A Heat-Transfer Model for Evaluating Frost Action and Temperature-Related Effects in Multilayered Pavement Systems

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A heat-transfer model for evaluating frost action and temperature-related effects was developed for a multilayered pavement system. The heat-transfer model was derived from one-dimensional, forward-finite-difference, heat-transfer theory and has been programmed for computer solution. The model was designed to include many input parameters and it can be easily expanded to include newly developed parameters. The heat-transfer model can be used to evaluate the temperature regime of varied pavement systems in different geographical locations.

Meteorological parameters such as short-wave radiation, long-wave radiation, convection, and air temperature are the basic extrinsic factors used in the heat-transfer model. Intrinsic factors considered are the physical properties and thermal properties of the pavement materials that include unit weight, moisture content, material classification, thermal conductivity, heat capacity, and latent heat. The heat-transfer model was developed so that appropriate thermal properties of the pavement materials are used depending on whether the unfrozen, freezing, or frozen state exists.

Pavement temperatures generated by the heat-transfer model were compared with laboratory temperature data and temperature data from the AASHO Road Test, and the model was found to give valid results. Use of the heat-transfer model for evaluating frost action in a pavement system at a specified location was demonstrated for 30 years of past climatic record. It was shown that quantitative data necessary for evaluating frost action in pavement systems could be obtained. Also, a clearer understanding of the qualitative factors involved in frost action research was provided.

•THE DETERIMENTAL effects of frost action are a major problem and continue to be a significant cause of pavement deterioration leading to high maintenance costs. In many cases, the cost of annual repairs and maintenance is greater than the cost of preventive measures that might have been incorporated into the original pavement design and construction.

Completely acceptable techniques, procedures, and criteria have not been developed for adequately assessing freeze-thaw durability of pavement systems. Most laboratory durability testing procedures use arbitrary exposure conditions that are not representative of actual conditions in the field. Current durability criteria do not acknowledge the fact that climatic conditions (maximum and minimum air temperatures, sunshine, wind velocity, precipitation, etc.) vary with geographical location in many states. For example, the average winter temperature for northern Illinois is approximately 25 F, whereas that for southern Illinois is approximately 35 F.

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In recognition of the need for developing a reasonable and realistic procedure for evaluating frost action in pavement systems, research was undertaken with the following objectives:

1. Determine the factors that significantly influence frost action and temperature effects in pavement systems;
2. Develop a heat-transfer model that uses past climatic records for predicting frost action and temperature in multilayered pavement systems;
3. Validate the heat-transfer model by using laboratory and field data; and
4. Demonstrate how the heat-transfer model can be used to characterize frost action and temperature in typical pavement systems.

FACTORS INFLUENCING FROST ACTION IN PAVEMENT SYSTEMS

The number of published reports pertaining to frost action and its effects has grown to vast proportions. A review of literature by Johnson (1) made reference to more than 800 publications that dealt either entirely or partly with soil freezing and frost damage. Lovell and Herrin (2) have also summarized much of the earlier knowledge on soil freezing and related frost problems.

Because the nature of frost action is complex and involves many variables, no systematic approach can be taken to increase knowledge of the subject without first separating the major variables and determining their relative influence. In recognition of this, Johnson and Lovell (3) divided the factors that influence frost action into extrinsic and intrinsic categories.

The extrinsic factors shown in Figure 1 are those that are outside but that act directly on the soil. These factors specify the nature of the climate and modify the influence of climate on the depth and rate of freezing and thawing in pavement systems. Although both climate and load are major external factors (Fig. 1), Johnson and Lovell (3) indicated that climate is the most important factor to be considered.

The major intrinsic factors (state of the soil mass, the physical properties of the soil mass, the composition of the soil, and the thermal properties of the soil) influencing frost action are shown in Figure 2 and are those governed by the properties of the soil and its cover.

The influence of the various extrinsic and intrinsic factors shown in Figures 1 and 2 on frost action and temperature-related effects in pavement systems has been described

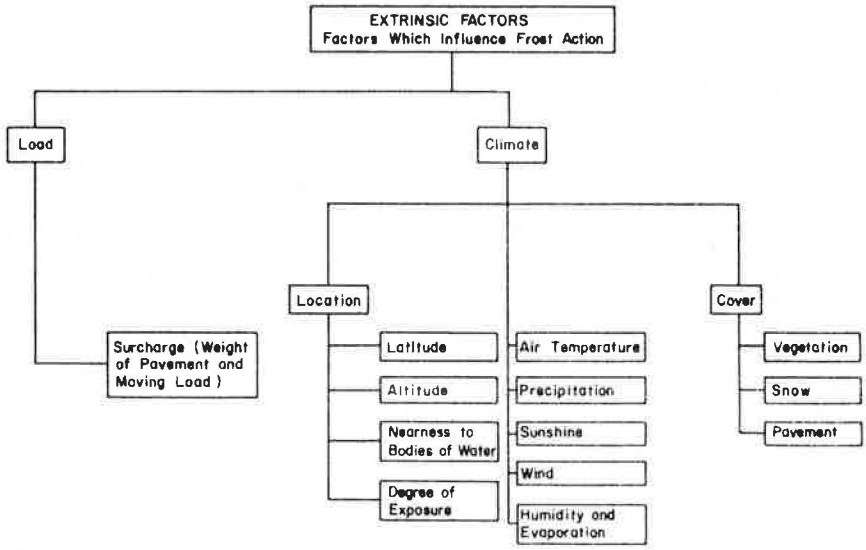

Figure 1. Extrinsic factors influencing frost action (3).

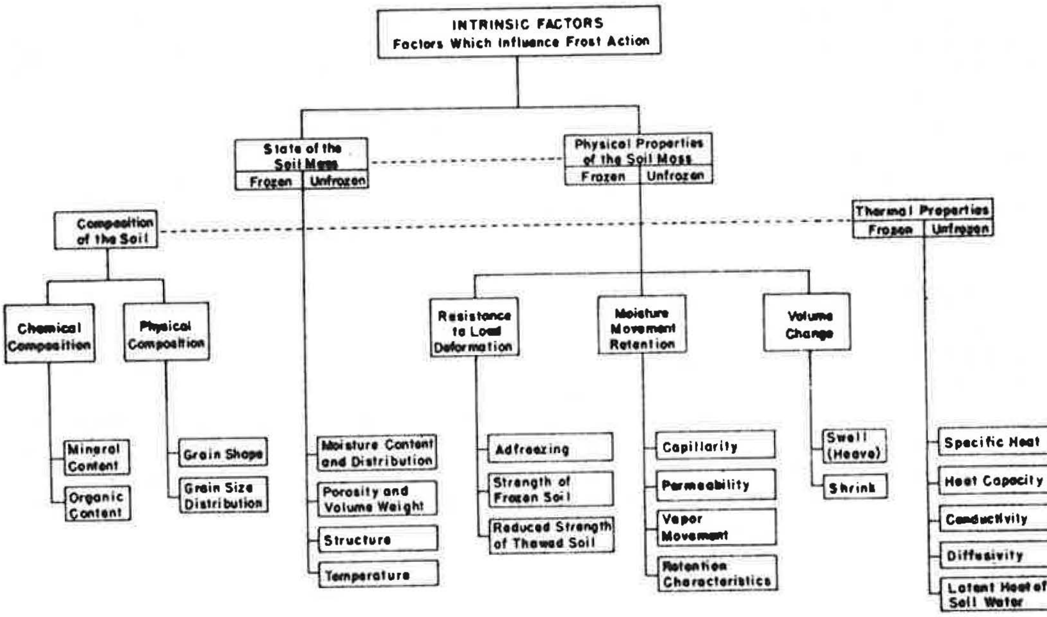

Figure 2. Intrinsic factors influencing frost action (3).

