Integrated Computer Model to Estimate Moisture and Temperature Effects Beneath Pavements

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The Integrated Model, developed for highway engineers involved in pavement design and management, provides a computer simulation of climatic effects on the behavior of pavement materials and subgrade conditions or characteristics over several years of operation of either asphaltic concrete or portland cement pavements. The results indicate that reasonable predictions of moisture and temperature conditions, frost penetration and heave, thaw weakening, and the accompanying effect on pavement moduli can be achieved. An overview of the model is provided and some typical results for two climatic regions in the United States are presented. The input variables were reduced to a minimum number and were assembled so that they were input in a free format on input user screens that appear sequentially in the course of data entry. Climatic data have been assembled and processed within the files of the program so that users are relieved of obtaining and entering large quantities of this information. At the same time, users can enter their own data if available. Carefully selected default options that are representative of material properties of many typical highway pavement structures may be used, or a compendium of alternative data for a variety of soils based on texture and index properties is provided in the User's Manual. Deep ground temperatures and moisture conditions can be estimated from regional maps supplied in the Manual. These features should make the Integrated Model attractive to most highway design offices. The results of this simulation procedure will provide an important contribution to the complex process of assessing climatic effects on pavement design and management.

Rational methods of pavement management for America's massive, aging road system require sophisticated computer models capable of simulating not only load repetitions and configurations, and material properties, but perhaps more importantly the environmental factors that affect pavement design, performance, and longevity.

Although the importance of climatic influences on pavement performance has been recognized for the last 50 years or more, efforts to incorporate these parameters into pavement management in a comprehensive manner have been less successful than have load response models.

Traditionally, the worst-case scenario, usually the fully saturated case, for base course, subbase, and subgrade has been adopted for design purposes. Recent studies are showing that important climatic factors such as temperature, rainfall, wind speed, and solar radiation can be modeled accurately enough for design purposes by using a combination of deterministic and stochastic analytical methods.

These techniques provide the input into climatic-materials-structural, infiltration-drainage, and frost penetration-frost heave and thaw weakening models that result in meaningful simulations of the behavior of pavement materials and of subgrade conditions or characteristics over several years of operation.

The Integrated Model, developed by the Texas Transportation Institute under contract with FHWA, U.S. Department of Transportation, has been designed to perform these tasks. It can be applied to either asphaltic concrete pavements or portland cement pavements.

The model shown in Figure 1 is composed of four major components: the precipitation model [Precip Model (*1*)], the infiltration and drainage model [ID Model (*2*)], the climatic-materials-structural model [CMS Model (*3*)], and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) frost heave-thaw settlement model [CRREL Model (*4*)]. A schematic interpretation of their interaction is shown in Figure 1.

For the most part, the component models were developed independently of one another to perform specific tasks. The purpose of the project in developing the Integrated Model was to combine these modules into one major pavement structure and subgrade analysis. As a result, portions of some of the original programs are no longer required, and methods of computations in some segments have been substituted for others. Significant modifications, additions, deletions, the assembly of data, and verification of the program have represented the major developments in the Integrated Model.

This paper is taken from a previously published report (*5*). The paper provides an overview of the model and presents some typical results for various climatic regions in the United States.

FEATURES

General

The Integrated Model has been modified to run on an IBM-compatible microcomputer with a minimum of 286 kilobytes of memory. Full-screen input processor capabilities now allow the user to enter data with considerably more ease and with substantially reduced opportunity for error. These modifications should make this program especially attractive to highway engineers.

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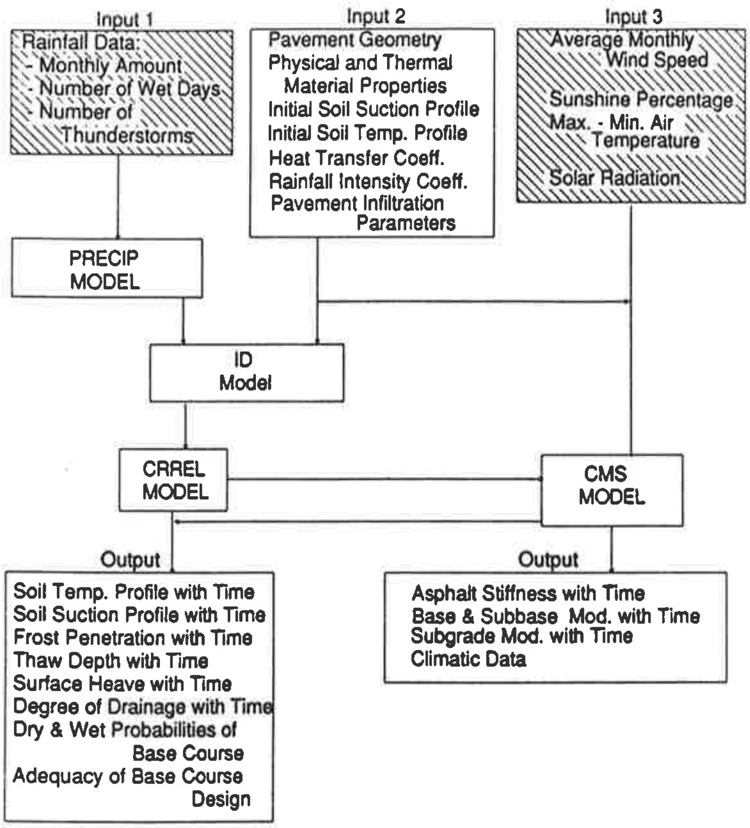

FIGURE 1 Integrated pavement model.

