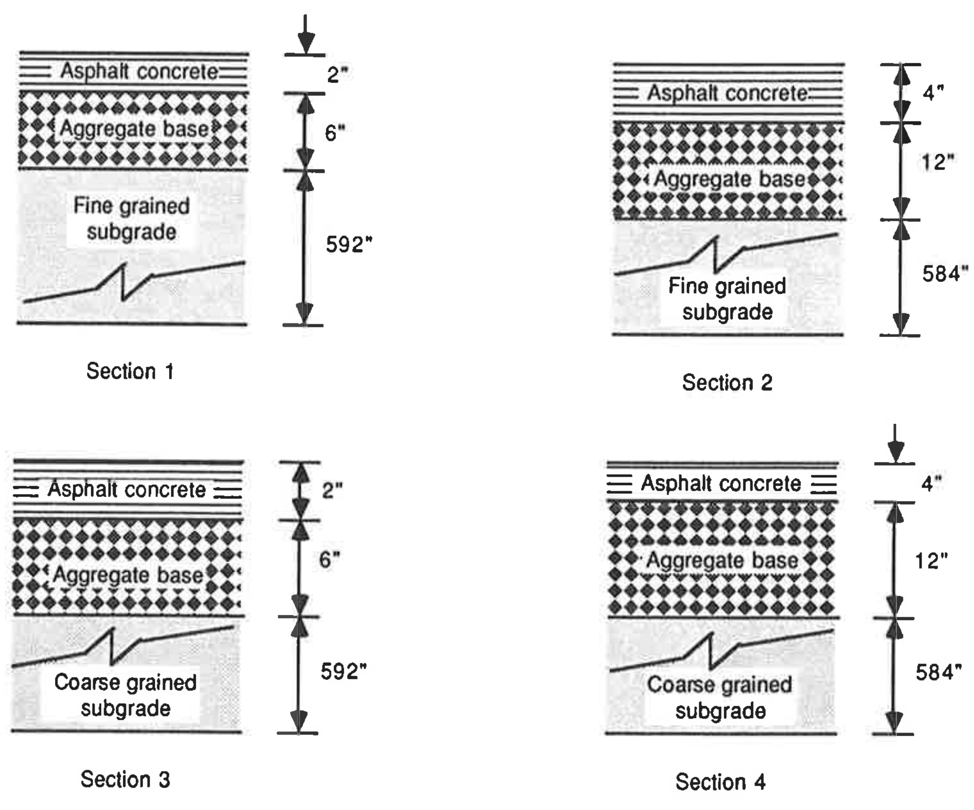

FIGURE 1 Pavement structures for thermal analysis.

TABLE 1 MATERIAL THERMAL PROPERTIES

Material	Dry Density d (lb/ft³)	Moisture Content w (%)	Thermal Conductivity k_u, k_f (Btu/lb ft °F)	Volumetric Specific Heat C_u, C_f (Btu/ft³)	Latent Heat L (Btu/ft³)
Asphalt Concrete	138	0	0.84	21.0	0
Aggregate Base	130	4	1.15 f* 1.36 u*	24.7 f 27.3 u	749
Fine-grained Subgrade	95	15	0.71 f 0.64 u	23.3 f 30.4 u	2052
Coarse-grained Subgrade	105	10	1.06 f 1.03 u	23.1 f 28.4 u	1512

* The letters f and u denote frozen and unfrozen respectively.

- Air temperature,
- Shortwave radiation,
- Longwave radiation, and
- Convection.

These effects were included in the following analysis.

Air Temperature Functions

The TDHC model utilizes a sinusoidal temperature function to model annual air temperature variation. The sinusoidal air temperature functions were obtained by equating the area under discontinuous monthly air temperature functions, obtained from monthly temperature data, to the area under a sine curve with the same average annual air temperature.

Sinusoidal air temperature functions were obtained for 60 locations in frost areas in the United States (*11*). Locations in Alaska were excluded because of the existence of permafrost and extremes in solar radiation because latitude alters the ground thermal regime compared with that of the "lower 48" states. The data used included the average annual air temperature and average monthly temperatures for 30 years from 1941 to 1970.

From these results five air temperature functions were defined to represent a range of intensity of freezing conditions. Freezing index was used to indicate the intensity of freezing. It is defined as follows:

$$FI = \sum_{\text{freezing season}} (32 - T_{\text{avg}}) \times (1 \text{ day}) \quad (1)$$

where FI is the freezing index, in degree-days Fahrenheit, and T_{avg} is the average daily temperature, in degrees Fahrenheit.