in detail by Dempsey (4) in other studies. Although there are differences of opinion concerning the relative importance of the various factors, it is generally agreed that the temperature variation of the earth at any location is caused by the climate of that area, and that the response of the soil and its cover to the climate is controlled by the thermal properties of the materials.

DEVELOPMENT OF A MODEL FOR EVALUATING FROST ACTION IN MULTILAYERED PAVEMENT SYSTEMS

A comprehensive literature review of the different methods for evaluating pavement temperatures indicated that a numerical method would be the most promising procedure for studying frost action in multilayered pavement systems with transient surface temperature conditions. The mathematics in the numerical method are simple, flexible, and well suited for programming on a digital computer. The method can be adapted to the complex heat-transfer conditions in multilayered pavements that occur as a result of changing thermal properties and changing climatic conditions.

Based on the initial success of several investigators (5, 6, 7), a one-dimensional, forward-finite-difference, heat-transfer model (hereafter referred to as heat-transfer model) was developed to evaluate frost action in multilayered pavement systems. In the heat-transfer model, the future temperature at a given nodal point is expressed as a function of time, its present temperature, and the present temperature of the adjacent nodal points. The finite-difference, heat-transfer equations were programmed on a digital computer so as to facilitate rapid solutions to large amounts of input data.

Studies by Aldrich (8), Straub, Dudden, and Moorhead (9), and Przybycien (10) have indicated that the assumption of one-dimensional heat transfer is applicable to the study of frost penetration below pavement surfaces. This is especially true in the case where the depth of frost penetration is small as compared to the pavement width.

In setting up the heat-transfer model, it was necessary to consider the basic mechanisms of heat transfer, which include conduction, convection, and radiation. The pavement system was divided into small vertical sections or nodes that had a cross-sectional area of 1 sq ft. The basic heat-transfer equations or a combination of these equations were used to relate the temperature of a specific node to the temperatures of the surrounding nodes and to determine the temperature of the specific node after a given time increment. Because the temperature computed for a given node is the average for the entire volume, the temperature is specified at the center of the nodal volume.

The energy balance procedures used by Scott (11, 12, 13) and Berg (14) to relate pavement surface temperatures to meteorological parameters were incorporated into the heat-transfer model.

The factors associated with frost action are easily determined by analyzing the temperatures generated by the heat-transfer model for the various nodes in the pavement profile.

Finite-Difference Pavement System

Figure 3 shows a typical finite-difference pavement system used in the heat-transfer model for computing pavement temperatures. The pavement system consists of a column of nodes that have a cross-sectional area of 1 sq ft.

Nodes 2 through 37 are termed normal nodes. The nodal depth, ΔX, and the number of nodes are chosen so as to ensure mathematical stability and so that the interface between pavement layers will be located at a nodal center. Nodes 2 and 6 are also mixed nodes because the thermal properties of these nodes correspond in part to the thermal properties of the adjacent pavement layers.

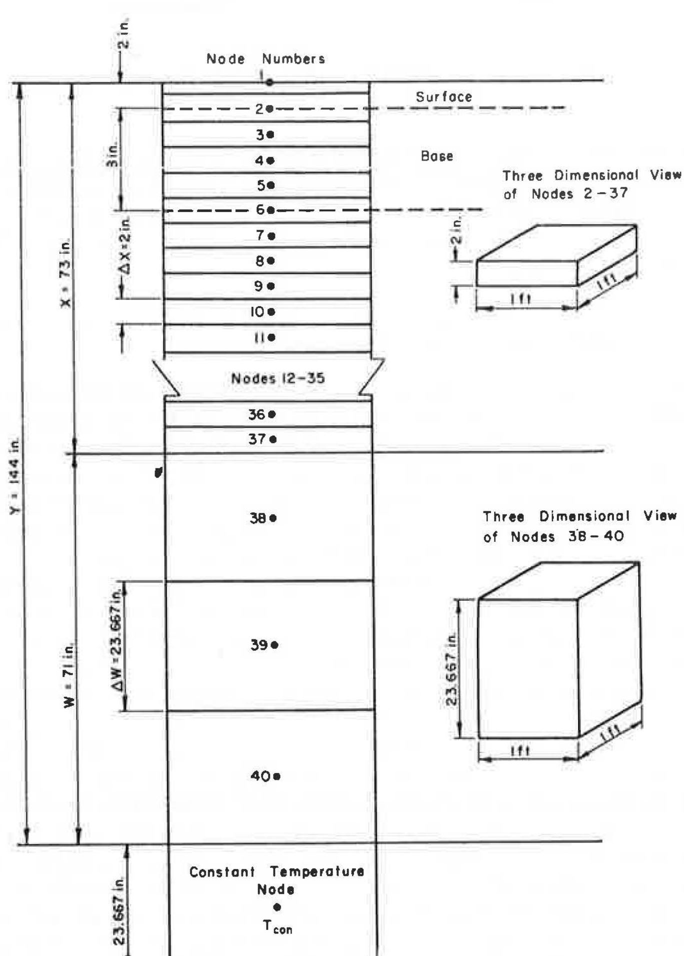

Figure 3. Typical finite-difference pavement system.

Node 1 consists of one-half of a normal node so that the nodal center will lie on the pavement surface. Node 1 at the pavement surface is the node at which the meteorological parameters are introduced and an energy balance is achieved.

Nodes 38, 39, and 40 are termination nodes and their purpose is to reduce computational time. The termination nodes replace the smaller nodes and reduce the total number of nodes in the finite-difference pavement system with only a small increase in the finite-difference error. Also, because the temperature variations decrease with increasing depth in the pavement, the increased depth of the bottom nodes, ΔW, will not cause a large increase in the computational error.

Flack (15) found that a finite-difference pavement system with a ratio of X/W of approximately one and three termination nodes would produce a finite difference error of less than 1 percent. He indicated that any termination strip configuration with more than three nodes would increase computational time without substantially reducing the error involved. Flack (15) further noted that the finite-difference error increased as the ratio X/W decreased and as the number of termination nodes decreased.

