Temperature and Suction Profiles Beneath Highway Pavements: Computed and Measured

D. E. Pufahl and R. L. Lytton

A computer model has been developed that computes the temperature and suction profiles beneath highway pavements (or other similar covered areas) throughout a specified time period of simulation. The model is referred to as the "integrated computer model" because several modules that were developed for specific tasks have been brought together to form one complete package. Using 30 years of accumulated weather data as a basis, the model generates its own weather patterns that are representative of typical climatic conditions for a particular region of the United States. As the pavement structure and subgrade respond to the changing climatic conditions throughout the year, the model computes the corresponding changes in temperature and suction. Specific boundary conditions at three locations are required: (a) the top pavement surface, (b) the bottom boundary—an extended distance into the subgrade, (c) an intermediate boundary—the top of the subgrade. The pavement surface boundary uses a heat and moisture flux condition that depends on climate. The bottom boundary requires temperature and moisture conditions that are either constant or that may vary in a specific manner. The intermediate boundary requires an initial temperature and a moisture condition that may be either suction (head) or moisture flux. The concept of a transfer coefficient between the granular base and the fine-grained subgrade has been developed to describe the process by which water from the base course and subbase infiltrates the subgrade. This transfer coefficient cannot be measured experimentally, but the selection of an appropriate value controls not only the changes in moisture conditions, but also the temperature profile computed in the subgrade. Three instrumented sites in the United States with widely varying climatic and soil conditions are used to provide comparisons between measured and computed values of temperature and suction profiles.

Load response computer models have been used for a number of decades for highway pavement design and management. Although the importance of environmental influences on pavement performance has been recognized for the last 50 years or more, efforts to incorporate these factors into routine design have been less successful. Usually, the worst-case scenario, that being saturated conditions, was adopted for initial design. This approach was often justified by observing that saturation was the most severe condition, and that little or no information was available to perform and to verify other assumptions. Studies are now indicating that important climatic variables such as temperature, rainfall, wind speed, and solar radiation can be used to model more complex and thus more realistic temperature and moisture conditions characteristic of the more arid regions of the world. Moreover, instrumentation required to measure base course and subgrade temperatures and suctions are becoming increasingly reliable. These procedures coupled with powerful deterministic and stochastic analyses are providing meaningful results for climatic influences on highways over several years of computer simulation.

The integrated computer model has been developed by the Texas Transportation Institute under contract with FHWA to simulate typical weather patterns and to assess their effects on the base course, subbase, and subgrade of highways throughout several years of operation. Although most emphasis has been placed on the continental United States, the program may be used in any part of the world where first-order weather data are available. The program has been described by Pufahl et al. (*1*) and in more detail by FHWA (*2*).

The model shown in Figure 1 is composed of four major components. They are the precipitation (precip) model (*1–3*); the infiltration and drainage (ID) model (*1,2,4*); the climatic-materials-structural (CMS) model (*1,2,5*); and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) model (*1,2,6*). Those wishing to investigate the details of the program are referred to the original papers, reports, and user's guides concerning them (*1–6*).

Preliminary results (*1,2*) have indicated that the boundary conditions selected within the program have a major influence on the temperature and suction profiles that are generated during the course of simulation. One boundary in particular, that between the subbase and subgrade, is of particular significance. Two different moisture conditions that may be assumed at this boundary in the simulation are described. The effects of these assumptions on the computed values of suction and temperature are compared with measured values for three different sites in the United States.

BOUNDARY CONDITIONS

Figure 2, which is a schematic of a typical pavement structure, shows where each of the modules in the integrated model are used during the course of simulation. The figure is separated into two temperature divisions: above and below freezing. Additional divisions are based on temperature and moisture conditions.

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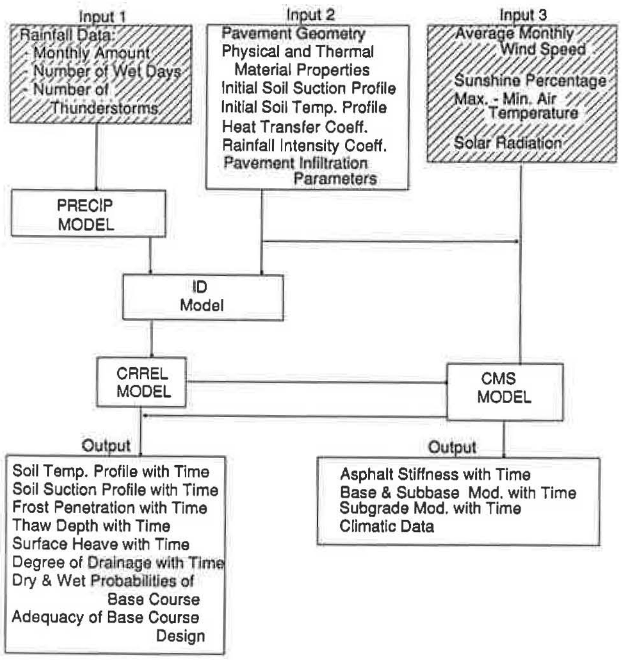
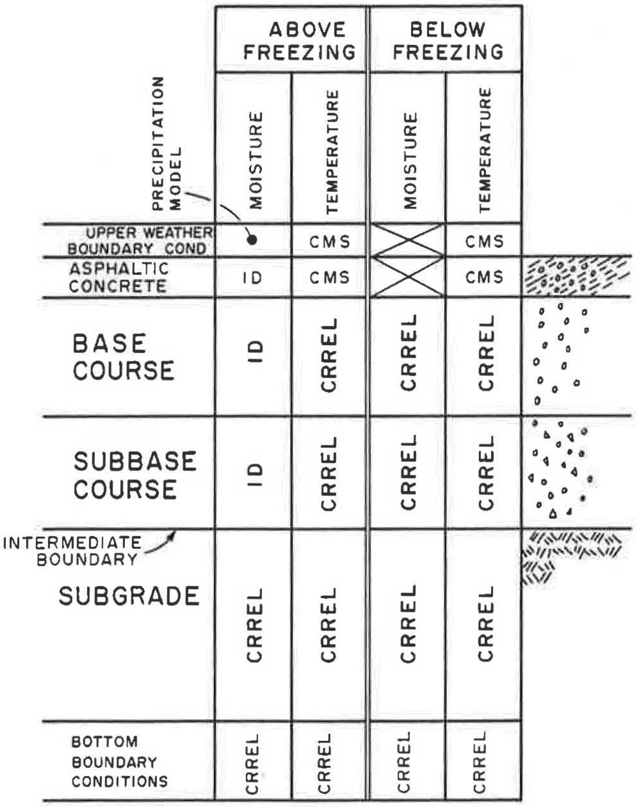