The freezing index cases used in the analysis ranged from 500 °F-days to 2,500 °F-days. This range was selected on the assumption that freezing in cases of fewer than 500 °F-days would not be too critical because of the limited amount of frozen material and the brief duration of the thawing period. The upper limit was chosen on the basis of the air temperature data.

Regression analyses were performed for the freezing index, and for five air temperature variables—average annual temperature (T_m), amplitude of temperature variation (T_a), duration of the freezing season, start of thawing, and the phase lag of the sine function (ϕ)—to obtain the sinusoidal air temperature functions required for TDHC. The results are shown in Table 2.

Shortwave Radiation

The data used for estimating the shortwave radiation were also obtained from Cinquemani et al. (*11*). Data were collected from pyranometer measurements of shortwave radiation over a period of 24 or 25 years. No correlation between the shortwave radiation data with location (latitude) or freezing index was found. The primary dependent variable for solar radiation was solar declination or time of the year. Therefore, average values of surface solar radiation heat flux for the months from January through May were calculated from the data and used in the analysis. The absorbed shortwave radiant heat flux is equal to $1 - \alpha_s$ times the incoming shortwave radiation, where α_s is the surface albedo. Scott (*12*) reported a value of 0.1 for α_s.

Longwave Radiation

No data for the broad study area were found for longwave radiation. Therefore a quasi-theoretical approach was used

TABLE 2 AIR TEMPERATURE FUNCTION DATA FOR TDHC ANALYSIS

Freezing Index Case (^{0}F days)	Mean Annual Temperature (^{0}F)	Amplitude of Temperature Variation (^{0}F)	Phase Lag (days)	Duration of Freezing (days)	Start of Thawing (days from Jan 1)	Thawing Index (^{0}F days)
500	47.8	23.7	17	99	67	6276
1000	45.0	25.3	16	118	74	5770
1500	42.3	26.9	14	136	82	5265
2000	39.5	28.5	13	154	90	4760
2500	36.7	30.1	11	173	97	4254

for estimating longwave radiation flux at the pavement surface. Theoretically, the longwave radiation at the pavement surface emitted from the ground and the atmosphere for clear sky conditions is

$$Q_{RLO} = \sigma\ \varepsilon_s\ T_s^4 - \sigma\ \alpha_e \varepsilon_a\ T_a^4 \tag{2}$$

where

Q_{RLO} = longwave radiation at the pavement surface,
σ = Stefan Boltzmann constant,
ε_s = emissivity of the pavement surface,
ε_a = emissivity of the atmosphere,
α_e = absorptivity of the pavement surface, and
$T_{s,a}$ = temperature of the pavement surface and atmosphere, respectively.

Two temperatures, T_s and T_a, are required for evaluation of longwave radiation. Results obtained in preliminary analyses suggested that pavement surface-air temperature differences vary from about 1°F in January to about 10°F in May. The values used for T_s were based on these results.

The value used for the longwave emissivity of asphalt concrete was 0.93 in Equation 2, reported by Kreith (*13*). The value of the atmospheric emissivity used was obtained from the following expression formulated by Swinbank (*14*):

$$\varepsilon_a = 0.398 \times 10^{-5}\ T_a^{2.148} \tag{3}$$

where T_a is equal to the reference air temperature in degrees centigrade.

Finally, the net ongoing longwave radiation is reduced because of the presence of clouds in the atmosphere (*10,15*). The effect of cloud cover on outgoing longwave radiation was treated empirically using the following relationship proposed by Lunardini (*16*):

$$Q_{RLN}/Q_{RLO} = 1 - 0.8C_e \tag{4}$$

where

Q_{RLN} = net outgoing longwave radiation caused by cloud cover,
Q_{RLO} = clear sky outgoing surface radiation, and
C_e = 24-hr average fraction of sky covered by clouds.

The value of C_e was obtained from cloud cover data from Ruffner and Bair (*17*) for 33 locations in the frost area of the United States. These data were averaged for use in the above expression.

Convection

Vehrencamp (*18*) developed a formula for the convection coefficient (h) based on data collected on a dry lake bed. Because the conditions on which the formula is based are the closest available to a pavement surface, the Vehrencamp equation was selected for use in the analysis.

$$h = 122.93\,[0.00144\ T_m^{0.3}\ V^{0.7} + 0.00097(T_s - T_a)^{0.3}] \tag{5}$$

where

h = convection coefficient in Btu/hr ft^2 °F,
$T_{s,a}$ = pavement surface and air temperature, respectively, in °C,
V = average windspeed, in m/sec, and
T_m = $(Ts + Ta)/2 + 273.0$.