The total depth, Y, of the finite-difference pavement system is a variable input parameter in the heat-transfer model. It can be determined from a study of deep soil temperatures at a specified geographical location. For example, studies of soil temperatures in northern Illinois have indicated that the ground temperature remains essentially constant (51 F) at a depth of 29 ft, and that ground temperature fluctuations are relatively small (9 F or less) below a depth of 10 ft (16). It was concluded that a finite-difference pavement system with a depth of 144 in. (Fig. 3) could be used for Illinois because the ground temperature differences below this depth are quite small, and the additional cost in computer time required for a greater depth did not appear to be justified. At the bottom of the finite-difference pavement system, a constant temperature node was added to account for the outward flow of heat from the interior of the earth [noted by Thompson (17)]. The value of the constant temperature node is a variable input parameter in the heat-transfer model because it may vary with geographical location. A constant temperature of 51 F was considered to be a realistic temperature value for a soil depth of 144 in. in Illinois.

When using the finite-difference pavement system (Fig. 3), it is necessary to determine the initial nodal temperatures at the start of the investigation period. Carroll (18) has indicated that the initial pavement profile temperatures can be estimated provided that the heat-transfer model is initiated prior to the time accurate temperature predictions are to be made. He found that, although this approach would produce an initial error in the computed pavement temperatures, the error would decrease after a very short period of time as more climatic data were inserted into the heat-transfer model.

Page (19) has shown that the average date of the first killing frost is approximately October 13 in northern Illinois and approximately October 23 in southern Illinois. These findings indicate that a frost action study for Illinois should be started about October 1 so that the pavement profile temperatures generated by the heat-transfer model will converge by the time frost action begins to occur. Starting dates in other geographical locations can be based on the average date of the first killing frost.

Finite-Difference Equations

Convection and radiation play a dominant role in transferring heat between the pavement surface and air, whereas conduction plays a separate role in transferring heat within the pavement system. The procedure used to develop the finite-difference equations in the heat-transfer model was similar to that used by Straub et al. (5), Carroll et al. (7), and Schenck (20). (Symbols used in the following equations are defined in the Appendix.)

To illustrate the finite-difference solution, it is first necessary to transform the one-dimensional, Fourier, heat-transfer equation for transient heat flow into the finite-difference form. The general form of the one-dimensional, Fourier equation for conductive heat transfer is expressed as

$$\frac{\partial^2 T}{\partial X^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \theta} \tag{1}$$

Kreith (21) has shown that the first and second derivatives in Eq. 1 can be replaced by the appropriate finite-difference terms and written as

$$\frac{T_{n-1} + T_{n+1} - 2T_n}{\Delta X^2} = \frac{1}{\alpha} \frac{T_n' - T_n}{\Delta \theta} \tag{2}$$

The thermal diffusivity, α, is equal to $K/C\gamma$. By arranging terms and substituting for α, Eq. 2 can be written for the heat balance on an arbitrary interior node as

$$\frac{K}{\Delta X}\left(T_{n-1} - T_n\right) + \frac{K}{\Delta X}\left(T_{n+1} - T_n\right) = \frac{\gamma C \Delta X}{\Delta \theta}\left(T_n' - T_n\right) \tag{3}$$

The terms $K/(\Delta X)$ $(T_{n-1} - T_n)$ and $K/(\Delta X)$ $(T_{n+1} - T_n)$ are the equations for the thermal conductivity of a nodal volume and the term $(\gamma C \Delta X)/(\Delta \theta)$ $(T_n' - T_n)$ is the heat storage in a nodal volume during an incremental time period, $\Delta \theta$.

It is apparent that the one-dimensional, finite-difference solution consists of the basic heat-transfer equations and an energy balance on a specified node. The energy balance for an increment of time, $\Delta \theta$, can be expressed qualitatively as follows: Heat added to a nodal volume + heat given up by a nodal volume = heat stored in a nodal volume.

The finite-difference equations used in the development of the heat-transfer model have been described elsewhere by Dempsey (4).

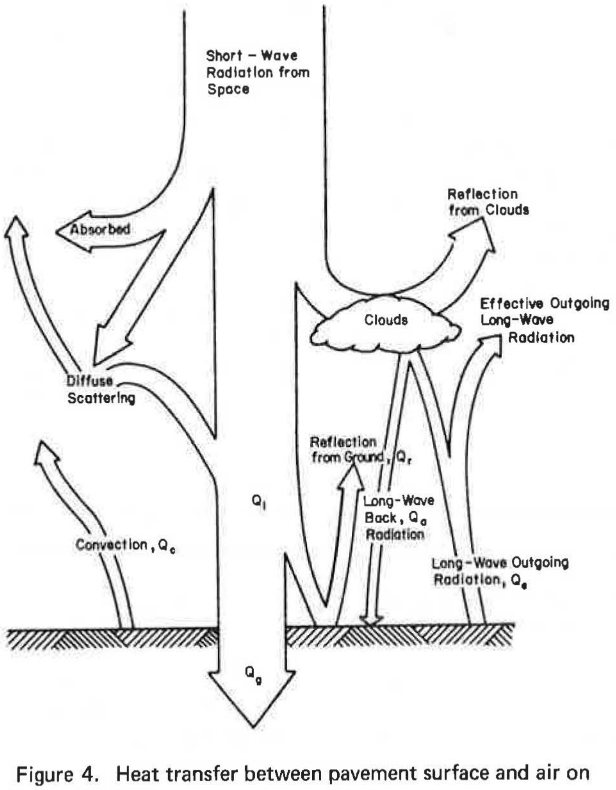

Figure 4. Heat transfer between pavement surface and air on a sunny day (8).

Meteorological Parameters

The most important parameters involved in the heat-transfer model are those related to the surface node. These are the meteorological parameters concerned with the net radiation heat transfer, Q_{rad}, and the convective heat transfer, Q_c, into or out of the pavement system (Fig. 4).

The finite-difference equation for the surface node is ideally suited for use with the meteorological energy balance approach proposed by Scott (11, 12, 13) and Berg (14). It is as follows:

$$Q_i - Q_r + Q_a - Q_e \pm Q_c \pm Q_h \pm Q_g = 0 \tag{4}$$

The degree of accuracy in predicting the pavement temperatures relies heavily on the choice of methods used to predict the radiation heat quantities and the convection heat quantity. Previous studies by Dempsey (4) have indicated that most equations are empirically determined from field and laboratory tests.

