APPENDIX B

PAVEMENT TEMPERATURE PREDICTION

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INTRODUCTION

A key factor that influences asphalt binder behavior and pavement performance is pavement temperature variation with time and depth. An accurate model is needed for temperature related pavement performance modeling, including calculating binder oxidation. Previous models, though remarkable, are limited either by model accuracy or limited input data availability.

In this work, an improved one-dimensional mathematical model, coupled with site-specific model parameters and recent improvements in the availability of required input climate data, was used to calculate pavement temperatures nationwide. Required input climatic data are: (in order of importance) solar radiation, air temperature, and wind speed. Hourly solar radiation and daily average wind speed can be obtained directly from existing databases. Hourly air temperatures were imputed from commonly recorded daily maximum and minimum air temperatures. Parameter estimation identified three critical site-specific model parameters: the albedo, the difference between the emissivity and absorption coefficients, and the absorption coefficient. The national distribution of these model parameters, optimized at 29 pavement sites based on the average hourly absolute error objective function, appears to correlate with climatic patterns, suggesting interpolating those parameters based on climate. The temperature model, proposed data sources and methods provided calculations that agreed well with experimental measurements.

The key environmental factor that influences asphalt pavement design and performance is pavement temperature, which varies with pavement site, time (day and seasonal) and depth. Hence, accurate representation of pavement temperature is extremely important, particularly in predicting pavement performance such as thermal cracking and oxidative aging. Thermal stress induced by rapid low-temperature changes have been widely accepted as the main cause of thermal cracking of asphalt pavement.

Note: this appendix was written by Rongbin Han, Xin Jin, and Charles J. Glover of the Department of Chemical Engineering, Texas A&M University

Many measurements of pavement temperature variations over time and depth have been reported in the literature. Also, fundamental early models of heat transfer in pavements, involving shortwave solar radiation, down-welling and upwelling long-wave radiation, and convective heat transfer at pavement surfaces and heat conduction inside the pavement have been thoroughly discussed (34, 35, 36, 42, 43, 44). Following these endeavors, a one-dimensional coupled heat and moisture simulation model, the enhanced integrated climate model (EICM), was developed and later integrated into the current mechanical-empirical pavement design guidance (MEPDG) to couple pavement design with modeled pavement temperature (26).

The EICM model uses a finite difference approximation for calculating heat conduction within the pavement and underlying layers, subject to heat fluxes at the surface (shortwave solar radiation, long-wave radiation, and convective heat transfer) and a constant-temperature boundary condition well below the pavement. Using required climatic input data including solar radiation, ambient temperature and wind speed and constant model parameters such as albedo, emissivity and thermal diffusivity, the model computes numerically changes in temperature and moisture over time and with depth.

Although temperatures predicted with the EICM model satisfy pavement design needs in general, there have been some large errors when compared to measured pavement temperature (18). These errors are most likely caused by several factors: the assumption that heat fluxes at the pavement surface are exactly balanced by conduction into the ground well below the surface, inaccuracy of climatic data (especially calculated solar radiation), plus the assumptions of the constant temperature boundary condition and site-independent model parameter values.

Recently, significant improvement over the EICM model has been achieved by several groups using a similar one dimensional heat transfer model, but with an unsteady-state surface heat flux boundary condition, measured model input data, and site-specific model parameters that were optimized based on measured pavement temperatures (19, 20, 21).

Figure B-1 presents a comparison of the temperatures measured at different depths below the pavement surface with those calculated with the EICM model (22).

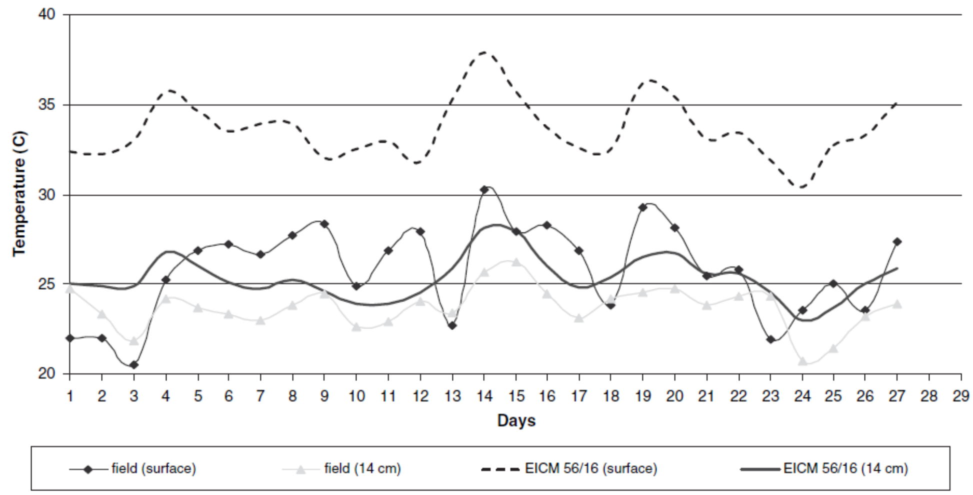


Figure B-1. Typical daily pavement temperature prediction using EICM model (22).