FIGURE 1 **Integrated pavement model.**



	ABOVE FREEZING		BELOW FREEZING	
	MOISTURE	TEMPERATURE	MOISTURE	TEMPERATURE
UPPER WEATHER BOUNDARY COND.	●	CMS	╳	CMS
ASPHALTIC CONCRETE	ID	CMS	╳	CMS
BASE COURSE	ID	CRREL	CRREL	CRREL
SUBBASE COURSE	ID	CRREL	CRREL	CRREL
SUBGRADE	CRREL	CRREL	CRREL	CRREL
BOTTOM BOUNDARY CONDITIONS	CRREL	CRREL	CRREL	CRREL

FIGURE 2 **Pavement segments where component models are used.**

The first boundary of moisture and temperature is encountered at the surface of the pavement, the second at the top of the subgrade, and the third (or bottom) boundary is in the order of 10 to 15 ft into the subgrade.

The pavement surface uses a heat and moisture flux condition that depends on climate. The heat flux is determined by establishing a heat balance at the surface by a combination of measurements and calculations that consider net radiation, average wind speed, and maximum and minimum mean air temperatures. These calculations are performed by the CMS model. The surface moisture influx condition uses the ID model to compute the amount of water infiltrating through the pavement and also handles the lateral drainage out of the base course. It also includes the precip model, which generates realistic rainfall patterns (*1–5*).

The bottom boundary requires temperature and suction values that are either constant during the course of simulation or that vary in a specified manner. If data from the site being considered are not available, techniques based simply on geographical location and soil type may be used as a first approximation (*1,2*).

The intermediate boundary requires initial temperature and suction conditions to be specified. These values must be provided as part of the initial input data. The original CRREL model uses a numerical solution of coupled heat and moisture transport to compute the changes in temperature and suction with time. For the most part, moisture movement occurred from the bottom upwards. Downward vertical drainage could occur when the ice lenses thawed, but no moisture was assumed to infiltrate through the pavement surface; this condition represented a zero-gradient boundary condition. Although this assumption is convenient, it is not often realistic (*2,6*).

MOISTURE FLUX AT THE SUBGRADE BOUNDARY

In many regions west of the Mississippi River, in the southern United States, in southern Canada and in other semiarid and arid regions of the world, highway subgrades are frequently composed of fine-grained, low-permeability soils that remain unsaturated throughout the year.

Infiltration of water through the pavement during or after a rainstorm will often produce free water in the base course and subbase (Figure 3). Thus, an abrupt boundary between

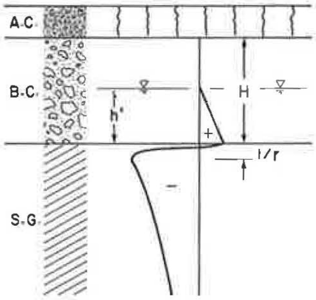


FIGURE 3 **Schematic sketch of pavement structure.**

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 inverse distance.

The concept has been adopted from the theory of an insulated, 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 in comparison to the air are different and the formulation reveals that the transfer coefficient in the case of the heated rod is a function of the Steffan-Boltzmann constant of heat transfer, the absolute temperature of the rod, and the thermal conductivity of the rod. The unit of this transfer coefficient is also inverse distance.

Mitchell (*7*), using this analogy, found 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. Using a value of 0.54/mm as a transfer coefficient for a column of soil 68 mm long, Mitchell was able to model the changes in suction with time throughout the length of the sample with acceptable accuracy. It is postulated here that changes in suction in the subgrade will occur because of changes in water pressure in the base and 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. Present indications suggest that a maximum value for *r* is numerically equal to the computed velocity of the water into the subgrade under a unit hydraulic gradient.

The gradient at the base course-subgrade interface is represented as

$$\frac{\delta h}{\delta z} = -r\left(\frac{p}{\gamma_w} - h_s\right) \tag{1}$$

where

$\delta h/\delta z$ = gradient,
r = pore pressure transfer coefficient,
γ_w = density of water
h' = height of water in the base course,
$p = \gamma_w h'$, and
h_s = negative pore water pressure in the subgrade at the interface.