The importance of solar radiation in pavement temperature studies has been shown by Straub et al. (5) and Aldrich (8). From Eq. 4 the net amount of radiation, Q_{rad}, influencing heat transfer at the surface node is expressed as

$$Q_{rad} = Q_i - Q_r + Q_a - Q_e \tag{5}$$

The amount of incident short-wave radiation used in the energy balance at the surface node is determined by use of a regression equation developed by Baker and Haines (22) and expressed as

$$Q_i = R^* \left(A + B \frac{S}{100}\right) \tag{6}$$

The extraterrestrial radiation, R*, can be theoretically calculated for a given location from the solar declination, latitude, zenith angle, and solar constant.

In Figure 5, it is observed that the intensity of solar radiation varies parabolically from the time of sunrise to the time of sunset. Based on this observation, the amount of short-wave radiation received at the pavement surface during a finite-time increment, $\Delta\theta$, is calculated by assuming that the total daily extraterrestrial radiation varies in a parabolic manner from the time of sunrise to the time of sunset. The values for the total daily extraterrestrial radiation and the time of sunrise and sunset are easily used in the finite-difference program because they essentially do not change from year to year at any given geographical pavement location. Furthermore, the parabolic radiation distribution is readily programmed for a digital computer. The value of R* is obtained from the parabolic radiation distribution at any specified time during the day. The value of R* is taken as zero during nighttime.

Part of the incident short-wave radiation, Q_i, is lost as reflected short-wave radiation, Q_r. The amount of short-wave radiation reflected is a function of the incident short-wave radiation, Q_i, and the absorptivity, a, of the pavement surface as follows:

$$Q_r = (1-a)\,Q_i \tag{7}$$

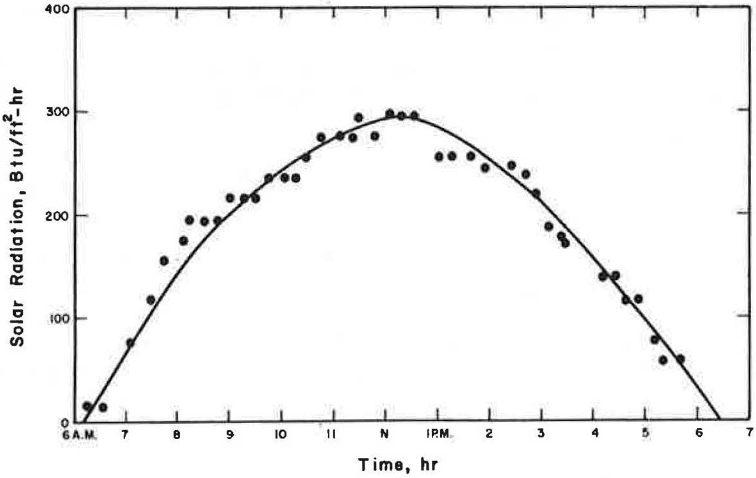

Figure 5. Variation in solar radiation intensity (5).

From Eqs. 6 and 7 the net amount of short-wave radiation that enters into the energy balance at the pavement surface, Q_s, is derived as follows:

$$Q_s = Q_i - Q_r \tag{8}$$

By substituting for Q_r in Eq. 8, the following equations are obtained:

$$Q_s = a\, Q_i \tag{9}$$

$$Q_s = a\, R^{*} \left(A + B\frac{S}{100}\right) \tag{10}$$

Essentially, Eq. 10 considers the influence of cloud cover, reflection from the clouds, diffuse scattering, absorption by the atmosphere, and reflection by the pavement surface on the extraterrestrial radiation.

An analysis of variance test on the constants A and B in Eq. 10 for more than 10 years of record at 6 radiation stations in the Midwest (Indianapolis, Indiana; Lansing, Michigan; Madison, Wisconsin; Columbia, Missouri; Ames, Iowa; and Lemont, Illinois) showed that there was no significant difference, $\alpha = 0.05$, between the various stations or within a given station. Therefore, it appears that average values of the constants A and B can be used for determining quantities of short-wave radiation in many geographical locations. The average value of A is 0.202 and the average value of B is 0.539 for the six midwestern states analyzed. The percentage of possible daily sunshine, S, can be obtained at any first-order Environment Sciences Services Administration (ESSA) Weather Bureau Station (formerly designated as United States Weather Bureau Station).

The long-wave radiation entering into the energy balance at the pavement surface consists of the long-wave radiation emitted by the pavement, Q_e, and the long-wave back radiation emitted by the atmosphere, Q_a. The long-wave radiation emitted from a unit area of pavement surface with no correction for cloud cover, Q_x, is expressed by the following theoretical equation:

$$Q_x = \sigma \epsilon T^4_{1R} \tag{11}$$

The emissivity, ϵ, varies according to the type of pavement surface, wave length, and average temperature of the pavement. The Stefan-Boltzmann constant, σ, has a value of 0.172×10^{-8} Btu/hr-ft^2-R^4.

Q_z, the long-wave back radiation affecting the energy balance at the pavement surface with no correction for cloud effects, is determined by an empirical formula developed by Geiger (23) as follows:

$$Q_z = \sigma T^4_{airR} \{G - J(10^{-\rho p})\} \tag{12}$$

In considering the work of a number of investigators, Geiger (23) assigned the following values to the constants in Eq. 12: $G = 0.77$, $J = 0.28$, and $\rho = 0.074$. The vapor pressure, p, in Eq. 12 can generally be considered to vary between 1 and 10 mm of mercury for climate near the ground surface (23).

Using the suggestion of Scott (13) that the net long-wave radiation entering into the energy balance at the pavement surface be corrected for cloud cover in a manner similar to that for short-wave radiation, an approach recommended by Geiger (23) was used as follows:

$$Q_e = Q_x \left(1 - N \frac{\overline{W}}{100}\right) \tag{13}$$

$$Q_a = Q_z \left(1 - N \frac{\overline{W}}{100}\right) \tag{14}$$

In Eqs. 13 and 14, N is a cloud-base factor whose value ranges between approximately 0.90 and 0.80 for cloud heights between approximately 1,000 ft and 6,000 ft respectively (23). These cloud heights are realistic for many geographical locations during the winter months. The percentage of cloud cover, $\overline{W}$, is equal to 0 percent for cloudless days and 100 percent for completely overcast days. $\overline{W}$ can be computed from the percentage of possible daily sunshine as follows:

$$\overline{W} = 100 - S \tag{15}$$

If average daily climatic input data are used in the heat-transfer model, it is necessary to assume that the percentage of cloud cover during the daytime carries into the nighttime also.

The rate of heat transfer by convection, Q_c, between the pavement surface and air is computed by the following method for a unit surface area:

$$Q_c = H \left(T_{air} - T_1\right) \tag{16}$$

The convection coefficient, H, is difficult to estimate because of the many variables involved. Previous studies by Dempsey (4) have shown that most investigations involving the convection coefficient have not been concerned with pavement surfaces. Most of the formulas apply to vertical walls and roofs of buildings.