The air surface temperature differences given above for longwave radiation were used to evaluate the convection coefficient (h). Average monthly windspeeds were obtained from Ruffner and Bair (*17*) for January through May for 38 locations in the northern United States. The monthly averages for all of the data for January through May were 10.7, 10.7, 11.4, 11.5, and 10.2 mph, respectively. The convection coefficients obtained for these months were 2.9 Btu/hr ft^2 °F for January and February, 3.1 for March, 3.2 for April, and 3.0 for May.

ANALYTICAL PROCEDURE

Many different edge conditions exist in pavements, depending on local topography, embankment requirements for construction, and shoulder size. These conditions, as well as snow cover conditions, result in various boundary conditions and problem geometry for two-dimensional modeling. Aldrich (*19*) and Straub et al. (*20*) concluded that one-dimensional modeling of pavement freezing or thawing is satisfactory for cases in which the depth of frost penetration is small compared with the width of the pavement. This is generally the case in seasonally frozen ground.

TDHC uses triangular elements in the problem formulation. A 1-ft-wide strip was assumed for the one-dimensional analysis. Elements in the upper 2 ft of the pavement structure, which included the asphalt surface course, the granular base course, and from 4 to 12 in. of subgrade were 2 in. thick. From 2 to 6 ft (this is always in the subgrade layer) the element thickness was increased to 4 in. From 6 to 10 ft, element thicknesses were 6 in. From 10 to 50 ft, the elements were 5 ft thick.

To initialize the problem, a thermal analysis was performed on the pavement structure using air temperature as the only thermal driving force. This analysis was done for a period of 1 year starting at midfreezing season. After this, all surface thermal variables were included to evaluate the ground temperature variation throughout the remaining freezing season and the thawing period.

The heat flux at the surface caused by the net radiation and the convection coefficient changed abruptly at the beginning of each month since the values for radiant heat flux and the convection coefficient were obtained from monthly data. This resulted in some oscillation of the surface temperatures at the start of the month when the new values were introduced. For freezing index cases, in which the start of thawing and a step input occurred simultaneously, "flash" thawing occurred, resulting in up to as much as 2 ft of thawing in one day. These effects were mitigated by defining new sinusoidal temperature functions for surface temperatures that included the radiant heat and convective effects. These temperature functions were obtained from the stepped results and are given in Table 3. Using these revised temperature functions, all cases were reevaluated from midfreezing season until the end of the thawing period.

RESULTS

Comparison of Pavement Air/Surface Temperature

The net effect of solar and longwave radiation and convection occurring at the pavement surface is a net heat flux into the pavement causing surface temperatures to be higher than air temperatures. It was found that all pavement structures experienced the same surface temperatures during thawing (within 0.2°F) on the same day for a given freezing index case, suggesting that layer thicknesses and subgrade thermal properties have almost no effect on the surface temperatures. Air temperature, windspeed, and net radiation heat flux were the primary variables governing the pavement surface temperatures. The absorptive properties of the surface material also affect the amount of heat absorbed and the resulting surface temperature.

The air temperatures and surface temperatures obtained from the analysis for each freezing index case from midfreezing season to June 1 indicate that surface-air temperature differences are approximately equal at the same time for all freezing index cases. On February 1 the surface-air temper-

TABLE 3 SURFACE TEMPERATURE FUNCTIONS FOR TDHC ANALYSIS

Freezing Index FI (^{0}F days)	Mean Annual Temperature T_m (^{0}F)	Amplitude of Temperature Variation, T_a (^{0}F)	Phase Lag ϕ (days since (Jan 1)
500	58.4	32.6	17
1000	54.0	32.3	16
1500	50.8	33.4	14
2000	48.1	35.1	13
2500	45.5	37.0	11

$$T = T_m - T_a \cos(2\pi t/365 - 2\pi \phi/365)$$

where
T = the surface temperature at time t
T_m = the mean annual temperature
T_a = the amplitude of annual temperature variation
t = the time in days after January 1
ϕ = the phase lag of the temperature sine curve, in days after January 1

ature difference ranged from 2.0 to 2.4°F for the five freezing index cases. On March 1 the temperature difference varied from 3.9 to 4.2°F. On April 1 and May 1 the surface-air temperature differences ranged from 6.9 to 7.1 and 10.5 to 11.0°F, respectively. Figure 2 shows the average daily pavement surface-air temperature difference versus time.