As the water builds up in the base course to a height, h', above the interface with the subgrade, the positive pore water pressure head in the base course at the interface is described as

$$\frac{p}{\gamma_w} = h'\left[\frac{1 - \frac{k_s}{k_b}(1 - rh_s)}{1 + \frac{k_s}{k_b}rh'}\right] \tag{2}$$

where k_s is the permeability of the subgrade and k_b is that of the base course.

The velocity of flow into the subgrade is found by equating the velocity of vertical flow in the base course to the velocity in the subgrade. The velocity in the subgrade, v_s is

$$v_s = -k_s\left[-r\frac{h'\left(1 - \frac{k_s}{k_b}\right) - h_s}{1 + \frac{k_s}{k_b}rh'} - 1\right] \tag{3}$$

Substituting Equation 2 into Equation 1 yields the following:

$$\frac{\delta h}{\delta z} = -r\frac{h'\left(1 - \frac{k_s}{k_b}\right) - h_s}{1 + \frac{k_s}{k_b}rh'} \tag{4}$$

The size of the gradient and thus the velocity of flow into the subgrade is controlled by the size of the transfer coefficient, *r*.

The flux boundary condition has been programmed in the integrated model to allow the flux to be set either at the base course subgrade interface (the intermediate boundary) or at the bottom boundary of the problem (lower boundary). The velocity at either boundary may be set independently of the other.

When the pore water pressures in the base and the subgrade are fairly close together, the flux boundary condition will perform just like a suction boundary condition. The farther apart the two pore water pressures are, the more active the flux boundary condition will be in controlling the rate of flow of water into or out of the subgrade.

The flux boundary condition with a positive *r* value imposes a velocity of flow from the base course into the subgrade that carries heat with it. This connection results in a cooling of the surface layer and base course. A negative value of the *r* imposes a velocity that flows upward and results in higher temperatures in the base and the surface courses. Thus, the measured temperatures are useful in adjusting the *r* values to fit the measured temperature and suction field data.

COMPARISON OF RESULTS

The integrated model has been used at three sites in the United States with widely varying climatic conditions.

1. College Station, Texas: a wet, nonfreeze climate with a clay subgrade.
2. Amarillo, Texas: a dry, freeze-thaw climate with a clay subgrade.
3. Deland, Piatt County, Illinois: a wet, hard-freeze climate with a silty subgrade.

The data from the first two sites were measured in a National Science Foundation study at Texas Tech University in collaboration with Texas A&M University. Data at the Illinois site were obtained by University of Illinois personnel.

The saturated permeability and the Gardner constants were selected from a compendium of data determined and collated by CRREL. This information is contained in the user's manual that accompanies the integrated model.

The soils classifications from the three sites reported here were matched with similar soils in the CRREL document. The properties used to identify and compare the soils were based mainly on density, water content, gradation, and the Unified Classification.

The measured and calculated suction and temperature values are compared on the dates when the measurements were taken.

College Station, Texas

The test site is a covered area 24 × 40 ft (7.3 × 12.2 m) placed on an expansive clay with a 6-in.-deep (15-cm) sand cushion topped by a layer of polyethylene plastic. Surface elevations, suctions, and temperatures were measured monthly, with the latter two measurements being made to a depth of 8 ft (2.4 m). Changes in suction were more pronounced near the edge of the covered area than near the center so that the suction measurements which are used for comparison purposes were those in the center, 10 ft (3.0 m) from the closest edge, and corresponding to the moisture conditions expected beneath the inner wheel path of a pavement with a 4-ft (1.2-m) shoulder.

The soil layers at the College Station site are shown in Figure 4 along with some measured and assumed soil properties. Figure 5 shows the initial suction and temperature conditions assumed for a typical January 1 date. The computed temperature and suction values are reported at 8:00 a.m. in the morning of the date noted. Calculations are begun at midnight on January 1 and the initial conditions shown in Figure 5 represent 8 hr of stepping forward in time. The boundary condition imposed between the base course and the subgrade makes a substantial difference in both the suction and temperature values computed in the base and the upper levels of the subgrade. For the flux boundary condition, an *r* value of 0.01 was used in all of the runs reported here. The flux boundary condition resulted in an initial temperature profile that was considerably colder than the profile derived from the suction boundary condition and also colder than the actual measured values of the temperature.

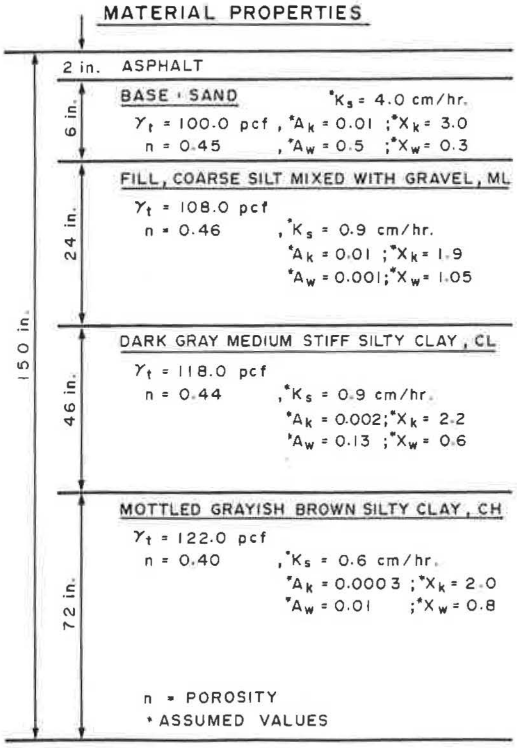


FIGURE 4 College Station, Texas: Soil profile and properties.