An empirical formula developed by Vehrencamp (24) appears to be the most applicable to a pavement surface. He developed an empirical formula for determining the convection coefficient by using data obtained from a very large, very smooth, hard-packed, dry lake bed. The formula for determining the convection coefficient is as follows:

$$H = 122.93 \left\{0.00144\ V_m^{0.3} U^{0.7} + 0.00097 \left(V_1 - V_{air}\right)^{0.3}\right\} \tag{17}$$

The surface temperature, V_1, and the air temperature, V_{air}, are both in degrees centigrade. V_m is the average of the air temperature and pavement surface temperature in Kelvin degrees temperature, and it is calculated as follows:

$$V_m = 273.0 + \frac{V_1 + V_{air}}{2} \tag{18}$$

The wind velocity, U, in Eq. 17 is the average daily wind velocity in m/sec. Since the original equation developed by Vehrencamp (24) gave the convection coefficient in terms of g-cal/min-cm^2-C, Eq. 17 contains a factor of 122.93 to give the convection coefficient, H, in the more familiar units of Btu/hr-ft^2-F.

Equation 17 takes into consideration both the forced convection resulting from wind turbulence and free convection resulting from the buoyancy effect of air.

The maximum value of the convection coefficient is controlled to some extent by the mathematical stability requirement established by the forward-finite-difference approach.

When using the radiation heat-transfer equations and convection heat-transfer equation at the pavement surface node, it is necessary to develop a method for determining the air temperature after each time increment, $\Delta\theta$. Generally most ESSA Weather Bureau Stations record only the maximum and minimum daily air temperatures without regard to the times at which these temperatures occur. To provide a continuous daily temperature record for the heat-transfer model, it was necessary to determine the times at which the maximum and minimum temperatures occurred and interpolate between these times for intermediate temperatures.

Straub et al. (5) have shown that during a typical winter day the temperature varies according to a sine wave so that generally the minimum daily air temperature occurs early in the morning and the maximum daily air temperature occurs in the early afternoon. An analysis of the hourly pavement surface temperatures at the AASHO Road Test at Ottawa, Illinois, during 3 winter seasons showed that the average time of occurrence of the minimum daily temperature was about 4:00 a. m., and the average time of occurrence of the maximum daily temperature was about 1:00 p. m. for both portland cement concrete and asphalt concrete pavements. These findings indicated that the approximate times at which the minimum and maximum air temperatures occurred in Illinois during winter could be estimated as 4:00 a. m. and 1:00 p. m. respectively.

Scott (11, 12, 13) and Berg (14) indicated that heat transfer caused by transpiration, condensation, evaporation, and sublimation, Q_h, could be neglected without greatly affecting the energy balance at the pavement surface. Both Scott (11) and Berg (14) expressed formulas for determining the heat transfer by several of these methods; however, they found the results obtained by the formulas to be highly variable and totally unpredictable.

In the development of the heat-transfer model, the effects of transpiration, condensation, evaporation, and sublimation were neglected because of the uncertainty of their values at this time. Large error was not expected to be created in the energy balance at the pavement surface by assuming Q_h as zero. Transpiration can be neglected in pavement studies because this is related to vegetation growth. The heat flux resulting from condensation is lost when the condensate evaporates. Heat transfer by evaporation should be minimal if rainwater quickly drains off the pavement surface. Because snow removal from most pavements takes place shortly after the snow has fallen, heat flux caused by sublimation can also be disregarded.

Heat fluxes resulting from precipitation and moisture infiltration into the pavement system were not included in the energy balance because there is no accurate procedure to calculate these heat quantities at the present time. Furthermore, the extent of surface moisture infiltration is questionable and highly dependent on the type and condition of the pavement surface (25, 26, 27). For ideal pavement conditions, the heat flux caused by infiltration can be considered negligible.

Thermal Properties of Pavement Materials

The most important intrinsic factors considered in frost action are the thermal properties of the pavement materials, which include thermal conductivity, heat capacity, and latent heat of fusion. The heat-transfer model recognizes three different sets of thermal properties depending on whether the pavement material is in an unfrozen, freezing, or frozen condition.

The procedures for determining the thermal properties of the pavement materials have been described in detail by Dempsey (4). The thermal properties of the surface materials were determined from general tables of physical properties or from scientific research. The methods developed by Kersten (28) were found to be suitable for determining the thermal properties of the base, subbase, and subgrade soils.

The heat capacity of a pavement material during freezing is determined from the latent heat of fusion of the moisture in the material. When the moisture in the pavement freezes, the portion that is about to change phase remains at a constant temperature, the freezing temperature, until the latent heat of fusion is released. The time lag caused by this process retards the rate of frost penetration. The latent heat effect is incorporated into the finite-difference equations by using an approach described by Schenck (20), which makes use of a freezing zone. The freezing zone is a small, hypothetical temperature range over which freezing takes place. Because only moisture effects are considered in this range, the freezing heat capacity, C_f, in the freezing zone is a function of the moisture content, dry density, and the small freezing temperature range.

In the development of the heat-transfer model, the freezing zone was set at a 2 F temperature interval between variable input temperatures of 30 F and 32 F. The freezing heat capacity, C_f is calculated as follows:

$$C_f = \frac{144w\,\gamma_d}{200\gamma} \tag{19}$$

Equation 19 is divided by the total unit weight, γ, in order to be properly used in the finite-difference equations.

A comparison of the freezing heat capacity and unfrozen and frozen heat capacities for a granular base material with about 9 percent moisture is shown in Figure 6. It should be noted that even for a small moisture content the freezing heat capacity of the moisture is far greater than the unfrozen and frozen heat capacities of the material itself.

VALIDATION OF THE HEAT-TRANSFER MODEL

The validity of the heat-transfer model was established by using temperature data from laboratory studies and the AASHO Road Test at Ottawa, Illinois.

Initial temperature studies were made in the laboratory because these facilities provided for close control over the factors influencing heat transfer in soils. In the laboratory study, it was possible to determine whether the thermal properties of soils computed by the proposed methods were satisfactory and to study the influence any variations in the thermal properties would have on pavement temperatures predicted by the heat-transfer model.

A typical comparison between the measured temperature and theoretical temperature at the 6-in. depth in a composite laboratory specimen during a 13-day time period is shown in Figure 7. The general laboratory results revealed that the heat-transfer model accurately predicts soil temperatures.

The theoretical temperatures computed by the heat-transfer model were compared with measured temperatures for a test pavement at the AASHO Road Test to see if the model would work properly under field conditions. A more detailed discussion of the AASHO test pavement, thermal properties, and climatic data can be found in a previous report by Dempsey (4).

For the purpose of evaluating the heat-transfer model, a winter period from October 1, 1959, through March 31, 1960, was analyzed. Because pavement temperatures near the surface vary within a given day as well as from day to day, comparisons between the theoretical temperatures and measured temperatures were made at 6:00 a. m. and 3:00 p. m.