Figure B-2 shows a comparison between the measured temperatures and those calculated with the new model used in this project. The new model is described later in this chapter.

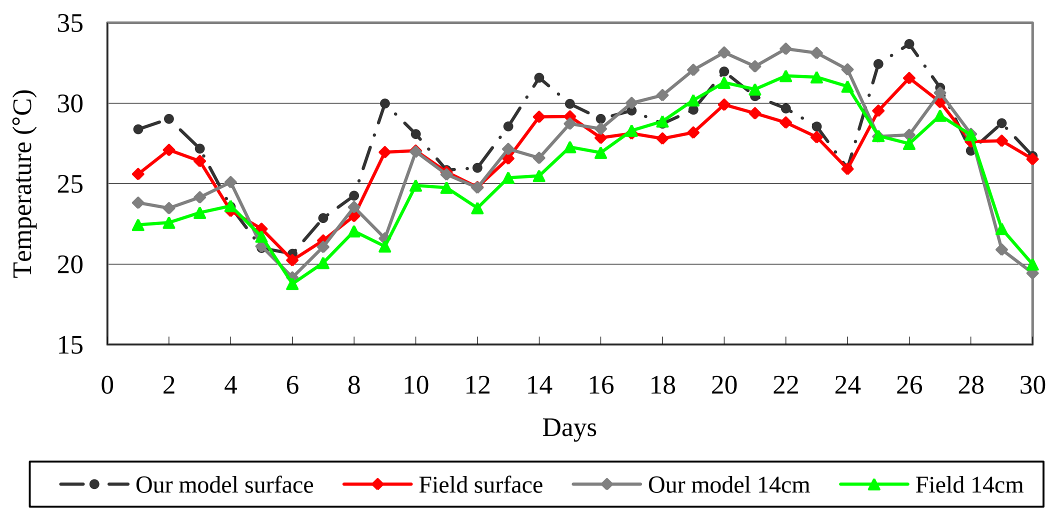


Figure B-2. Typical daily pavement temperature prediction using improved model.

The one dimensional heat transfer model employs an unsteady-state heat flux boundary condition at the pavement surface, a depth-independent heat flus 3 m below the surface, and the ability to estimate site-specific model parameters using known measured pavement temperatures.

MODEL DEVELOPMENT

The one dimensional model was developed based on radiation and conduction energy balance fundamentals. The heat transfer process is depicted in the schematic shown in Figure B-1. There are multiple sources of heat transfer at the pavement surface: solar radiation and reflection of the solar radiation at the surface by a fraction $\tilde{\alpha}$, the albedo, absorption of atmospheric down-welling long-wave radiation by the pavement surface, emission by long-wave radiation to the atmosphere, and convective heat transfer between pavement surface and the air close to the surface, which is enhanced by wind. As suggested by the reviewer, a definition of albedo was inserted into the first paragraph in the section of Appendix B entitled “Model Development” on page B-4. The definition is worded as follows: “albedo is a reflection coefficient with values that can range between zero and 1.0. A perfectly absorbing black object has an albedo of 0 and a perfectly reflecting white object has an albedo of 1.0.” Typical values of the albedo are given in the discussion on pages B-12 through B-18 and are illustrated in Figures B-6 and B-8. Below the surface and within the pavement and ground beneath it, heat is transferred by conduction. Not included in this model is heat transfer enhancement by precipitation. Mathematical details of this model follow.

Heat Transfer in Pavement

Heat transfer in the pavement is governed by the classical thermal diffusion equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad \text{(B-1)}$$

where T is the pavement temperature as a function of time and depth below the surface (x), and α is the thermal diffusivity, $\alpha = k / \rho C$ where k is the thermal conductivity, ρ is the density, and C is the pavement heat capacity. Together with this equation, we consider a flux boundary condition at the pavement surface and a second flux condition at 3 m below the surface.

The Surface Boundary Condition

Considering a differential element of the pavement surface, its thermal energy (temperature) will change to the extent the fluxes from above and from below do not balance. The various fluxes shown in Figure B-3 lead to the following surface condition:

$$\rho C \frac{\Delta x}{2} \frac{\partial T_s}{\partial t} = Q_s - \tilde{\alpha} \cdot Q_s + Q_a - Q_r - Q_c - Q_f \tag{B-2}$$

where

ρC is volumetric heat capacity of the pavement

T_s is pavement surface temperature

x is the depth below the pavement surface

$\frac{\Delta x}{2}$ is the (differential) pavement thickness for the energy balance

Q_s is heat flux due to solar radiation

$\tilde{\alpha}$ is albedo of pavement surface, the fraction of reflected solar radiation