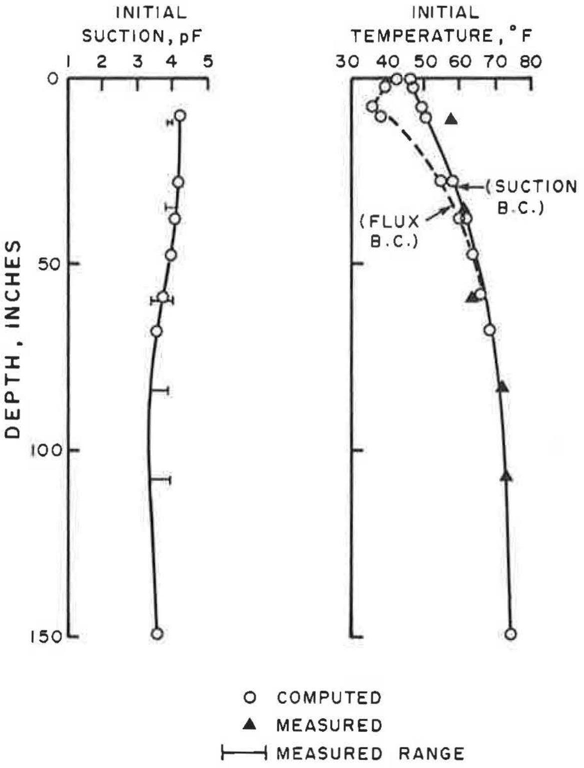


FIGURE 5 College Station, Texas: Assumed and actual suction and temperature conditions on a typical January 1.

Figure 6 shows the measured and computed suction profiles at several different times of the year. Figure 7 shows the measured and computed temperature profiles at the same times of the year. For the flux boundary condition, an *r* value of 0.01 was used in all of the runs reported here. The flux boundary condition resulted in an initial temperature profile that was considerably colder than the profile derived from the suction boundary condition and also colder than the actual measured values of the temperature. The flux boundary condition with a positive *r* value imposes a velocity of flow from the base course into the subgrade that carries heat with it. This results in a cooling of the surface layer and base course. A negative value of *r* imposes a velocity that flows upward and will result in higher temperatures in the base and the surface courses. Thus, the measured temperatures are useful in adjusting the *r* value to fit the measured temperature and

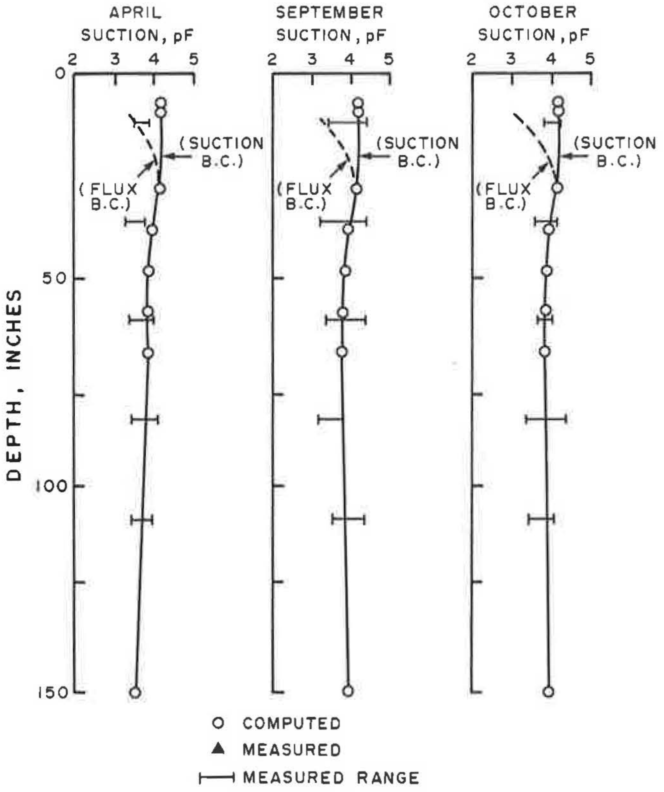


FIGURE 6 College Station, Texas: Computed and measured suction profiles at different times of the year.

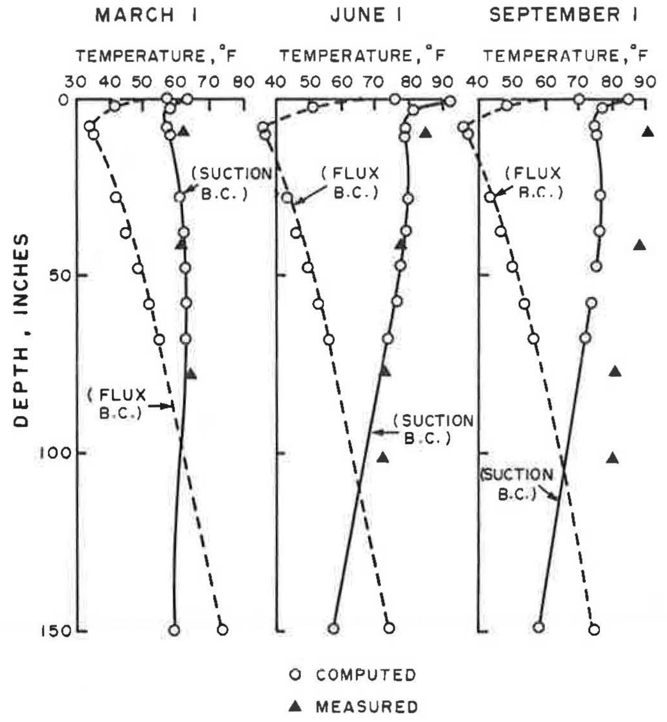


FIGURE 7 College Station, Texas: Computed and measured profiles at different times of the year.