Input

Because a large quantity of climatic input data are required to obtain statistically significant results, users may elect to use representative data from any one of the nine climatic zones in the United States rather than entering their own data for a specific site (Figure 2 and Table 1).

The input data in Figure 1 is shown in three windows. The shaded windows represent data that have been provided in the files of the program. Input 1, which is required for the Precip Model, contains 30 years of precipitation data from the National Oceanic and Atmospheric Administration (NOAA) for each of the nine climatic zones shown in Figure 2. In some cases additional cities have been included, making a total of 15 specific sites. Where the data from more than one city in a region have been tabulated, the average values from the two weather stations may be selected for computations. The data consist of the average monthly rainfall, the number of wet days per month, and the number of thunderstorms.

Input screens allowing users to enter their own data appear sequentially in the course of entering data for the Integrated Model. This information may be obtained from U.S. Weather Bureau Data Summary Sheets for numerous locations throughout the United States.

Input 3 also appears as a shaded window and represents the data required to generate the heat flux boundary conditions at the surface of the pavement. The data in Input 3 consist of monthly averages of air temperature (maximum and minimum), wind speed, and sunshine percentage. Solar radiation is computed in a subroutine that requires only latitude as input. Because air temperature, wind speed, and sunshine percentage represent relatively large quantities of data, the user may prefer to use the information that is tabulated and stored in the program. However, because solar radiation requires only the latitude of the location, users are encouraged to input this value. Again the option of using site-specific data is provided in this input file.

Input 2, which is represented by the clear window in Figure 1, is unique to each site. It consists of pavement structure geometry, material components, physical and thermal material properties, surface heat transfer coefficients, pavement infiltration parameters, and initial soil temperature and suction profiles. Although this list of input variables may appear somewhat daunting at the outset, many of the values can be selected from a list of typical values, or the default options will often be acceptable.

Output

The amount of the level of detail of output from the Integrated Model may be selected by the user. For example, output from the Precip Model consisting of the amount of precipitation, the sequence of wet and dry days, the number of thunder-

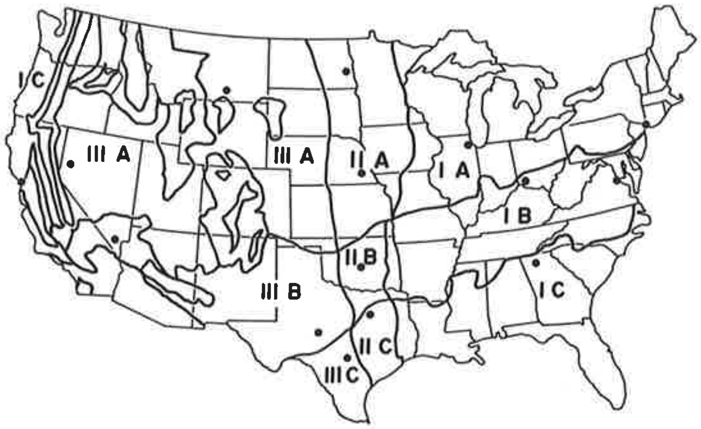

FIGURE 2 Locations of selected cities for each environmental region.

storms, and the distribution of wet days for each month of the analysis may not always be of interest. However this information may occasionally be relevant in assessing the reasonableness of the results. Similarly, the ID Model provides a variety of probabilistic events that generally will be of little interest to the typical user. As a result, either this output has been suppressed or it may appear at the user's discretion.

The output shown at the bottom of Figure 1 will prevail. Since the program will generally simulate conditions for a period of a year or more, monthly or bimonthly samples should be adequate. Provision is made to regulate the frequency of the output.

Although the output in Figure 1 is shown in two different windows, no distinction is made in viewing the results from the program. It is shown here in separate windows only to give the user a general idea of where the computations occur.

The output information is fairly self-evident and will not be reviewed here. Details of the output will be addressed in examples presented later in the paper. A variety of graphic displays allow the user to view many of the results in graphical form.

Pavement Segments In Which Component Models are Used

The four major components of the Integrated Model are used in individual regions of the pavement structure for various temperature and moisture conditions. Figure 3 shows where each of the component models is employed in a typical pavement structure during the course of calculations.

Figure 3 has been divided into two temperature zones: above freezing and below freezing. Additional divisions are based on moisture and temperature conditions.

1. The Precip Model provides the upper-boundary moisture conditions when temperatures are above freezing.
2. The ID Model accounts for the infiltration analysis and the moisture conditions in the materials above the subgrade.
3. Moisture conditions above the surface and infiltration into the base course are not considered when temperatures are below freezing.
4. The heat flux boundary condition at the surface and the temperature profile through the asphaltic or portland cement concrete layers are determined by the CMS Model.
5. All moisture and temperature calculations in the remaining segments of the pavement structure are performed by the CRREL Model.
6. The moisture and temperature conditions at the base of the bottom layer may be held constant with time or varied in a specified manner.
7. Values of resilient moduli depend on moisture content. The moisture contents are determined by the CRREL Model, but the CMS Model is responsible for all calculations of moduli in the base course, subbase, and subgrade.