Q_a is down-welling long-wave radiation heat flux from the atmosphere

Q_r is outgoing long-wave radiation heat flux from the pavement surface

Q_c is the convective heat flux between the surface and the air

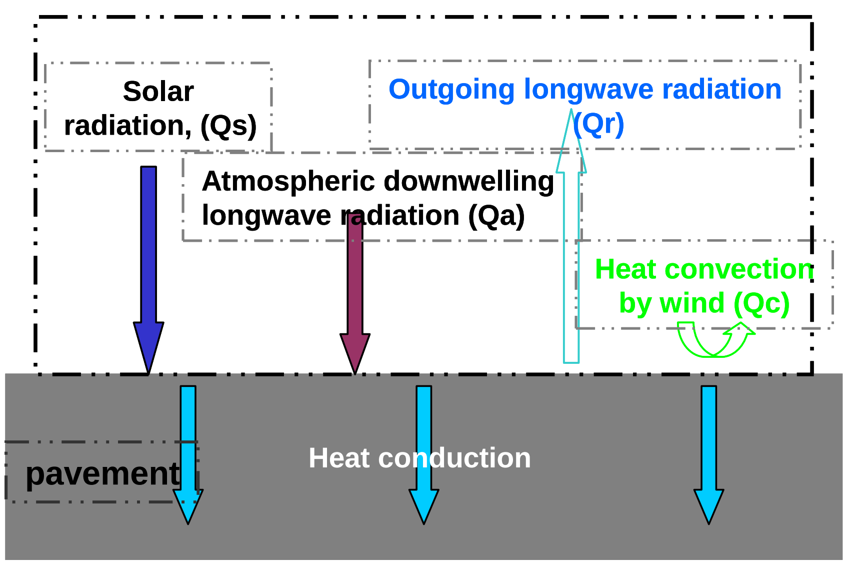


Figure B-3. Schematic representation of heat transfer model of pavement.

The incoming and outgoing long-wave radiation are calculated by:

$$Q_a = \varepsilon_a \sigma T_a^4 \tag{B-3}$$

$$Q_r = \varepsilon \sigma T_s^4 \tag{B-4}$$

where

ε_a is absorption coefficient of pavement

ε is emission coefficient of pavement

T_s is pavement surface temperature

T_a is air temperature

$$\sigma = 5.68 \times 10^{-8} W \cdot m^{-2} K^{-4} \text{ is Stefan-Boltzman constant} \tag{B-5}$$

The convective heat flux is calculated as:

$$Q_c = h_c (T_s - T_a) \tag{B-6}$$

where

h_c is the heat transfer coefficient from the empirical equation (34)

$$h_c = 698.24 \cdot a \cdot [0.00144(\text{abs}(\frac{T_s + T_a}{2}))^{0.3} U^d + 0.00097(\text{abs}(T_s - T_a))^{0.3}] \tag{B-7}$$

U is the hourly wind speed

a and d are two dimensionless empirical parameters.

The heat flux within the pavement at the surface is expressed by Fourier's equation:

$$Q_f = k \frac{\partial T_s}{\partial x} \tag{B-8}$$

where

T_s is pavement surface temperature

k is thermal conductivity of asphalt concrete

Combining these results, the following equation serves as the surface boundary condition:

$$\rho C \frac{\Delta x}{2} \frac{\partial T_s}{\partial t} = Q_s - \tilde{\alpha} \cdot Q_s + \varepsilon_a \sigma T_a^4 - \varepsilon \sigma T_s^4 - h_c (T_s - T_a) + k \frac{\partial T_s}{\partial x} \qquad \text{(B-9)}$$

The Bottom Boundary Condition

Commonly, a constant-temperature boundary condition, some distance below the surface, is reported in the literature. For example, Hermansson (19) used the annual mean temperature 5 m below the surface as a bottom boundary condition. Gui (20) used a measured temperature of 33.5 ^{o}C at a depth of 3 m as the boundary condition. In the EICM model, temperatures were measured from water wells across the country at a depth of 10 to 18 m, from which an isothermal map was constructed. Such a constant-temperature boundary condition has the advantage of simplicity.

For this work, an alternate approach was used. From measured data in the LTPP database, it was observed that temperatures at a depth beyond 2 m tend to vary approximately linearly with depth. Using this result, an alternate boundary condition was used at a depth of 3 m. That is

$$\frac{\partial T}{\partial x}\Big|_{3\,\mathrm{m}} = \text{independen t of depth} \qquad \text{(B-10)}$$

Such a boundary condition, which is based on field observation, has the advantage over the constant boundary condition in that it is location independent and does not require a specific value for the boundary condition. In addition, it is quite straightforward to implement this boundary condition in the finite difference calculation procedure. Of course, this linear variation with depth condition is not strictly correct as extrapolating it to too great a depth will lead to significant error.