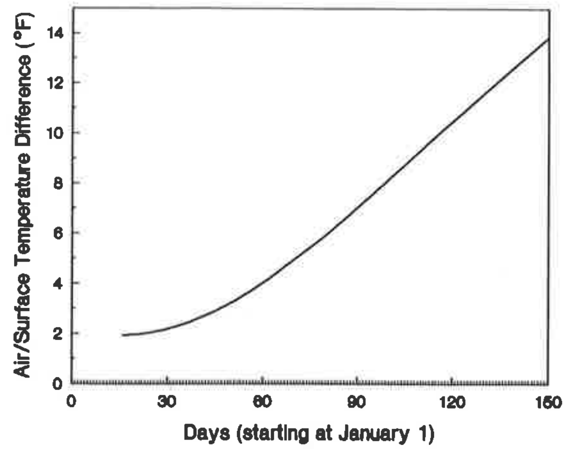

FIGURE 2 Average daily pavement surface/air temperature difference versus time.

Advancement of the Thawing Plane

In a previous work (*4*) the results of structural analyses on these pavement structures were reported. Based on this work and findings from other studies (*1–3*) the times selected for structural analysis of the pavement were base thawing, 4 in. of subgrade thawing, and complete thawing. The advancement of the 32°F isotherm, assumed to be coincident with the thawing plane, was obtained from the TDHC analysis. The results are given in Table 4. Included in this table is the day starting with day 1 on January 1 when (a) air temperatures reach 32°F, (b) pavement thawing begins, (c) base thaw occurs, (d) 4 in. of subgrade thawing occurs, and (e) complete thaw has occurred.

These results suggest that the intensity of the prior freezing season, date, and the type of subgrade have little effect on the time required for base thawing to occur for the range of climatic conditions studied. Thin pavements consisting of 2 in. of AC and 6-in. granular base courses took from 1 to 4 days to thaw through the base with an average of 2.7 days. The thick pavements analyzed consisted of 4 in. of AC and 12 in. of unbound base material. Base thawing for these pavements ranged from 4 to 9 days, with an average of 6.4 days. No trend of increasing duration of base thawing with increasing freezing index was evident from the results.

Four-Inch Subgrade Thaw

Early subgrade thawing also appeared to be unaffected by date or intensity of the previous freezing season. Thin pavements thawed more quickly to this level than did the thick pavements. The effects of the subgrade thermal properties were also apparent in the results. The time required for 4-in. subgrade thawing for pavement sections with thin pavement structures and fine subgrades ranged from 3 to 10 days, with an average of 6.8 days, whereas thin pavements on coarse subgrades thawed in an average of 5.8 days.

The thick pavements founded on the fine subgrades achieved 4 in. of subgrade thawing in 5 to 14 days in the analysis with an average of 12.4 days. By comparison, the coarse subgrade cases thawed in 6 to 13 days, with an average of 9.8 days. In the analysis of the thick pavements with fine subgrades an atypically short duration of thawing of 5 days was obtained from the results for a freezing index of 1,500 °F-days. If one were to eliminate this data point from the group, the average time for thawing would increase to 14.2 days.

Total Thaw

The results for total thawing suggested that the duration of thawing was dependent on the intensity of the previous freezing season and also on the subgrade thermal properties. The duration of thaw increased with increasing freezing index for all cases. In addition, the duration of thawing for similar structures and freezing indices for fine subgrades was usually longer than the comparable coarse-grained subgrade case caused by the lower thermal conductivity and increased latent heat of the subgrades. Table 4 shows the duration of total thaw for all cases. Total thawing for thin pavements with fine subgrades ranged from 16 days for an FI of 500 °F-days to 58 days for 2,500 °F-days. Thin pavements with coarse subgrades took from 20 to 54 days to thaw. Thick pavements with fine subgrades took 21 to 70 days to thaw for the range of freezing index cases. Similar pavements with coarse subgrades thawed in 16 to 51 days.