Figure 8 shows a graphical comparison between the

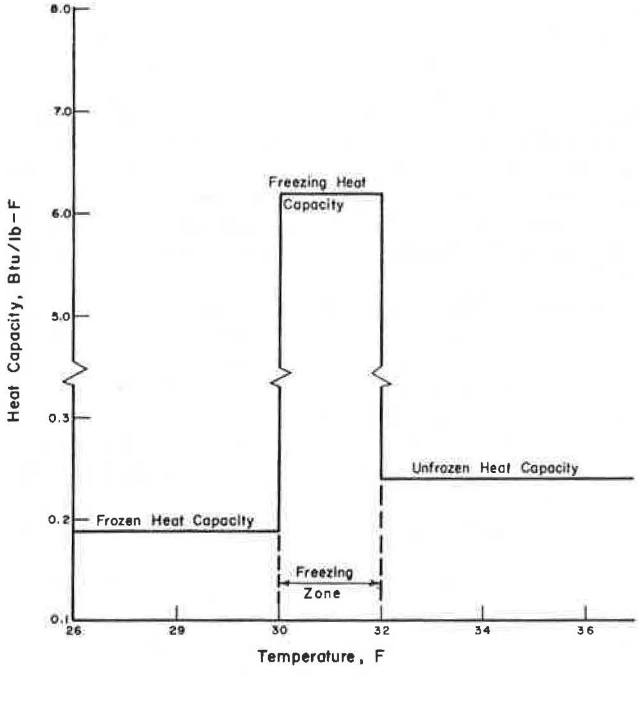

Figure 6. Effect of temperature on the heat capacity of a granular base material.

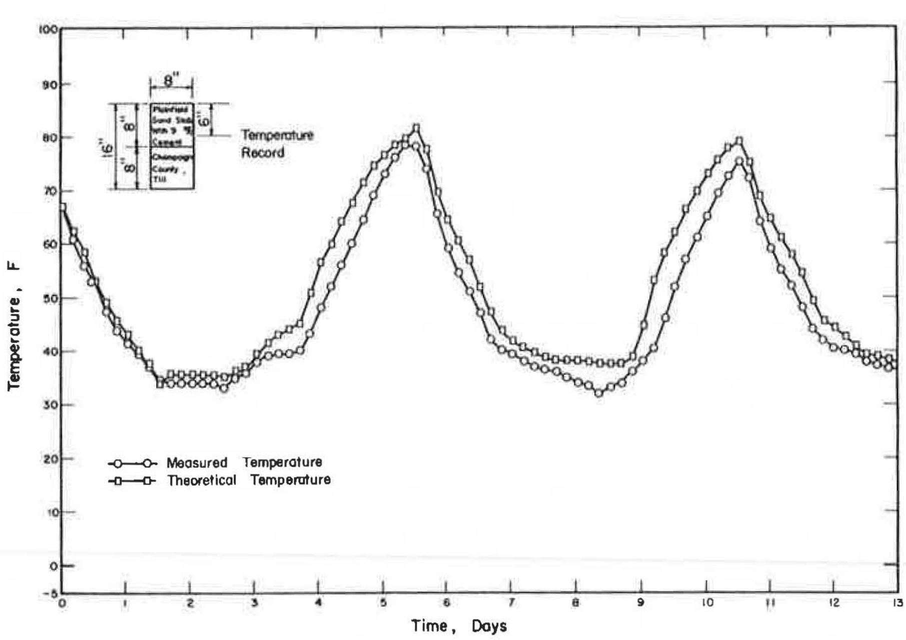

Figure 7. Comparison of measured and theoretical temperatures at 6-in. depth in a composite laboratory specimen.

measured temperature and theoretical temperature at the bottom of a 6-in. pavement surface at 6:00 a.m. The average difference between the measured temperature and theoretical temperature is 0.97 F.

A typical grpahical comparison between the measured temperature and theoretical temperature at 3:00 p.m. is shown in Figure 9. The average difference between the measured temperature and theoretical temperature is 0.73 at the 3-in. depth.

The validity of the heat-transfer model was further checked by comparing the number of freeze-thaw cycles predicted by the model with the number of freeze-thaw cycles in the actual pavement at the AASHO Road Test. Freezing in the pavement was considered to occur whenever the pavement temperature reached 30 F or less and remained at that temperature for more than 2 hours. Similarly, thawing was considered to occur whenever the pavement temperature exceeded 30 F and remained above that temperature for more than 2 hours.

At a depth of 3 in. in the pavement, 41 freeze-thaw cycles were determined from the theoretical temperatures as compared to 38 freeze-thaw cycles determined by analyzing the measured hourly temperatures. At the 6-in. depth, 15 theoretical freeze-thaw cycles were observed as compared to 17 freeze-thaw cycles determined from the measured temperatures for the test pavement at the AASHO Road Test.

Temperature comparisons for the subgrade would have been desirable, but measured data from the AASHO Road Test were not available. However, good agreement between the theoretical and measured temperatures at depths of 3 and 6 in. indicated that good temperature comparisons at greater depths would also exist if the thermal properties of the paving materials are carefully determined.

The excellent comparisons between the theoretical temperatures and measured temperatures and the good agreement between the number of freeze-thaw cycles at various depths indicate that the heat-transfer model is valid for predicting temperatures for use in frost action studies in multilayered pavement systems.

APPLICATIONS OF HEAT-TRANSFER MODEL

Engineering construction is greatly influenced by climate. The type of structure, its design, and its operation and maintenance are all affected by meteorological

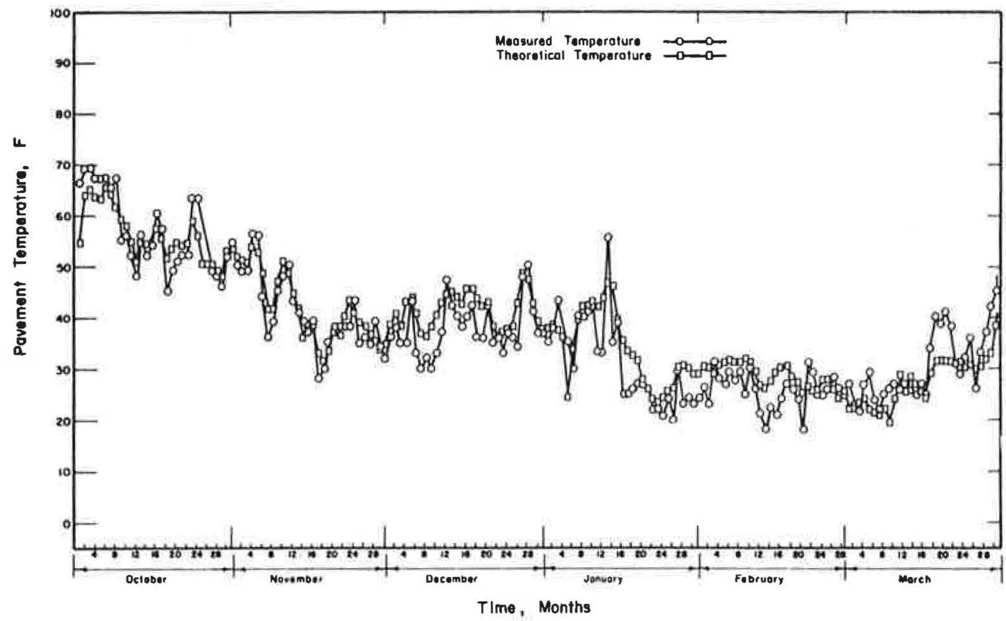

Figure 8. Comparison of measured and theoretical temperatures at the 6-in. depth of a 6-in. asphalt concrete pavement at 6:00 a. m. (AASHO Road Test, 1959 to 1960).