Numerical Solution of the Model

This model was solved numerically using a finite difference approximation method, together with required input data, including hourly solar radiation, air temperature, and wind speed, plus model parameter values. In the numerical solution, the pavement thickness was divided into cells, which are thinner near the surface and thicker at deeper levels. Each cell is given a temperature (equal to air temperature) at the start of the calculation as an initial condition. The model then calculates a new temperature for each cell (several times for each simulated hour) at each time step.

OBTAINING MODEL INPUT DATA

For any pavement site, model calculation requires accurate data input including site-specific hourly climatic data and model parameters. Obtaining or interpolating accurate model input data is discussed below.

Obtaining Hourly Climatic Input Data

Climatic input data for the model includes hourly solar radiation, hourly air temperature, and daily average wind speed data in an hourly format.

Hourly solar radiation can be collected from the National Solar Radiation Database (NSRDB). Hourly solar radiation data are modeled using SUNY or METSTAT models based on satellite images, covering nearly all parts of the country from 1990 to 2005.

Daily average wind speed can be directly collected from the Virtual Weather Station program in the Long Term Pavement Performance database (LTPP). Additionally, daily wind speed can be obtained directly from the National Climatic Data Center (NCDC) or the meteorological network at each state. Although hourly wind speed is preferred, site-specific hourly wind speed data are difficult to obtain and more vulnerable to environmental conditions, adding difficulty in interpolation endeavor. Fortunately, the model is not overly sensitive to the wind speed and daily values work quite well.

Hourly air temperature data are not commonly available in favor of daily maximum and minimum air temperatures, but reasonable estimates of hourly temperatures are needed for accurate temperature calculations. In order to provide the model with hourly wind speed data, a method was developed to interpolate hourly air temperature from daily maximum and minimum air temperatures. Recorded daily maximum and minimum air temperatures can be obtained easily from the Virtual Weather Station program in the LTPP database or NCDC.

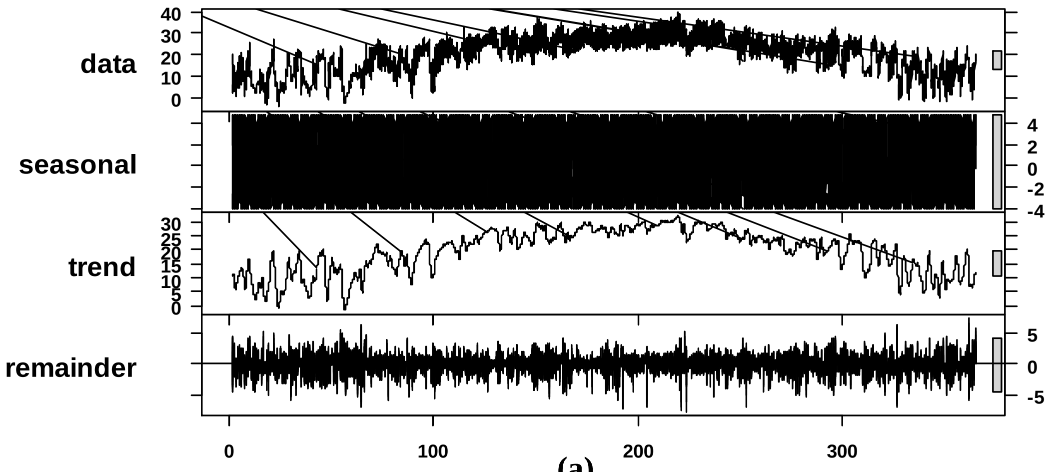
A conventional method to impute hourly air temperatures fits a sinusoidal function to daily maximum and minimum air temperatures. However, the daily profile of air temperature is not exactly sinusoidal. Typically, the time for the air temperature to rise from the daily minimum temperature to the daily maximum temperature is about 9 hours, while 15 hours are taken for the air temperature decrease from the daily maximum temperature to the daily minimum. A more accurate air temperature interpolation method should incorporate this non-sinusoidal pattern.

In order to obtain a more representative pattern of daily air temperatures, data over an entire year were obtained from the Automatic Weather Station (AWS) in the LTPP database and analyzed using a seasonal trend decomposition time series analysis (Figure B-4). The figure contains two sets of four rows; the top set covers an entire year while the bottom set covers five days. In each set, the first row graphs the measured hourly air temperature. The trend trace is a moving average of the measured data, which represents the daily average temperature throughout the year. The “seasonal” trace is obtained by subtracting the trend line from the measured data and finding a local polynomial which best fits the result. This trace represents the regular pattern of daily air temperature, which is used instead of a sinusoidal function. The remainder is what is left after the trend and the seasonal traces are extracted from the measured data, and shows the effect of weather on air temperature.