Duration of Thaw

The results for duration of total thawing were used to see if a relationship could be found between the freezing index and duration of thawing. A regression analysis was performed for all fine subgrade cases and all coarse subgrade cases. In addition, all cases analyzed were combined in a regression analysis. The results are shown in Figures 3 through 5. Also shown are the regression equations, correlation coefficients, and R^2 values for each regression performed. The regression equations obtained are as follows:

Fine-grained subgrade materials:

$$D = 0.0233FI + 8.0 \tag{6}$$

Coarse-grained subgrade materials:

$$D = 0.0176FI + 10.9 \tag{7}$$

All subgrade materials combined:

$$D = 0.02\ FI + 9.5 \tag{8}$$

where D is the duration of the thawing period in days and FI is the freezing index in °F-days.

TABLE 4 ADVANCEMENT OF THE THAWING PLANE

Freezing Index Case (^{0}F days)	Air Temperature = 32 ^{0}F (day from Jan 1)	Start Thaw (day from Jan 1)	Base Thaw (day from Jan 1)	4" Subgrade Thaw (day from Jan 1)	Total Thaw (day from Jan 1)
2/6 Fine*					
500	66	54	54	62	70
1000	76	64	67	67	96
1500	83	71	74	81	117
2000	89	77	81	84	125
2500	94	81	84	87	139
4/12 Fine					
500	66	54	61	70	75
1000	76	64	70	78	94
1500	83	71	76	76	110
2000	89	77	83	91	132
2500	94	81	88	94	151
2/6 Coarse					
500	66	54	54	60	74
1000	76	64	67	71	94
1500	83	71	75	77	110
2000	89	77	80	83	123
2500	94	81	83	87	135
4/12 Coarse					
500	66	54	62	64	70
1000	76	64	68	70	93
1500	83	71	76	80	108
2000	89	77	84	90	128
2500	94	81	90	92	132

*** 2/6 Fine denotes 2" AC, 6" Base, Fine Subgrade.**

The correlation coefficients for all fine subgrade cases combined and all coarse subgrade cases combined were 0.94 and 0.96, respectively. The results for all cases was 0.92. Although the regression of all cases combined resulted in the lowest correlation of all combinations, the results obtained from TDHC consistently reflect a relationship between freezing index and duration of thawing.

SENSITIVITY

Reference Case

The results reported apply to specific values for climatic variables, and pavement and subgrade material properties. It was of some interest to perform a sensitivity analysis to see how the results varied with changes in the values assumed for the external and internal variables.

The freezing index case of 1,000 °F-days was selected to perform the sensitivity analysis. The average *FI* for the locations from which climatic data were collected was 929 °F-days. Therefore, it was felt that this case would best represent the "typical" freezing intensity. The pavement structure selected was a thin pavement (2 in. AC and 6 in. base) with a fine subgrade because this case represented the most critical pavement sections with regard to timely application of load restrictions. Three thin pavements with coarse subgrades were also analyzed to consider the variation in thawing for coarse subgrades with varying thermal properties.

Variables Selected for Study

A total of 15 cases were included in the sensitivity analysis. They included the following variations:

1. Maximum and minimum latitude;
2. Maximum and minimum cloud cover;
3. Maximum and minimum windspeed;
4. Three fine subgrade thermal property cases;
5. Three coarse subgrade thermal property cases; and
6. Three location-specific temperature cases.

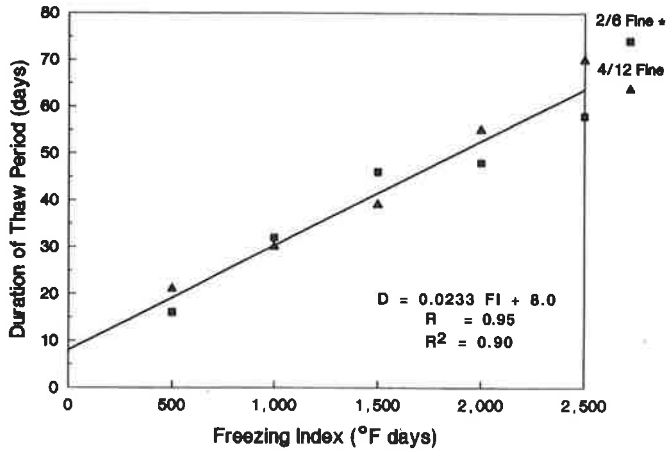

FIGURE 3 Duration of thaw versus freezing index, fine subgrades.* 2/6 fine denotes 2-in. AC, 6-in. base, fine subgrade.