suction field data. Additional simulations will establish more precisely the role of the selected *r* values. The effect of the flux boundary condition with a positive *r* value of 0.01 is evident in both Figures 6 and 7. The effect on suction diminishes rapidly with depth. Figure 8 shows the computed variation of suction throughout the year at a depth of 3 ft (0.9 m) together with the total simulated rainfall that fell during each month of the year. The measured suctions at the same depth are shown on the same figure. Suction measurements were taken with psychrometers and temperatures were measured with thermocouples.

Amarillo, Texas

The site at Amarillo, Texas, is similar to the College Station site. It is a covered area analogous to a slab on an expansive clay subgrade with the same 6-in. (15-cm) sand layer beneath a polyethylene plastic sheet 24 × 40 ft (7.3 × 12.2 m) in plan dimensions. Suction and temperature measurements to a depth of 8 ft (2.4 m) were made each month. Surface elevations were also determined. Suction and temperatures were measured with psychrometers and thermocouples, respectively.

The soil layers at Amarillo are shown in Figure 9, along with the total unit weight, porosity, and permeability properties. Figure 10 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. The difference in temperature profiles generated by the flux and suction boundary conditions is not as strikingly different as was the case in College Station, Texas. This is probably because the difference in suction level at the boundary between the base course and the subgrade is lower than was the case in College Station, and this implies a lower velocity of flow

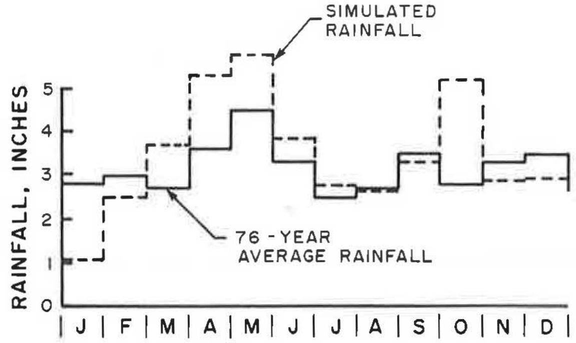


FIGURE 8 College Station, Texas: Computed and measured suctions at 36-in. depth below the surface and monthly rainfall.

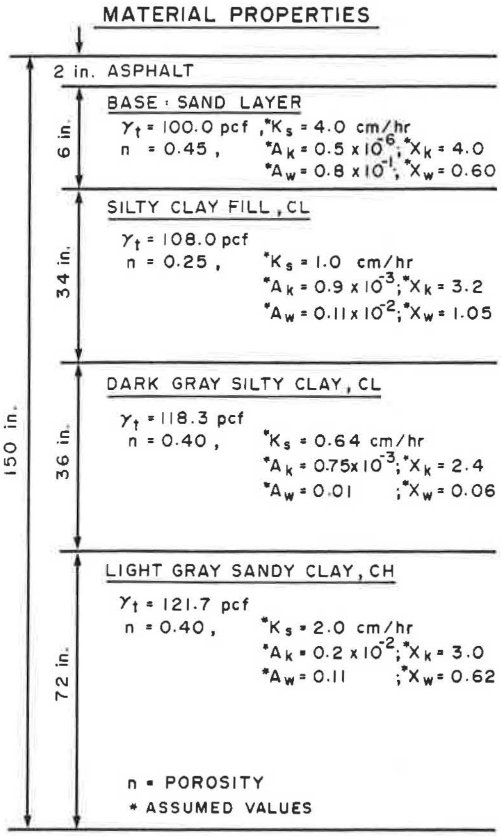


FIGURE 9 Amarillo, Texas: Soil profile and properties.

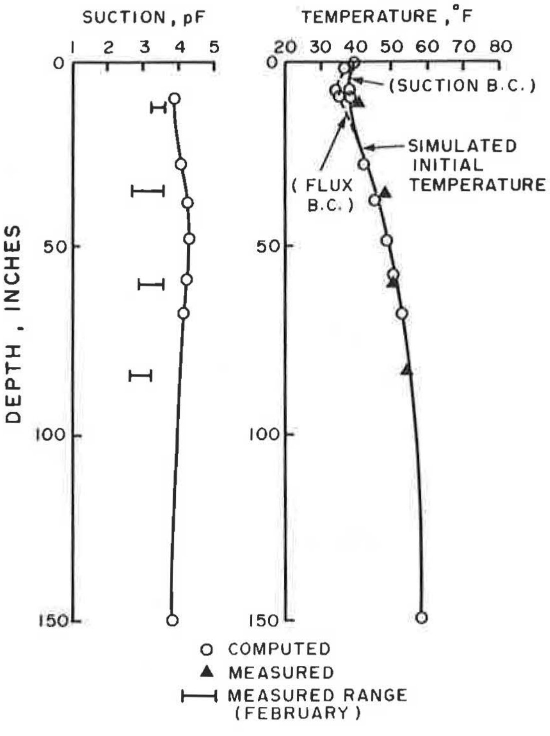


FIGURE 10 Amarillo, Texas: Initial measured and simulated suction and temperature profiles on January 1.

of both water and heat into the subgrade. Figure 11 shows the measured and computed suction profiles at several times during the year. Figure 12 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 condition cases 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 well while, at the same time, falling within the measured suction range consistently. Figure 13 shows the computed variation of suction throughout the year at the 1-ft (0.3-m) depth in the silty clay layers together with the simulated rainfall that fell during each month, and the 44-year average monthly rainfall in Amarillo, Texas. The simulated rainfall was 82 percent higher than the normal average rainfall accounting for the computed suctions falling toward the wetter side of the measured range of suctions. The years during which the site was monitored were all wetter than the average year. The range of suctions that were measured at the same depth are also shown in Figure 13.