With a daily pattern of air temperature now known, we can reconstruct hourly air temperatures from daily maximum and minimum measured data. First, the daily average air temperature data are taken from the trend trace. Then, the trend and the seasonal traces obtained from the time series analysis are added together. Finally, the result is linearly transformed to fit the measured data, day by day. This step indirectly incorporates to some extent the remainder data into the obtained dataset.

To evaluate the time series analysis method, calculated hourly temperature data were compared to measurements over an entire year, plus a comparison was made of imputed temperatures using a sinusoidal temperature pattern. The dataset was from a Texas LTTP site. From the comparison (data not shown), it is clear that the time series analysis interpolation method is significantly better than the sinusoidal method, although not perfect, of course. The standard deviation of calculated versus measured errors is 1.95 ^{o}C for the pattern interpolation method and 3.07 ^{o}C for the sinusoidal method.

An interesting question that dramatically affects the applicability of the pattern interpolation method is: “Can we apply the same daily pattern obtained from one pavement site to another one?” If we can, what are the limitations?



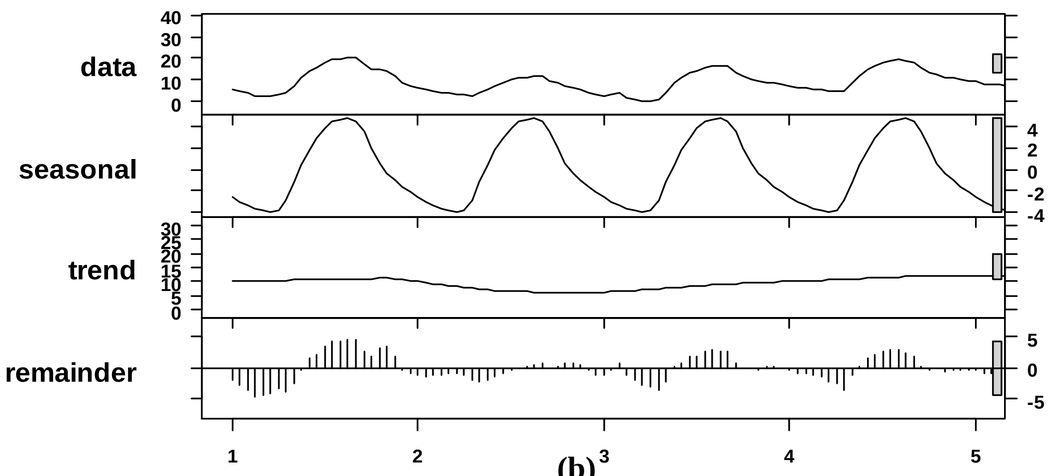


Figure B-4. Seasonal trend decomposition of hourly air temperature a) for a whole year and b) magnified view of 5 days period.

To address this question, several patterns were calculated for three sites in Texas, and one site each for Utah, Nevada, and South Dakota, Figure B-5. The patterns for the sites in Texas compare quite well to each other, especially the first two sites, while the difference between patterns from different states are quite apparent, especially Nevada and South Dakota.

Figure B-5. Daily air temperature patterns at 6 different pavement sites.

Though the patterns from different states are different, the patterns share the same basic shape. When the pattern obtained from Nevada was used for interpolation of hourly pavement temperature in Texas, offsite imputed temperatures were obtained. While the result (not shown) is not as good as that with onsite pattern interpolation, it is still better than that for the sinusoidal pattern method.

In summary, the pattern interpolation method is better than the sinusoidal method, and the onsite pattern should be used when available. An offsite pattern produces less accurate results but, the deviation can be acceptable, especially if a close-to-site pattern is used when the onsite pattern is not available.

Obtaining Site-Specific Model Parameters

In order to obtain good model estimates of pavement temperatures from accurate hourly climate input, the specific numerical values of the model parameters need to be determined. Although some parameters are fairly well known (ρ, k, C, e.g.), others require a parameter estimation process. Site specific parameters, as discussed in the model development section, are albedo, emissivity, absorption coefficient, thermal diffusivity, and the parameters *a*, *d* in the heat convection coefficient correlation.

The following discussion presents results of a parameter sensitivity analysis, optimization of the model parameters using 29 pavement sites widely distributed across the country, an analysis of the distribution of these model parameters over a wide range of climatic regions, and interpolation strategies for each model parameter so that at any pavement site across the country reasonable values for the model parameters can be assumed.

Parameter Sensitivity

To assess the sensitivity and importance of each parameter in the pavement temperature prediction model, parameters were varied independently of one another over a range of values based on typical literature values. The average absolute error was used as a statistical measure of model error.

By changing a parameter over its practical range, the temperature average absolute error induced by the change was calculated so as to evaluate the sensitivity of the prediction to the parameter. Note that the abscissa scale in Figure B-6 varies for each parameter with the parameter values shown in the legend.