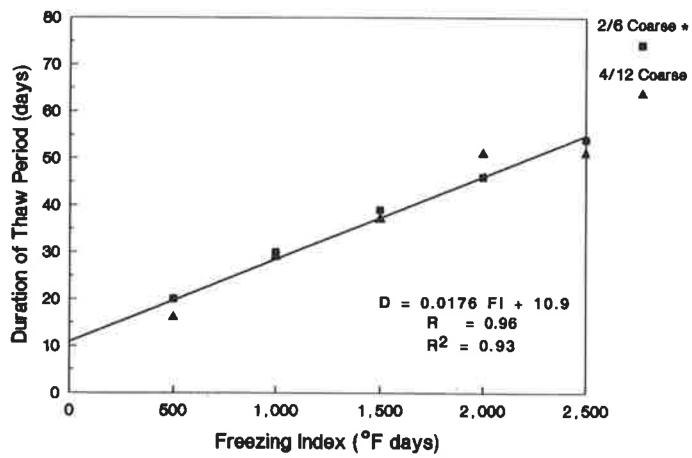

FIGURE 4 Duration of thaw versus freezing index, coarse subgrades.

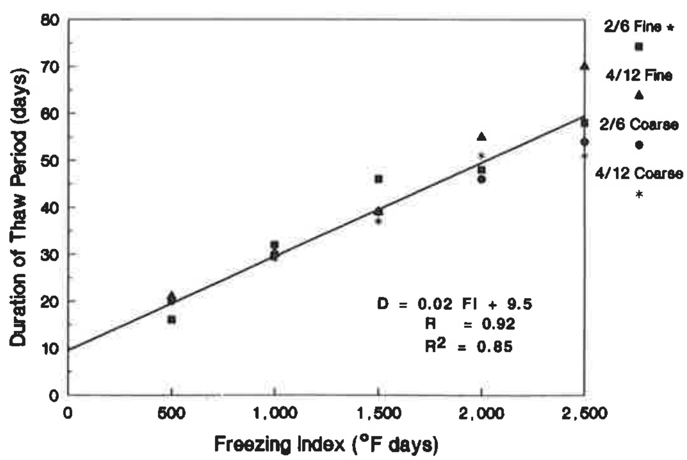

FIGURE 5 Duration of thaw versus freezing index, all cases.

The variables related to climate that were selected were chosen from an in-depth analysis of the primary variables that affect the radiation and convection coefficient at the surface (*21*).

Results

It was found that the smoothing procedure used to obtain the sinusoidal surface temperature functions could not be used for the sensitivity analysis. Therefore, the sensitivity results that will be presented for variations in external variables will be from stepped TDHC analyses.

Latitude Sensitivity

The variation in pavement surface temperature compared with the reference case for the minimum and maximum values of latitude assumed ranged from approximately 0.5°F to 1.5°F. The greatest variation occurred in February and March when the differences in heat flux caused by latitude variation are the greatest.

Thawing started on day 63 or March 4 for the maximum latitude case as compared with day 60 and day 62 for the minimum latitude and reference case, respectively. The duration of thaw ranged from 30 days for the minimum latitude to 33 days for the maximum latitude compared with 32 days for the reference case.

Cloud Cover Sensitivity

The effect of varying the amount of cloud cover on net radiant heat flux was found to increase with time into the thawing period. However, even during the late freezing season the effect of variations in the amount of cloud cover on net radiant heat was found to be rather small. Reductions in incoming solar radiation were approximately balanced by reductions in outgoing longwave radiation. During the thawing period, pavement surface temperatures for maximum and minimum cloud cover conditions varied by no more than +1°F.

Thawing started on day 63 or March 4 for the case of maximum cloud cover condition. Thawing for the minimum cloud cover assumed for analysis started on day 61. The duration of thawing for the minimum cloud cover case was 25 days compared with 32 days for maximum cloud cover.

Windspeed Sensitivity

Variations in windspeed that affect the convection coefficient caused the greatest variation in pavement surface temperatures. In early February, pavement surface-air temperature differences for maximum windspeed conditions were about 2.7°F. At the same time, minimum windspeed conditions produced surface-air temperature differences of about 4.5°F, compared with 3.5°F for the reference case. As thawing progressed into early April, pavement surface-air temperature differences ranged from 7.5 to 11.7°F for the maximum and minimum values of windspeed, respectively, compared with 8.7°F for the reference case.

The start of the thawing period and the duration of thawing were most significantly affected by the assumed variation in windspeed compared with the results from the other external variables considered in the sensitivity analysis. For the minimum windspeed case, thawing started on day 58 or February 27, as compared with March 3 (day 62) for the reference case and March 4 (day 63) for the maximum windspeed case. Thawing took 28 days under minimum windspeed conditions and 35 days for the maximum case.