TABLE 1 SELECTED CITIES FOR EACH ENVIRONMENTAL REGION

Moisture Region	Temperature Region		
	A	B	C
I	New York, NY Chicago, IL	Washington, D.C. Cincinnati, OH	San Francisco, CA Atlanta, GA
II	Fargo, ND Lincoln, NE	Oklahoma City, OK	Dallas, TX
III	Reno, NV Billings, MT	Las Vegas, NV San Angelo, TX	San Antonio, TX

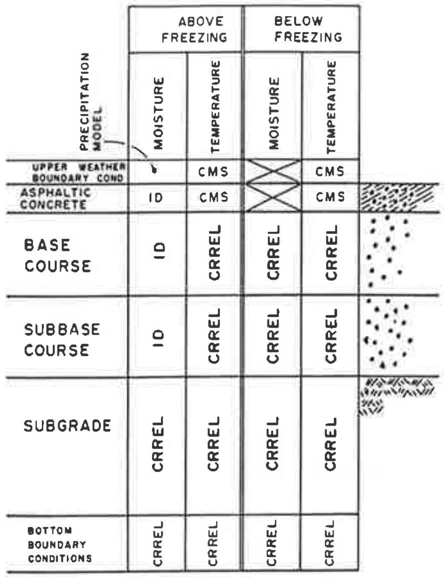

FIGURE 3 Pavement segments where component models are used.

INNOVATIONS IN THE INTEGRATED MODEL

Boundary Condition Subroutines

Surface Conditions

Temperatures throughout the pavement structure are dominated by atmospheric conditions at the surface. Although it is easy to monitor air temperatures, there is not a direct correspondence between air temperatures and surface temperatures. The Corps of Engineers (*6*) has used the surface correction factor (n) to relate air temperatures to surface temperatures. Although the Corps was cognizant of the shortcomings of this approach, a heat flux surface boundary condition was not incorporated into the CRREL Model before the assembly and development of the Integrated Model. The CMS Model is now used to generate a heat flux at the surface, which then establishes the temperature profile through the asphalt or portland cement concrete layers.

Top of Subgrade

In many regions west of the Mississippi River, highway subgrades are composed of fine-grained, low-permeability soils that remain unsaturated throughout the year.

Infiltration of water through the pavement during or after a rainstorm often will produce free water in the base course and subbase. Thus, an abrupt boundary between a positive water pressure in the subbase and a negative water pressure or suction in the subgrade will exist at the interface. The gradient at this boundary equals the sum of the positive pressure in the subbase plus the suction in the subgrade times a pore pressure transfer coefficient (r). The transfer coefficient has units of l/distance.

The concept has been adopted from the theory of an insulted, heated steel rod of initial uniform temperature with one end radiating heat to the air at a constant lower temperature. The physical and thermal properties of the rod compared with those of the air are vastly different, and the formulation reveals that the transfer coefficient in the case of the heated rod is a function of the Stefan Boltzmann constant of heat transfer—the absolute temperature of the rod and the thermal conductivity of the rod. The units of the transfer coefficient are l/distance.

Mitchell (*7*), using this analogy, showed that a cylinder of soil of known constant suction, enclosed on all sides but open on one end to the atmosphere at a higher suction, underwent increases in suction at the exposed surface and along its entire length in general accordance with the theory used to predict the cooling of the steel rod.

It is postulated here that changes in suction in the subgrade will occur because of changes in water pressure in the base course/subbase in general accordance with the theory of the cooling steel rod or with the changes in suction along the column of unsaturated soil with one end exposed to the atmosphere.

The appropriate range of values for r in the Integrated Model appears to lie between 1.0×10^{-6}/in. and 1.0/in. and is controlled by the magnitude of the permeabilities on each side of the interface. A suggested maximum value for r is numerically equal to the computed velocity of the water into the subgrade under a unit hydraulic gradient.

Bottom Boundary Conditions

Suction

Bottom boundary conditions of temperature and water pressure or suction are entered every 2 weeks for the period of 1 year.

Russam and Coleman (*8*) have found that, in arid climates, if the water table exists within a depth of 25 ft of the pavement surface it will dominate the moisture conditions in the subgrade. Thus, for initial conditions a linear hydrostatic variation of suction from the water table to the top of the subgrade is assumed unless data from locally instrumented sites indicate otherwise. Under the latter circumstances, the minimum depth of the water table must be taken as the maximum depth of the analysis because the CRREL Model is not designed to deal with moisture conditions extending below the water table. As the water table falls in drier periods of the year, suctions can be calculated and input to the lower boundary conditions as specified.

If the water table is below 25 ft, another technique has been adopted in which measured values of suction are not available. Russam and Coleman (*8*) have suggested that the Thornthwaite Moisture Index (*9*) may be used to predict equilibrium soil suction conditions. Figure 4 shows the relationship of soil suction and Thornthwaite Moisture Index for three different soils. Figure 5 provides contours of the Thornthwaite Moisture Index for the continental United States. Thus, an estimate of the bottom boundary moisture conditions can readily be determined from the two figures.

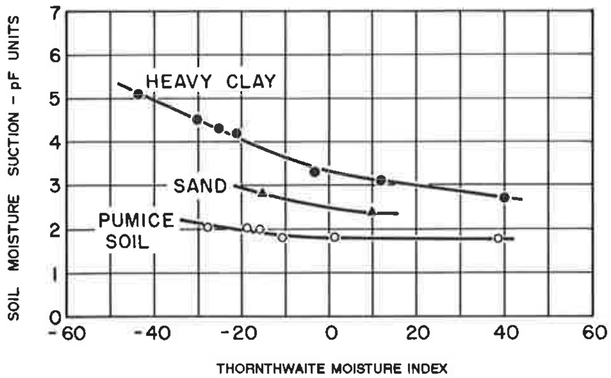

FIGURE 4 Variation of soil suction of road subgrade with Thornthwaite Moisture Index (*8*).