As shown in Figure B-6, when the albedo increased from 0.15 to 0.4, the average absolute error of the model prediction increased dramatically from about 1.5 to about 3.5 (^{o}C), implying an important role of the albedo in temperature prediction. Similarly, changing the emissivity (from 0.8 to 0.95) or the absorption coefficient (from 0.7 to 0.85) alone induced a significant variation in the model prediction accuracy. Interestingly, although the individual change of the emissivity or the absorption coefficient values alone can result in great variation in model accuracy, if both parameters are changed at the same time, while keeping the difference between those two values fixed, there is very little effect on the model prediction. The difference between the two parameters, rather than the each one's specific value is the more important factor. We also observe from Figure B-6 that the thermal diffusivity, *a* and *d* are relatively less important in terms of their effect on model accuracy and thus, constant values of these three parameter are suggested. Based on literature reports, a constant value of 0.005cm^2/s was selected as a reasonable value for thermal diffusivity of the pavement. For *a* and *d*, values of 1.4 and 0.5 respectively were used. Based on these results, it's clear that accurate values for the albedo and the difference between the emissivity and absorption coefficients are important for obtaining a good temperature prediction for each pavement site.

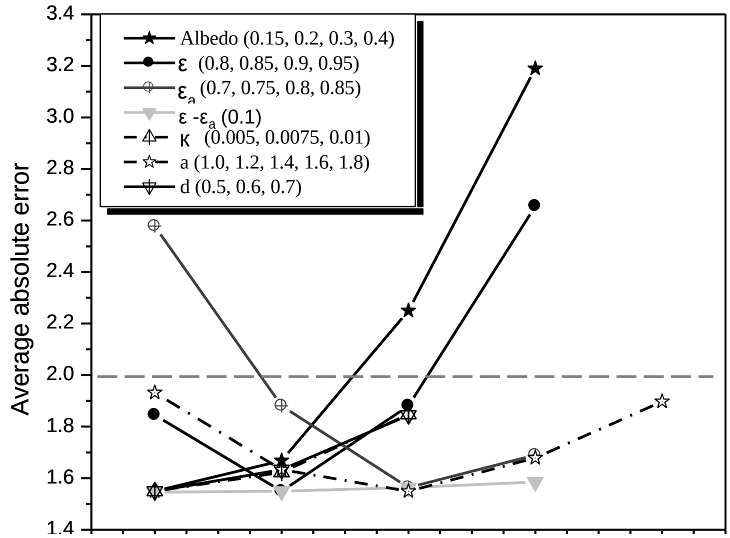


Figure B-6. Model parameters sensitivity analysis: Effect of changing mode parameters in their practical ranges to average of absolute error of model prediction.

In addition to the difference between the emissivity and absorption coefficients, a value of either the emissivity or the absorption coefficient is required. In what follows, we use the absorption coefficient, recognizing that having its exact value is not critical.

Optimization and Interpolation of Model Parameters

Although albedo, emissivity and the absorption coefficient are site specific, there is no clear understanding of how these parameters vary with climate and pavement properties. Understanding such variation is important to improving the value of the temperature prediction model. To address this issue, parameter optimization has been conducted for these model parameters at 29 pavement sites across the country by comparing model estimates of pavement temperature to reported measurements. Previous studies revealed that albedo and emissivity values are seasonally sensitive in that their values in the winter are different from their values the rest of the year. Therefore, in this work, two separate sets of model parameters have been obtained, one set for the winter and one set for the other seasons (represented by summer), to take into account this seasonal variation. Then from further analysis of the distribution and seasonal variation of those model parameters, interpolation strategies have been developed for each model parameter and are presented below.

The algorithm to find values of the three parameters identified by sensitivity analysis (albedo, difference between emissivity and absorption coefficient, and the absorption coefficient) is quite straightforward. Each parameter was given a range of values and increments within the range based on literature reports. By examining the ability of each set of model parameters to give the best match between the measured and the calculated pavement temperatures, the optimum set was obtained. As a measure of the model's accuracy, the average hourly absolute difference between the measured and the calculated pavement temperatures was used. This estimation method using average of absolute error is preferred to, for example, the least-squares error by which a section with unusual properties receives more weight than a section with more normal properties.

Twenty-nine pavement sites were identified with recorded hourly pavement temperatures from the seasonal monitoring program of the long term pavement performance database (LTPP), Figure B-7, with all of the studied pavement sites marked on a United States terrain map. Those pavement sites all have at least one month of continuous hourly temperatures measured in both the winter and summer. Model parameters were optimized by examining the ability of each set of model parameters to minimize the average absolute error in temperature. Pavement temperatures in the middle depth of the asphalt layer, rather than the pavement surface, have been used to optimize these model parameters.