Location-Specific Temperature Functions

It was also apparent from review of the sinusoidal temperature functions obtained for individual locations that some variation in mean annual temperature, amplitude of temperature variation, and phase lag could occur and still produce an equivalent freezing index. Therefore, three location-specific air temperature and freezing index cases were analyzed and compared to those of the reference case. The locations selected were Miles City, Montana; Burlington, Vermont; and LaCrosse, Wisconsin. The freezing indices computed for these locations were 1,022, 1,012, and 1,026 °F-days, respectively. When these location-specific temperature functions were analyzed, it was found that the pavement surface-air temperature differences varied by less than 1°F on any given date for the three locations studied compared with those from the reference case.

The start of thawing dates for LaCrosse, Miles City, and Burlington were March 4, 5, and 8, respectively. For all of these locations the start of thawing occurred after the start of thawing for the 1,000 °F-day reference case, which was on March 3. Total thaw occurred in 29 days in LaCrosse, 32 days in Burlington, and 36 days in Miles City.

Thermal Property Sensitivity

In the thermal property sensitivity portion of the sensitivity analysis, the air temperature functions and surface fluxes used were the same as those in the reference case. Therefore, no comparisons of surface temperatures or pavement surface-air temperature differences were made. The thaw period started on the same day, March 3, for all cases. Only the duration of thawing varied with changes in thermal properties. For the fine subgrade cases the duration of thawing ranged from 20 days for denser subgrades with lower moisture contents to 36 days for less dense materials with high water contents as shown in Table 5. The advancement of the thawing plane was similar for the third fine subgrade case analyzed, assumed to be 95 percent saturated, for the case in which the dry density was 80 lb/ft^3 and the reference case (γ_d = 95 lb/ft^3). The subgrade with a dry density of 110 lb/ft^3 thawed much more rapidly (20 days). This rapid thawing was probably caused by reduced conductivity and latent heat effects.

The duration of thaw for coarse subgrade cases is also shown in Table 5. The thaw period ranged from 16 days for denser subgrades with lower moisture contents to 36 days for looser subgrades with greater moisture contents compared with 30 days for the reference case. The 95 percent saturated case thawed in 34 days. The rapid thawing of the dense coarse subgrade case is evident in these results. It is also interesting

TABLE 5 THAW PLANE ADVANCEMENT FOR SENSITIVITY ANALYSIS OF EXTERNAL VARIABLES

CASE	Day Air Temperature = 32 °F (from 1/1)	Start Thaw (from 1/1)	Base Thaw (from 1/1)	4 Inches Subgrade Thaw (from 1/1)	Total Thaw (from 1/1)	Duration of Thaw (days)
Maximum Latitude	76	63	65	74	93	30
Minimum Latitude	76	60	60	60	93	33
Maximum Cloud Cover	76	63	63	66	95	32
Minimum Cloud Cover	76	61	65	71	86	25
Maximum Windspeed	76	63	64	70	98	35
Minimum Windspeed	76	58	58	64	85	28
Miles City, MT	84	64	61	70	100	36
Burlington, VT	83	67	69	76	99	32
LaCrosse, WI	75	63	64	64	92	29

to note the early rapid thawing of the 95 percent saturation case. It is not known if one could expect such rapid thawing in actual field conditions.

Conclusions on Sensitivity Analysis

The results of pavement surface-air temperature differences and the duration of thawing from the sensitivity analysis are of importance in developing guidelines (and their limitations) for timing load restrictions. The results reported suggest that latitude variations cause the greatest variation in pavement surface-air temperature differences in late February and early March (early thawing), and windspeed variations resulted in the greatest variation in pavement surface-air temperature differences in late March and early April (late thawing).

Figure 6 shows the variation in duration of thawing for all climatic variables and subgrade thermal properties for fine subgrades. The greatest range in response occurred because of variations in subgrade thermal properties. Variations in latitude had the least effect on the variation in duration of thawing. The remaining variables, cloud cover, windspeed, and air temperature functions resulted in variations of 6 to 7 days in duration of the thawing period compared with those of the reference case.