Deland, Piatt County, Illinois

The instrumented site in Piatt County, Illinois, near Deland is on a rural road, FAS Route 537. The pavement consisting of a double bituminous surface treatment on an 8-in. (20-cm) aggregate base course, is 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 at 3 to 4 months apart. Suction was measured with tensiometers, moisture cells, and psychrometers. Temperatures were measured with thermocouples. At this site mainly because of the low suctions, the tensiometer readings were considered to be most reliable.

The soil profile is shown in Figure 14, along with assumed soil properties for each layer. The water table fluctuated throughout 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 15 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 16 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 17 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 the two previous cases. In the present case, both boundary conditions predict

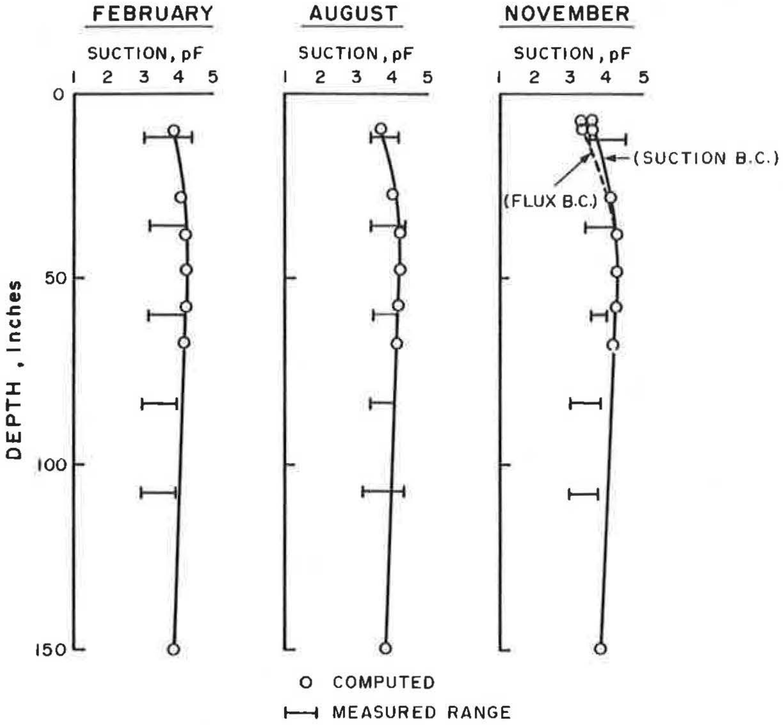


FIGURE 11 Amarillo, Texas: measured ranges and computed suction profiles at different times of the year.

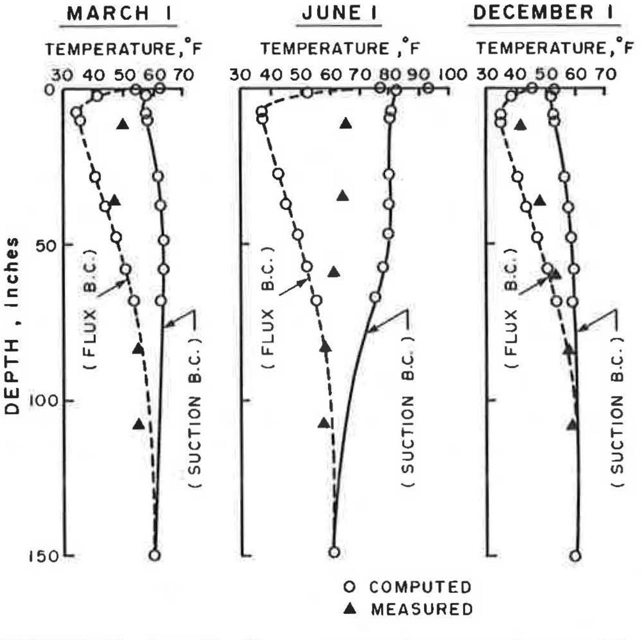


FIGURE 12 Amarillo, Texas: measured ranges and computed temperature profiles at different times of the year.

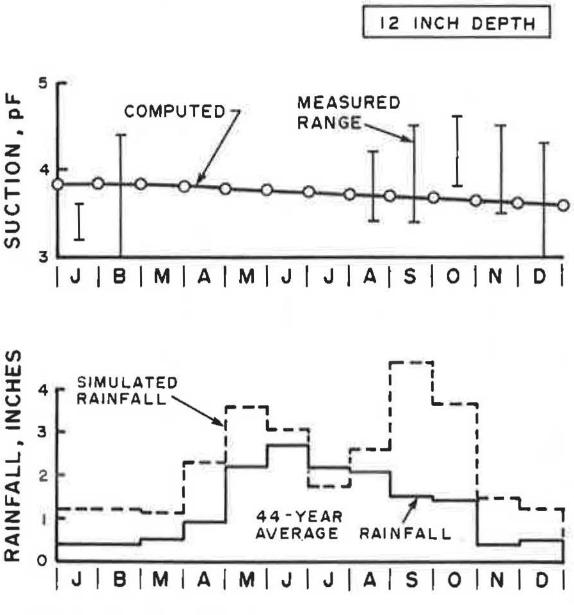


FIGURE 13 Amarillo, Texas: Computed and measured suction at a 12-in. depth below the surface and monthly rainfall.

a temperature profile that is fairly close to the values measured in the field.