conditions. To evaluate properly the effect of these conditions on a structure, it is necessary to have a knowledge of the climate in which the structure is to be built and

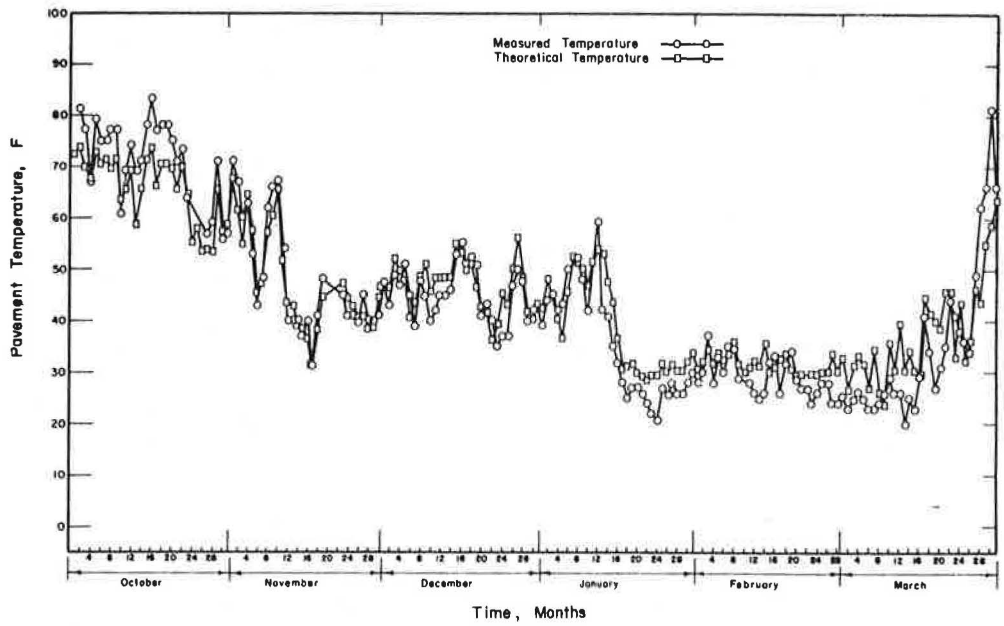

Figure 9. Comparison of measured and theoretical temperatures at the 3-in. depth of a 6-in. asphalt concrete pavement at 3:00 p. m. (AASHO Road Test).

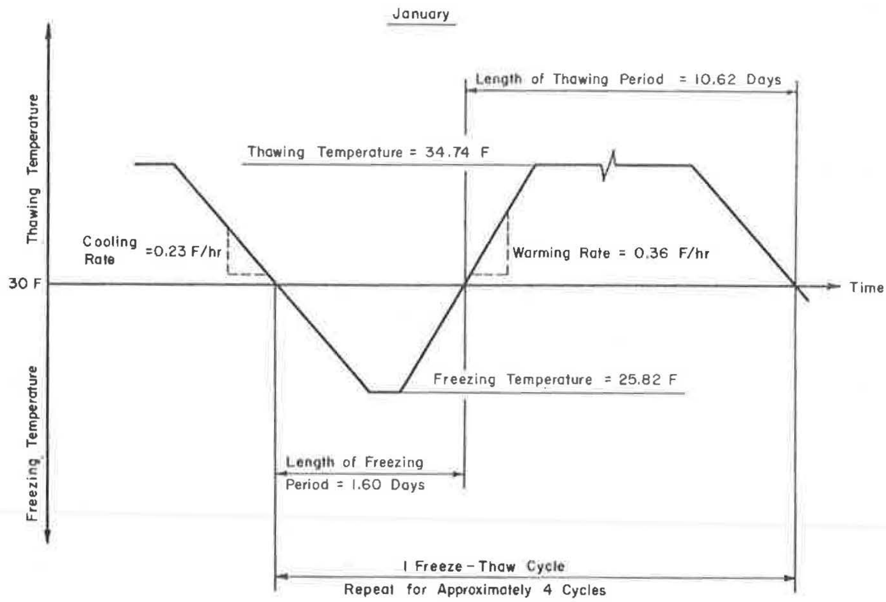

Figure 10. Characteristic frost action cycle.

to understand how the relevant meteorological parameters should be considered in its design, construction, and operation.

The heat-transfer model has application to an extensive range of engineering systems that are influenced by environmental factors. Thompson and Dempsey (29) have used the heat-transfer model to study frost action in pavement systems at various geographical locations in Illinois. Figure 10 shows a characteristic frost action cycle for central Illinois in January that was obtained by use of the model.

The heat-transfer model has numerous other applications in the areas of cold weather construction, asphalt pavement design, placement of underground utilities, and design of insulated pavements.

DISCUSSION OF HEAT-TRANSFER MODEL

Only a basic outline of the heat-transfer model has been presented in this report. A more detailed presentation of the development, validation, and utilization of the heat-transfer model can be found in previous work by Dempsey (4).

The heat-transfer model, which was developed by using basic heat-transfer theory, provides a means for accurately predicting temperatures in multilayered pavement systems. The model is very flexible and ideally suited for the study of frost action in pavements. It can be used for any pavement system, meteorological conditions, and geographical location.

The accuracy of the temperatures predicted by use of the heat-transfer model depends mainly on the quality of the input data and not the numerical methods of solution. The surface energy balance provided the most comprehensive procedure for incorporating the meteorological parameters into the heat-transfer model. It was important that the boundary conditions at the pavement surface be properly programmed because they are the major factors contributing to heat transfer in the pavement.

Close agreement between the measured and theoretical temperatures for laboratory and field data indicated that the assumptions, idealizations, and approximations made during the development of the heat-transfer model were sufficiently correct. Average differences between the measured temperatures and theoretical temperatures for depths of 3 and 6 in. in a test pavement at the AASHO Road Test were approximately 1 F.