Albedo

Figure B-8 shows the distribution of the optimized albedo values across the country in the 29 pavement sites for both summer and winter. As seen in Figure B-8a, the summer optimized albedo values for most of the pavement sites is constant at 0.2, with a slight variation from 0.2 to 0.15 in several pavement sites in Texas. In the winter (Figure B-8b), the optimal albedo values in the southern part of the country are the same as in the summer, while the albedo values in the north increased from 0.2 to from 0.3 to 0.35. Although the exact reason for the albedo increase in the winter in the north is not clear, it seems the pavement surface property changes associated with snow coverage and the freeze state in the winter likely is a key. Similar observations and conclusions have been reported in the literature (19, 45).

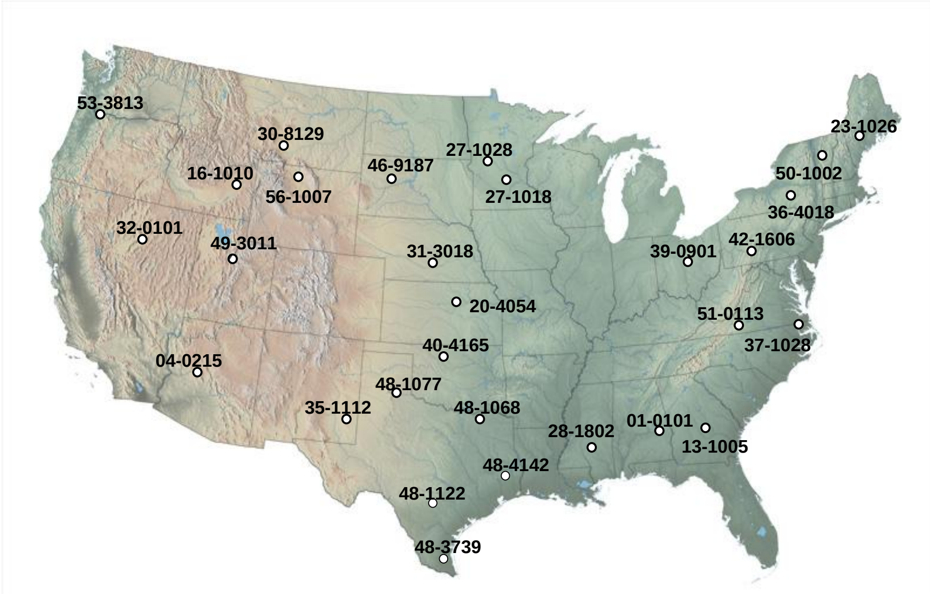
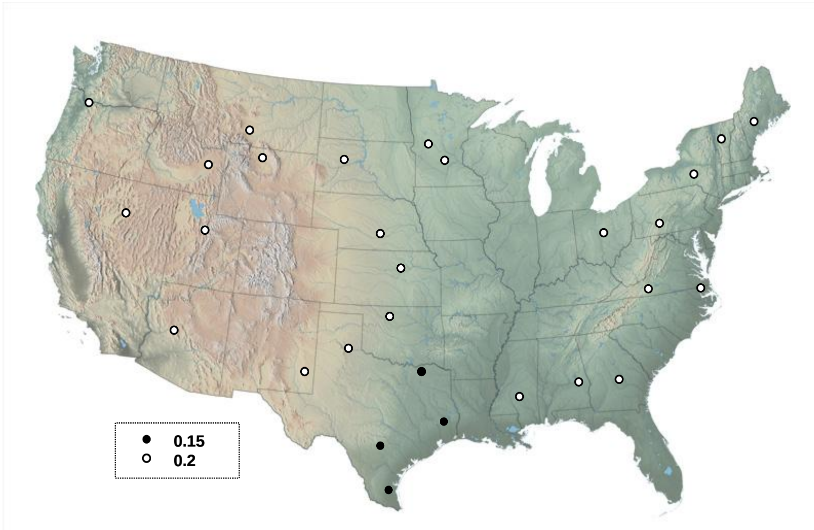


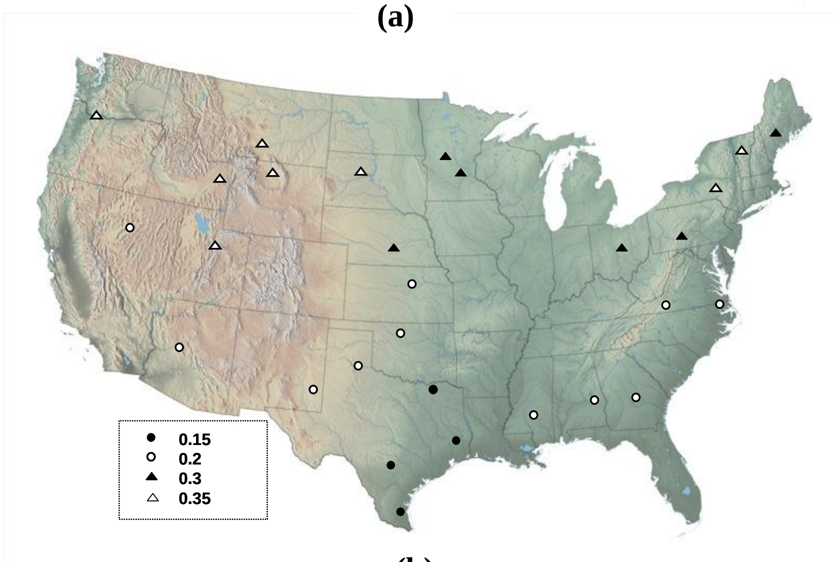
Figure B-7. Distribution map of 29 SMP pavement sites studied.