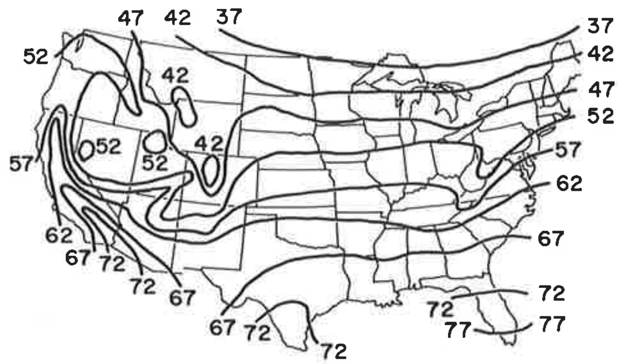

FIGURE 6 Temperature (°F) of water from nonthermal wells at depths of 30 to 60 ft (*11*).

An initial soil suction profile from the bottom boundary to the top of the subgrade on January 1 of the beginning year is required. Thus, an estimate of the position of the water table at that time of year must be made. If no water table is present, the equilibrium suction value may be used throughout the depth of the subgrade.

Temperature

Bottom temperature conditions are handled in much the same way as values of suction. It is desirable to extend the analysis to a depth of constant ground temperature. This value varies with location, but frequently it is on the order of 12 ft [Dempsey et al. (*3*), Fluker (*10*), and others]. Figure 6 provides a measure of bottom soil temperature values for the continental United States if local data are unavailable.

If the depth of the analysis is significantly less than 12 ft because of a high water table, some accommodation will have to be made for changing soil temperatures at the bottom nodes over the period of analysis. It is not possible to provide default options for every situation, and users will have to provide their best estimates based on data and local experience at their location.

An initial soil temperature profile is also required for January 1. A linear relationship between the January mean monthly air temperature at the surface and the bottom constant ground temperature may be assumed. This procedure is equivalent to using an n factor of 1 for surface conditions.

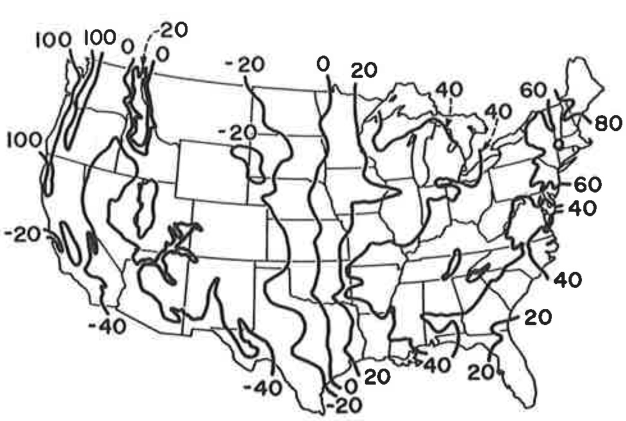

FIGURE 5 Thornthwaite Moisture Index distribution in the United States (*9*).

Base Course/Subbase Moisture Conditions

The drainage analysis in the ID Model considers an initially saturated subbase/base course and computes the time for varying degrees of drainage. However, it is unrealistic to assume that this pavement component ever becomes saturated, especially for free-draining base courses in the more arid regions of the nation. The depth of free water in the subbase/base course is estimated by multiplying the probability of having a wet base course for a given month (one minus the probability of having a dry base course) times the thickness of the subbase/base course. Values for intervening days are computed by linear interpolation.

Unsaturated, Unfrozen Permeability and Temperature-Vapor Pressure

Moisture flow in unsaturated soil conditions requires a model to characterize permeability with changing soil suction and with the formation of ice in the pore spaces of the soil.

The changes in unfrozen water content with time can be expressed as

$$\frac{\delta\theta_u}{\delta t} = \frac{\delta\theta_u}{\delta h_p} \cdot \frac{\delta h}{\delta t} \tag{1}$$

where

θ_u = volumetric water content (unfrozen),
h_p = pore water pressure (suction), and
h = total head (pressure head plus elevation head).

$\delta\theta_u/\delta h_p$ is the slope of the volumetric water content suction relationship or the moisture characteristic curve. This function can be linearized by plotting it on a log-log plot, resulting in

$$\theta_u = \frac{n}{A_w|h_p|^{X_w} + 1} \quad (2)$$

where n equals porosity. A_w and X_w are Gardner's coefficients (*12*), which can be characterized for specific soils based on grain size and plasticity characteristics.

The permeability is related to the soil suction in a similar manner.

$$K_h = \frac{K_s}{A_k|h_p|^{X_k} + 1} \quad (3)$$

where K_s is saturated permeability and A_k and X_k are Gardner's coefficients for permeability.

The original formulation of moisture flow in the CRREL Model divided a freezing column of soil into three zones: a "fully frozen zone," a "freezing zone," and an "unfrozen zone."

Moisture flow was not considered in the fully frozen zone, and Equations 2 and 3 were applied in the unfrozen zone. However, in the freezing zone, the CRREL Model required some method to account for the apparent decrease in permeability that accompanied the formation of ice in the pore spaces of the soil. In the freezing zone the permeability was described as

$$K_f = K_h|h_p|\ 10^{-E\theta_i} \quad (4)$$

where θ_i is ice content and E is a parameter required to reduce K_h accordingly. The E parameter was evaluated by trial and error until the model predicted what was observed in the laboratory or field for various soils.