CONCLUSIONS AND RECOMMENDATIONS

The results of the thermal analysis suggest that pavement surface temperature relative to air temperature is primarily a function of date. The relationship of pavement surface-air temperature is of great importance in the timely application of load restrictions because it is apparent from the results that thawing will begin well in advance of air temperatures reaching 32°F. The minimum air temperature that will be sufficient to initiate pavement thawing on a given date in the spring is shown in Figure 7.

Further, it was found that the number of days required for pavement structures to thaw to the bottom of the base layer was 1 to 4 days for thin pavements and 4 to 9 days for thick

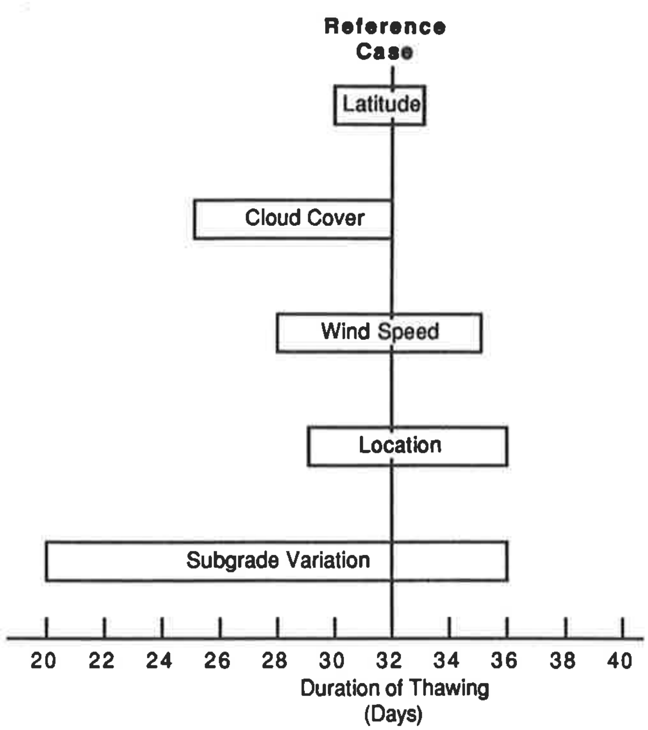

FIGURE 6 Sensitivity of duration of thawing of fine subgrades.

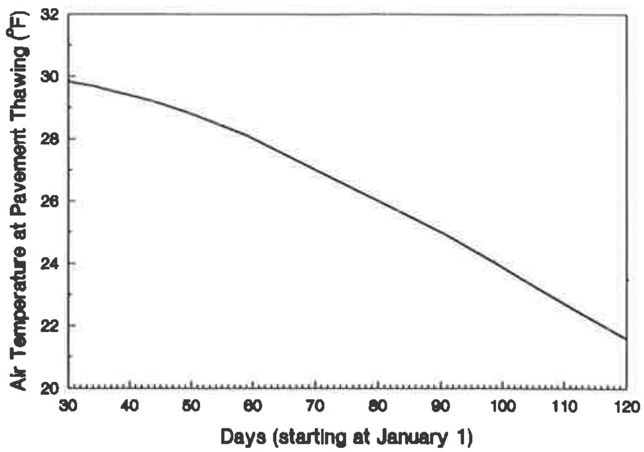

FIGURE 7 Air temperature at pavement thawing versus time.

pavements. When thawing proceeds into the subgrade, previous studies (*4*) suggest that asphalt tensile strains and subgrade vertical strains may be significantly increased; that is, the "critical" period has been reached.

Thawing proceeded into the subgrade at a slower rate because of greater moisture contents in these materials and the effects of latent heat. Equations 6 through 8 were presented for the duration of the thawing period as a function of freezing index for coarse subgrade materials, fine subgrade materials, and all subgrade material types combined.

It is intended that personnel involved with management of low-volume roads where spring load restrictions are typically applied could use Figure 7 to aid in determining when pavement thawing will begin. Further, these individuals could collect air temperature data during the freezing season to calculate the freezing index that could be used to estimate the duration of the thawing period using either Equation 6, 7, or 8.

However, the duration of thawing should not be confused with the duration of the critical period. Although the end of the thawing period indicates the limit of time when excess moisture is being generated from previously frozen materials, many pavements, particularly those with fine-grained subgrades, are not sufficiently recovered at this time to sustain normal load levels without damage.

In using the results presented, it is important to recognize that the greatest variation in the results occurred for variations assumed for dry density and moisture content of the subgrade materials in the analysis. Therefore, the results obtained for the duration of thawing are expected only to approximate the duration of the thaw period for an arbitrary pavement structure.

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