Figure 18 shows the computed variation of pore water pressure throughout the year at a depth of 28 in. (0.7 m) below the subgrade level (which is in the brown silty clay soil layers), together with the simulated rainfall that fell during each month and the simulated snow melt. The measured pore water pressures at the same depth are also shown. The calculated negative pore water pressures at that depth change rapidly with time, particularly at the end of January when the ground freezes and at the beginning of February when the snow begins to melt. The computed patterns match the measured rise and fall of pore water pressure although the magnitudes are slightly different.

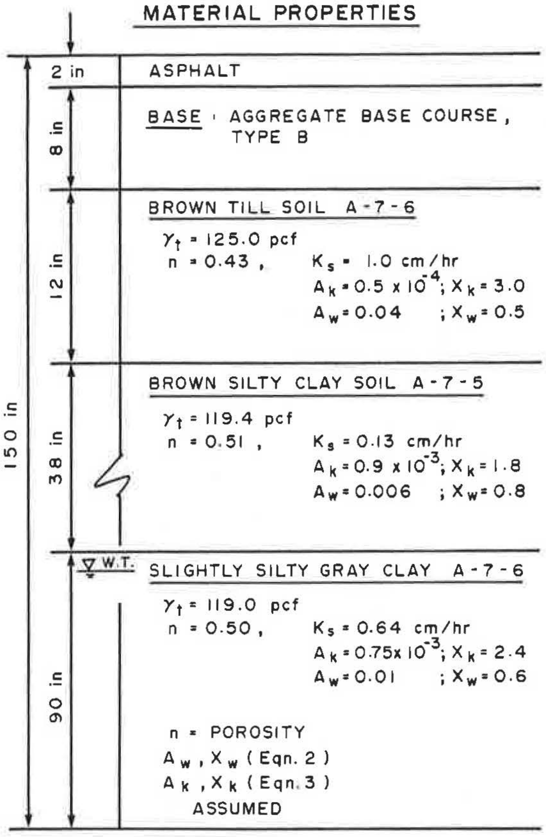


FIGURE 14 Deland, Piatt County, Illinois: Soil profile and properties.

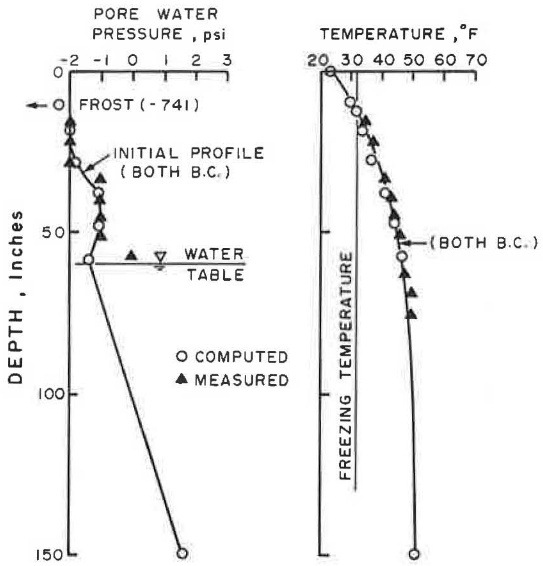


FIGURE 15 Deland, Piatt County, Illinois: Initial measured and assumed pore water pressure and temperature profiles, January 1.

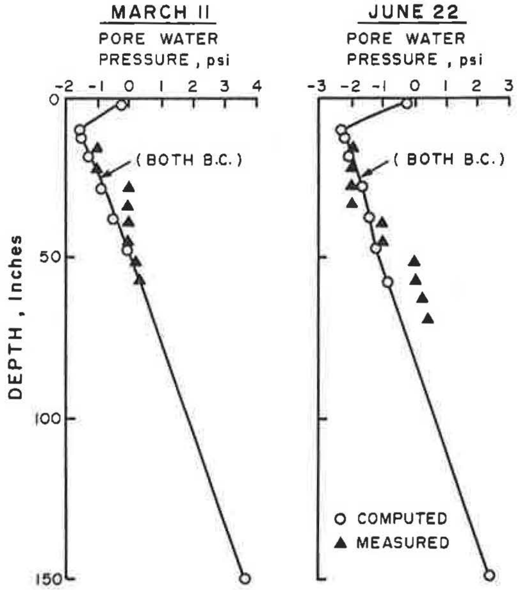


FIGURE 16 Deland, Piatt County, Illinois: Measured and computed pore water pressure profiles at different times of the year.