The Integrated Model eliminates the E parameter by adopting the principle that changes in permeability in the freezing zone occur because of the high suctions that are developed in that zone rather than from ice blocking the pore spaces in the soil structure. This principle implies that Equations 2 and 3 remain applicable, and that a relationship between suction and temperature is required at temperatures below freezing.

This relationship has been developed from the original work by Washburn (*13*) and is described in equation form as

$$h_p = 2.3026 \left(\frac{RT}{\nu}\right) \log_{10} \left(\frac{p_w}{p_0}\right) \quad (5)$$

where

h_p = the suction (in cm) of water at the Kelvin temperature (T),
R = the universal gas constant (= 8.314×10^7 erg/°K-mole),
T = the absolute temperature (°K),
ν = 1.7686×10^4 gm-cm/mole-sec² for water,
pw/p_0 = the relative vapor pressure of water,

and

$$\log_{10}\left(\frac{p_w}{p_0}\right) = \frac{1.1389t + 2445.5646}{273.1 + t} + 8.2312 \log_{10}(273.1 + t) - 11.09691 - 0.01019t - 0.12486 \times 10^{-5}t^2 + 9.084 \times 10^{-8}t^3$$

where

t = the temperature (°C),
p_w = the vapor pressure of unfrozen water at t°C, and
p_0 = the vapor pressure of water at 0°C (= 4.579 mm of mercury).

Thus, knowing the temperature allows the suction to be determined, and from the moisture characteristic curve, the unfrozen water is determined. Equations 2, 3, and 5 provide a continuous physical relationship among the variables of temperature, suction, and permeability. This addition has eliminated the need to identify zones as frozen, freezing, and unfrozen. A continuous process is now used to move from the unfrozen to the frozen condition.

Time Step-Depth Increment Relationships

The size of the time steps used in the program to march forward in time is of interest to the user for two reasons: (*a*) it controls the running time of the program to complete a full year and (*b*) if the time step is too large, it causes an unstable growth of the errors in computation. The CMS Model uses the forward difference method for which stability criteria are known. Experimentation with the CRREL Model has shown that it remains stable for much longer time steps than does the CMS Model. The maximum time steps that can be used in the Integrated Model are therefore controlled by the CMS Model and are summarized as follows:

Increment Size (in.)	*Time Step (hr)*
1.0	Unstable
2.0	0.125
4.0	0.50

TYPICAL OUTPUT RESULTS

The Integrated Model has been used at several sites to demonstrate both the accuracy and the discrepancies that may be expected between the predicted results and the actual observed values in the field. The source of the discrepancies is systematic errors in the Integrated Model. Such errors are introduced by assumptions that do not match the reality. They may be stated briefly as

1. The temperature and rainfall patterns generated by the Integrated Model.
2. The assumed water content-versus-suction relation in each soil layer, which does not include hysteresis.
3. The assumed permeability-versus-section relation in each soil.

4. The inability of the permeability relation to represent the effects of cracks in transmitting water in both liquid and vapor phases.

The Integrated Model does not "predict;" instead it computes expected results based on historical weather trends and is intended to be used for design purposes. In design, it is not essential to match exactly the measured temperatures, suctions, and layer moduli at the exact time they occur, but it is important to determine realistic ranges of these during each month and each season. This capability is more useful in design than any other; the comparisons made below demonstrate and compare typical results that can be expected from this computer model.

Measured field data from three sites were compared with the model, but because of space limitations only two are presented.

1. Amarillo, Texas, which represents a dry, freeze-thaw cycling climate with a clay subgrade.
2. Deland, Piatt County, Illinois, which represents a wet-hard freeze climate with a silty subgrade.

Comparisons at Amarillo, Tex.

The instrumented site in Amarillo has been built as a covered area analogous to a slab on an expansive clay subgrade with a 6-in. (15-cm) sand layer beneath a polyethylene plastic sheet 24 ft by 40 ft (7.3 m by 12.2 m) in plan dimensions. Surface elevations, suction, and temperature measurements to a depth of 8 ft (2.4 m) were made each month.

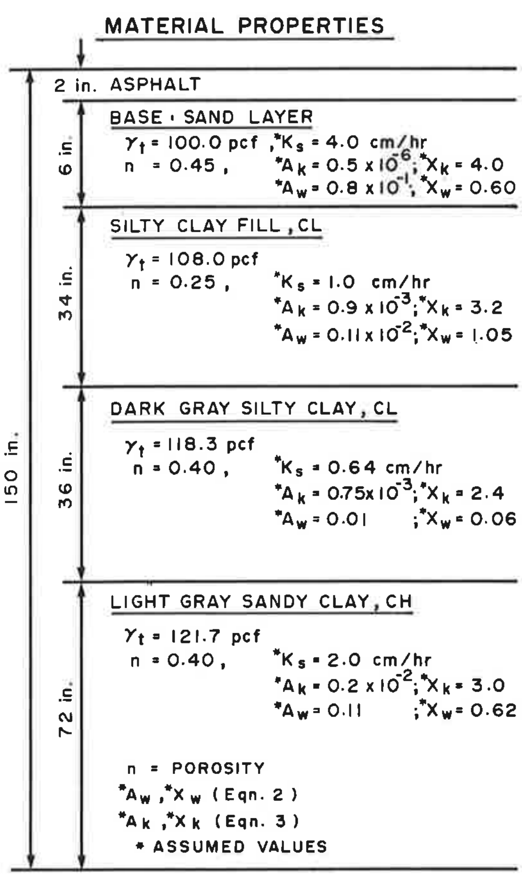

FIGURE 7 Amarillo, Texas: soil profile and properties.