In developing the heat-transfer model, the thermal properties were considered to be unaffected by changing moisture conditions. This assumption is reasonably correct because the thermal conductivity term and heat capacity term as used in the heat-transfer equation counteract each other to some extent. In general, the use of thermal properties that are not corrected for changing moisture conditions is considered to furnish good temperature results provided the moisture changes are small.

It is apparent that improvement in the accuracy of the pavement temperatures predicted by the heat-transfer model will result if a comprehensive procedure for analyzing moisture changes in the pavement system is developed. The procedure would have to consider the influence of such factors as the groundwater table, percolating rainwater, snowmelt, and unsaturated flow in the soil.

It was found during this investigation that usable field data for checking the heat-transfer model were difficult to find. The main reason for this problem was the fact that most available pavement temperature measurements in the field were made at sporadic time intervals. In this study, field temperature measurements recorded hourly during each day were found to be best suited for checking the temperatures predicted by use of the heat-transfer model. Hourly temperature records are especially desirable when making temperature comparisons near the pavement surface because these temperatures can vary considerably within a single day. It was evident from this study that field temperature measurements that have been made at regular time intervals and that have been well documented are needed for future model checks. It is also necessary to record other climatic conditions such as maximum and minimum air temperatures, wind velocity, amount of daily sunshine, rainfall, snowfall, and relative humidity. The condition of the pavement surface (snow cover, precipitation, cleanness, etc.) should also be recorded.

The heat-transfer model can be used to provide more complete records of pavement temperatures than field studies. The model provides a fast, efficient, and economical method for determining temperatures for frost action studies in pavement systems based on many years of climatic record. Complete frost action analyses, which would include characterizing frost action at five or six critical depths in a pavement system for a period of 10 years, would require approximately 60 min of IBM 360/75 computer time. It is apparent that the cost would be considerably less than that required for even a short-duration frost action study of 1 or 2 years in the field. Instrumentation and labor costs would exceed the cost of using the modeling procedure after a very short time. Therefore, it is apparent that the heat-transfer model provides an economical as well as accurate procedure for predicting frost action in pavement systems.

SUMMARY AND CONCLUSIONS

Summary

An investigation was conducted to develop a satisfactory and realistic procedure for evaluating frost action in multilayered pavement systems. Climatic data were the major input information required. An extensive literature review was conducted to determine the extrinsic and intrinsic factors that were important to the development of a heat-transfer theory for a pavement system. The various methods for predicting pavement temperatures and frost depth were investigated. Based on available information, a heat-transfer model was developed to evaluate frost action in multilayered pavement systems. The theoretical temperatures predicted by use of the heat-transfer model were checked with laboratory data and with field data, and the heat-transfer model was determined to be valid.

While checking the heat-transfer model, it was found that the quality of the input data would exert considerable control on the accuracy of the predicted temperatures. It was apparent that the heat-transfer model was adaptable to the climatic data for any geographical location and for any pavement system.

The application of the heat-transfer model to the study of frost action in a typical pavement system was demonstrated. It was determined that the heat-transfer model was satisfactory for characterizing frost action and temperature-related effects in multilayered pavement systems.

Conclusions

From the results of this investigation, the following conclusions were made:

1. The one-dimensional, forward-finite-difference, heat-transfer model provides a valid means for predicting pavement temperatures for evaluating frost action.
2. The approach developed furnishes frost penetration data as well as detailed predictions of temperatures throughout the pavement profile based on past climatic record.
3. The heat energy balance method used to relate meteorological conditions to the pavement surface temperature provides a comprehensive approach to temperature predictions in pavements.
4. Long-wave and short-wave radiation are important heat energy sources affecting pavement temperatures.
5. The heat-transfer model can be used to predict quickly and economically temperatures and depths of frost penetration in pavements over long periods of time.
6. The heat-transfer model displays potential uses for many types of environmental research.

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the state of Illinois, Division of Highways, or the Bureau of Public Roads.

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Appendix A

DEFINITION OF SYMBOLS

The symbols used in the finite-difference equations are defined in the following:

A = radiation equation constant;

a = absorptivity of radiation by a surface;
B = radiation equation constant;
C = general mass heat capacity designation, Btu/lb-F;
C_f = mass heat capacity of a freezing material, Btu/lb-F;
G = Geiger constant;
H = convection coefficient, Btu/hr-ft^2-F;
J = Geiger constant;
K = general thermal conductivity designation, Btu/hr-ft-F;
N = cloud-base factor;
p = vapor pressure, mm;
Q_a = heat flux resulting from long-wave radiation emitted by the atmosphere, Btu/ft^2-hr;
Q_c = heat flux resulting from convective heat transfer, Btu/ft^2-hr;
Q_e = heat flux resulting from long-wave radiation emitted by the pavement surface, Btu/ft^2-hr;
Q_g = heat flux conducted into pavement, Btu/ft^2-hr;
Q_h = heat flux resulting from transpiration, condensation, evaporation, and sublimation, Btu/ft^2-hr;
Q_i = heat flux resulting from incident short-wave radiation, Btu/ft^2-hr;
Q_r = heat flux resulting from reflected short-wave radiation, Btu/ft^2-hr;
Q_{rad} = net radiation flux influencing heat transfer at a surface, Btu/ft^2-hr;
Q_s = net short-wave radiation entering into the energy balance at the pavement surface, Btu/ft^2-hr;
Q_x = long-wave radiation emitted from a surface without cloud cover correction, Btu/ft^2-hr;
Q_z = long-wave back radiation not corrected for cloud cover, Btu/ft^2-hr;
R^* = extraterrestrial radiation, Btu/ft^2-day;
S = percentage of possible daily sunshine, percent;
T_1 = temperature of surface node, F;
T_{1R} = Rankine temperature of surface node, F;
T_{air} = air temperature, F;
T_{airR} = Rankine temperature of air, F;
T_{con} = temperature of constant temperature node, F;
T_n = nodal temperature, F;
T_n' = nodal temperature after a time step, F;
U = wind velocity, m/sec;
V_1 = surface temperature, C^e;
V_{air} = air temperature, C^e;
V_m = average of air temperature and surface temperature in Kelvin temperature, C^e;
W = total depth of termination nodes, ft, in.;
$\overline{W}$ = percentage of cloud cover at night, percent;
ΔW = depth of a termination node, ft, in.;
w = water content based on dry weight, percent;
X = total depth of normal nodes, ft, in.;
ΔX = depth of a normal node, ft, in.;
Y = total depth of finite-difference pavement system, ft, in.;
α = thermal diffusivity, $K/C\gamma$, ft^2/hr;
γ = total unit weight, pcf;
γ_d = dry unit weight, pcf;
ϵ = emissivity of radiation by a surface;
$\Delta\theta$ = time step, hr;
ρ = Geiger constant; and
σ = Stefan-Boltzmann constant, 0.172×10^{-8}, Btu/hr-ft^2-R^4.