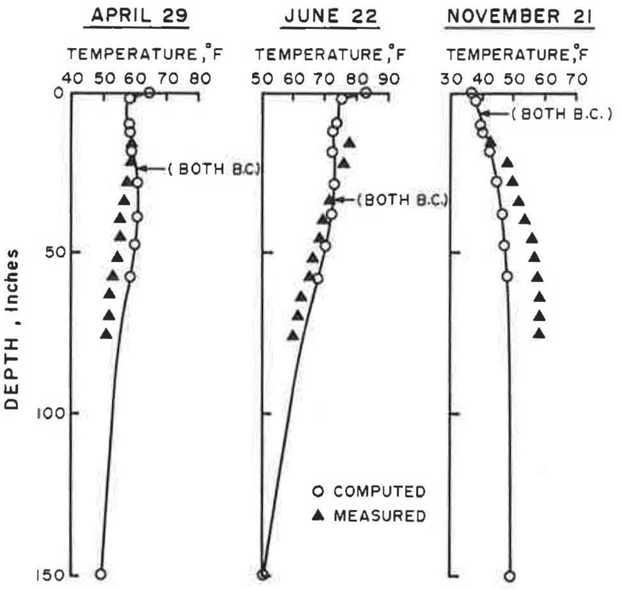


FIGURE 17 Deland, Piatt County, Illinois: Measured and computed temperature profiles at different times of the year.

Figure 19 shows the depth of frost penetration, both observed and computed, together with the computed frost heave and the period of time during which either snow or freezing temperatures sealed off the penetration of water from the surface into the sublayers. The depth of the frost zone observed in the field is matched better using the suction boundary condition than using the flux boundary condition. The largest mean frost heave is nearly the same using both boundary conditions but is more realistic when using the suction boundary condition because of the shallower depth of frost penetration.

EVALUATION AND CONCLUSIONS

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

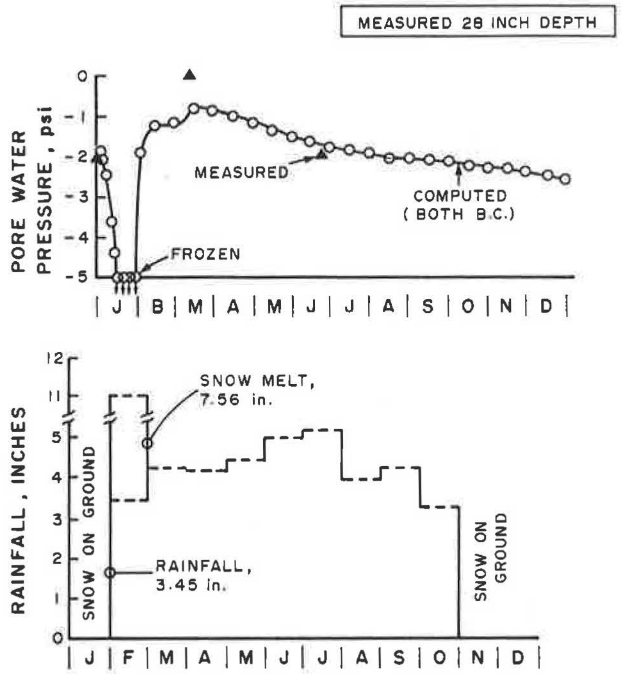


FIGURE 18 Deland, Piatt County, Illinois: Computed and measured pore water pressures and simulated rainfall and snowmelt.

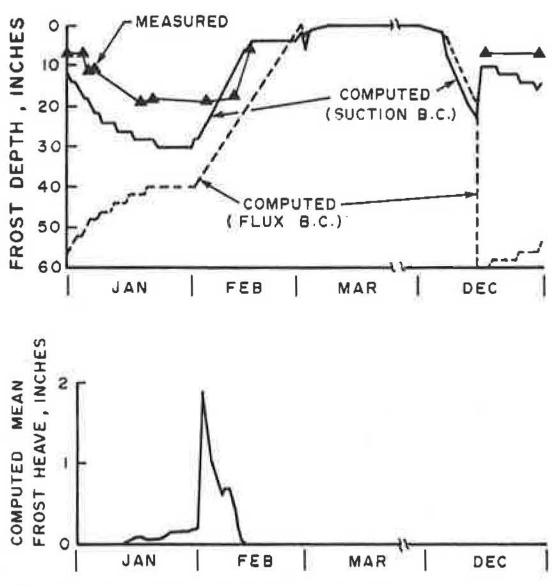


FIGURE 19 Deland, Piatt County, Illinois: Computed and measured frost depths and frost heaves.

generally within the measured ranges. The temperature profiles 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 suction values in College Station, Texas, and in Amarillo, Texas, had a much broader range at any given depth and time than the computed values. This is undoubtedly caused by the cracks in the clay soil subgrade, which 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.

Reliable suction measurements extending over significant periods of time are not easily obtained in the field. Temperatures can be measured much more easily and reliably. Relatively high suctions such as those at the Amarillo site can be measured quite accurately with psychrometers. Low suctions such as those at the Deland site can be monitored reasonably well with tensiometers. Intermediate values may be more difficult to determine. Perhaps the greatest difficulty is to maintain the instrumentation and to keep it calibrated for more than a year. Areas of significant frost penetration represent even greater problems. To obtain field suction data of the extent and quality described in this paper is truly remarkable. Monitoring field suctions over long periods of time in a variety of soil climatic conditions remains an ongoing challenge.

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

Although it is not the objective of the simulation to duplicate field measurements exactly, it is reasonable to assume that adjusting the transfer coefficient *r* at the base course subgrade boundary will have a significant effect on the values of temperature and suction that are computed in the subgrade. The transfer coefficient *r* controls the magnitude and direction of the flux at the upper boundary. This flux carries heat along with it. Thus, both the temperature and suction profiles will be affected by the value of *r* selected for the analysis. This effect was described at the College Station site. It is hoped that ongoing simulations will establish a relationship between subbase and subgrade properties and the transfer coefficient.

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