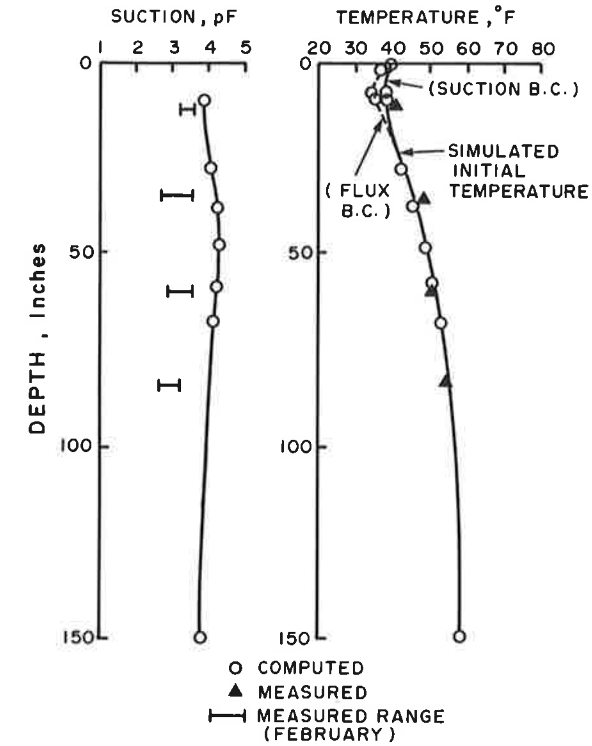

FIGURE 8 Amarillo, Texas: initial measured and simulated suction and temperature profiles, January 1.

The soil layers at the Amarillo test site are shown in Figure 7 along with the total unit weight, porosity, and assumed soil properties. Figure 8 shows the initial suction and temperature profiles assumed for a typical January 1 date along with measured values of the same profiles made in January. Figure 9 shows the measured and computed suction profiles at various times during the year. Figure 10 shows the measured and computed temperature profiles at the same times of the year. The difference in temperature profiles between the flux and suction boundary conditions brackets the actual measured temperatures, indicating perhaps that a different "*r*-value" for the flux boundary condition may be able to match the field temperature data very well while falling consistently within the measured suction range.

Comparisons at Deland, Piatt County, Illinois

The instrumented site in Piatt County, Illinois, near Deland was on a rural road, FAS Route 537. The pavement consists of a double bituminous surface treatment on an 8-in. (20-cm) aggregate base course that was 24 ft (7.3 m) wide with 6-ft (1.8-m) unpaved shoulders. Suction, temperature, and frost depth measurements were made periodically with the measurement dates spaced 3 to 4 months apart.

The soil layers and soil properties at the Piatt County site are shown in Figure 11. The water table fluctuated throughout

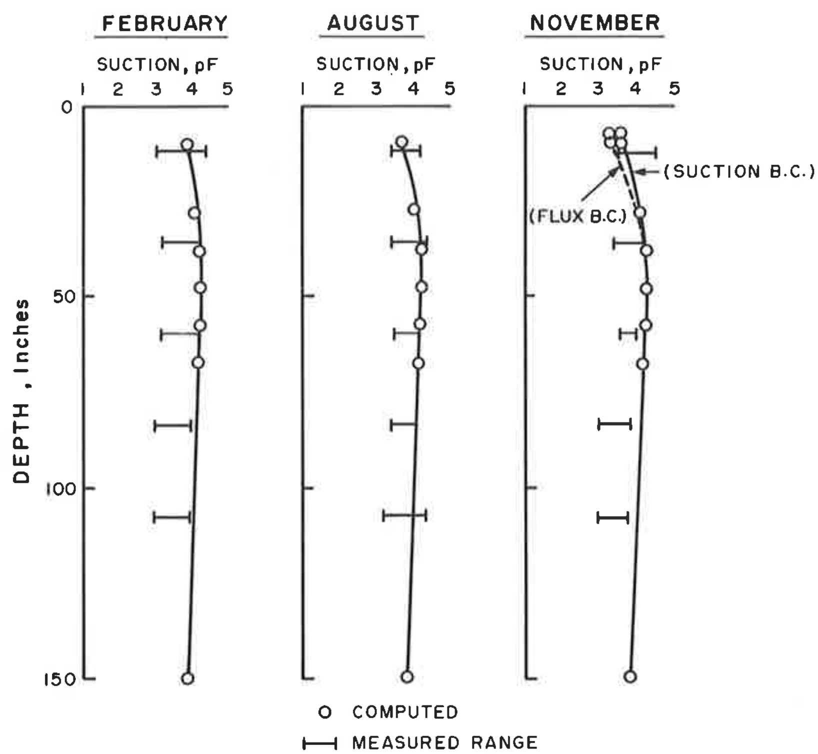

FIGURE 9 Amarillo, Texas: measured ranges and computed suction profiles at various times of the year.

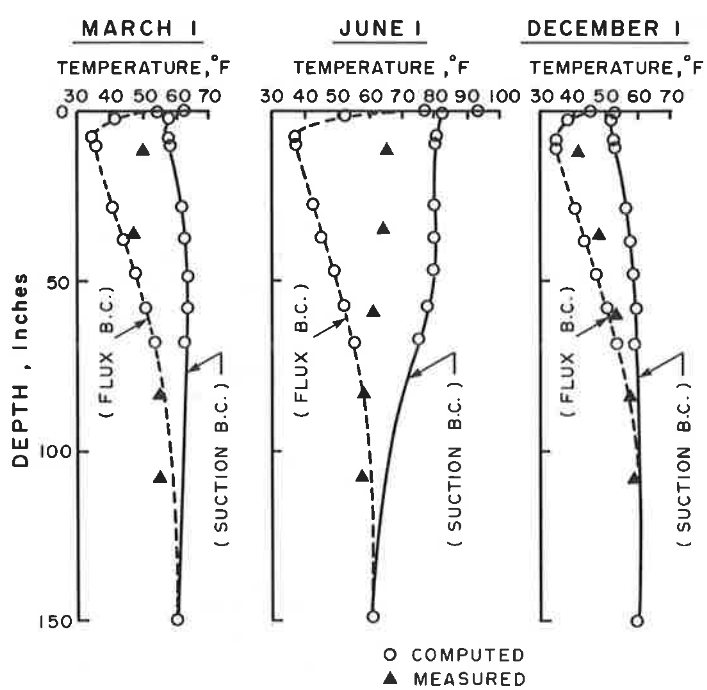

FIGURE 10 Amarillo, Texas: measured ranges and computed temperature profiles at various times of the year.

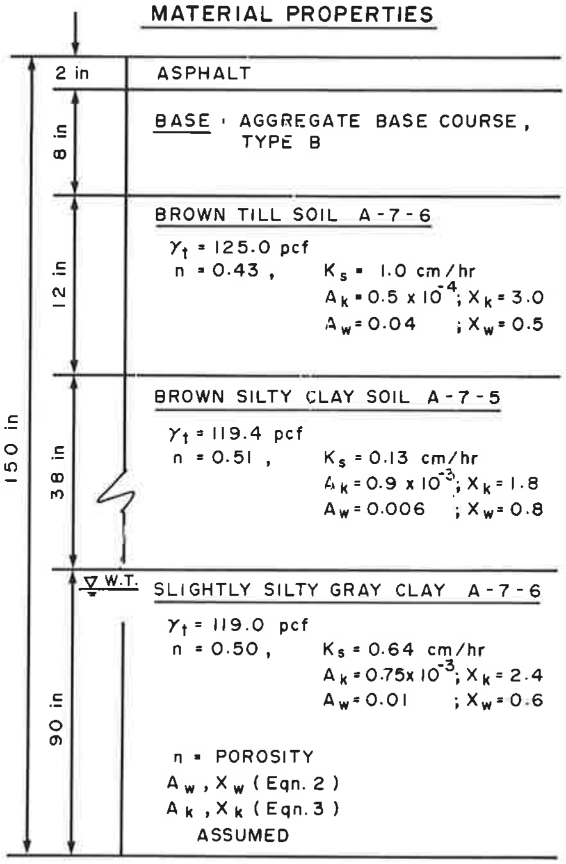

FIGURE 11 Deland, Piatt County, Illinois: soil profile and properties.

the year from a high elevation of 46 in. (1.2 m) below subgrade level to a low of 105 in. (2.7 m) below the subgrade. Figure 12 shows the assumed initial suction and temperature profiles for January 1 of the simulated year. In this case, both the flux and the suction boundary condition between the base course and subgrade provide practically the same pore water pressures as an initial condition. This is because of the small difference of negative pore water pressures at the interface between the base course and the subgrade. The initial temperature profile is virtually the same with both boundary conditions. Figure 13 shows the measured and computed pore water pressure profiles at two different times during the year. The computed pore water pressures are practically the same for both boundary conditions. Both have the same profile pattern and are nearly the same as the values measured with tensiometers.

Figure 14 shows the measured and computed temperature profiles at three different times during the year. The computed temperature profiles are the same to three significant figures for the two boundary conditions, unlike those for the Amarillo site. In the present case, both boundary conditions predict a temperature profile that is fairly close to the values measured in the field.

Evaluation of Simulations

The simulated temperatures using the two boundary conditions, flux and suction, commonly bracketed the measured values. The simulated suctions and pore water pressures followed the same patterns as in the measured data and were generally within the measured ranges. The temperature pro-

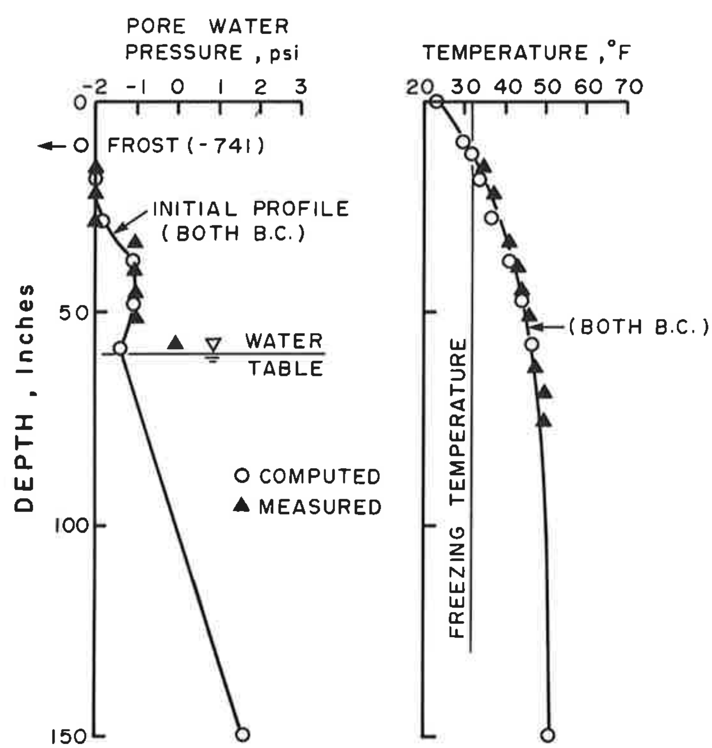

FIGURE 12 Deland, Piatt County, Illinois: initial measured and assumed pore water pressure and temperature profiles, January 1.

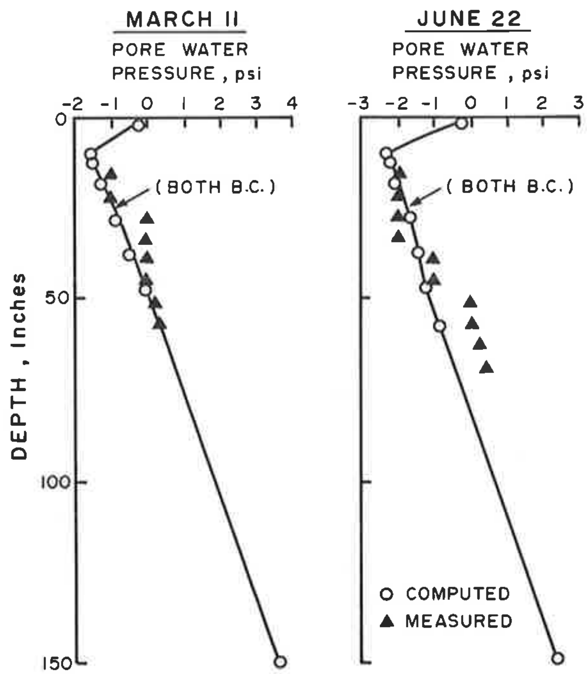

FIGURE 13 Deland, Piatt County, Illinois: measured and computed pore water pressure profiles at various times of the year.

files were particularly sensitive to the base course subgrade boundary condition. Because of this sensitivity, it is possible, by adjusting the flux by trial and error, to get the measured and computed temperatures to match as closely as desired, but there is no guarantee that the same boundary conditions and soil properties will provide as good a match to the temperature values observed in the following year. The measured suction values in Amarillo, Tex., had a much broader range at any given depth and time than the computed values. This range was undoubtedly because of the effects of the cracks in the clay soil subgrade that transmit water faster along specific paths than is estimated by the program. There is a tendency for the computed subgrade suction beneath pavements in these areas to become irreversibly wetter with time.

The positive and negative pore water pressures in Deland, Illinois, were predicted with reasonable accuracy.

As noted earlier, the objective of this program should not be to duplicate field measurements but rather to be able to generate patterns and ranges of the values that realistically match those measured in the field, for that is what is important in design. The program serves that purpose well.

CONCLUSIONS

The Integrated Model provides a simple, user-friendly simulation of weather patterns and computes temperature, suc-

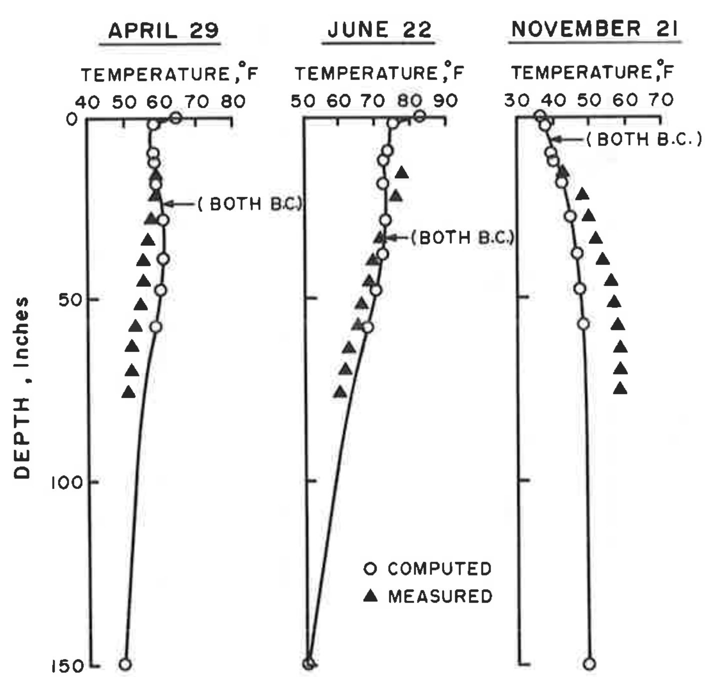

FIGURE 14 Deland, Piatt County, Illinois: measured and computed temperature profiles at various times of the year.

tion, and frost penetration profiles with depth that are realistic in their patterns and ranges when compared with those of actual field data. Because of this, the Integrated Model is expected to be a particularly useful method of simulating moisture and temperature conditions in pavements for use in design.

The final report, prepared for the Federal Highway Administration, provides a substantially more detailed description of the model, including additional simulations. In addition, the computer program is contained on IBM-compatible floppy disks. The final report, the computer program, and the user's Manual are available through the National Technical Information Service, Springfield, Virginia.

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