This hypothesis was validated by plotting the optimized winter albedo values on a national snowfall map from the National Climatic Data Center (NCDC) that was generated based on the average of recorded data from 1961 to 1990 (Figure 8c). This snowfall map also matches the NCDC freeze state distribution across the country, recorded from 1961 to 1990. Clearly, in the southern regions the albedo values are the same in winter and in summer and range from 0.15 to 0.2, while in northern regions with heavy snowfall and freeze condition, the albedo values changed from 0.2 in summer to from 0.3 to 0.35 in the winter. There exists a distinct separating line, snowfall of 48 inches, which separates the northern and southern regions. From these results, it seems that the seasonal albedo variation of pavement is more affected by the freeze state and snowfall, and less affected by other environmental factors and material properties of the pavement.

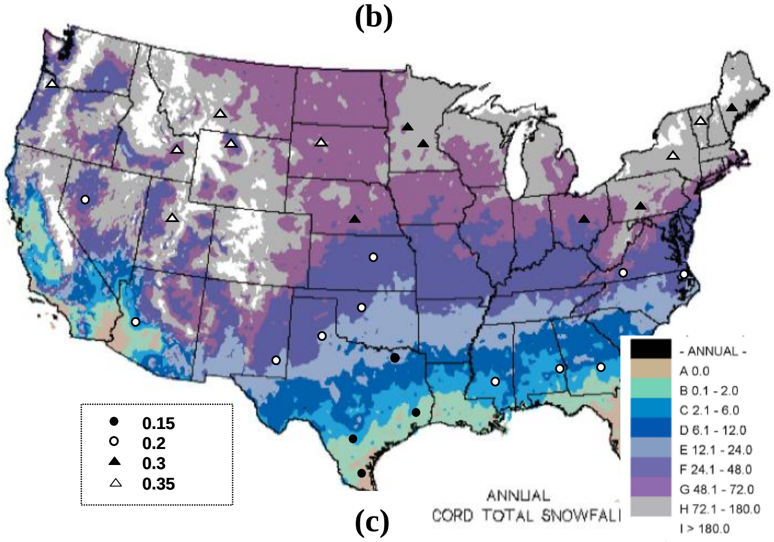
To interpolate albedo values at other pavement sites, a reasonable approach is to use the snowfall distribution map across the country as a reference with 48 inches snow fall to separate the northern and southern parts of the country. As the albedo value in each region is quite stable in either the winter or summer, albedo values obtained at the nearest pavement site in the same



(a)



(b)



(c)

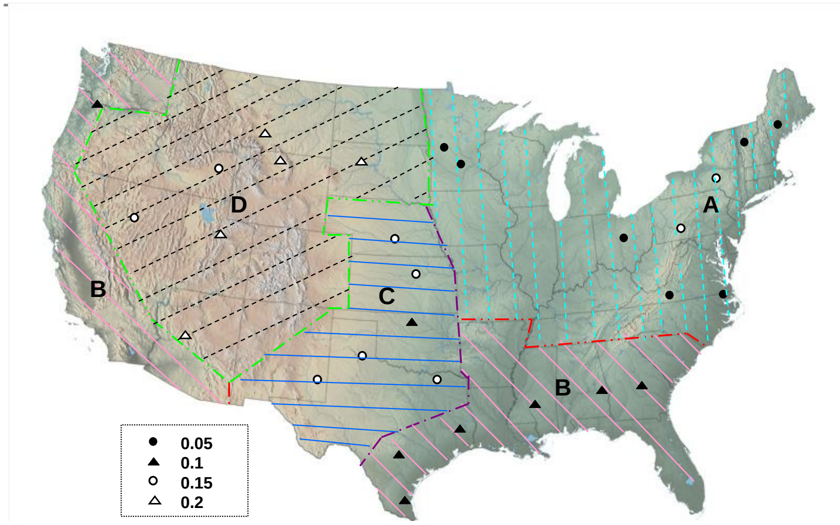
Figure B-8. Optimized albedo values in: a) summer and b) winter, along with c) winter optimized albedo values on an annual average snowfall map.

region, based on 29 pavement sites studied in the work, can simply be interpolated to give the albedo value for the specific pavement site. Alternatively, the albedo value at the nearest three pavement sites in the same regions can be averaged to obtain the albedo value in pavement site of interest.

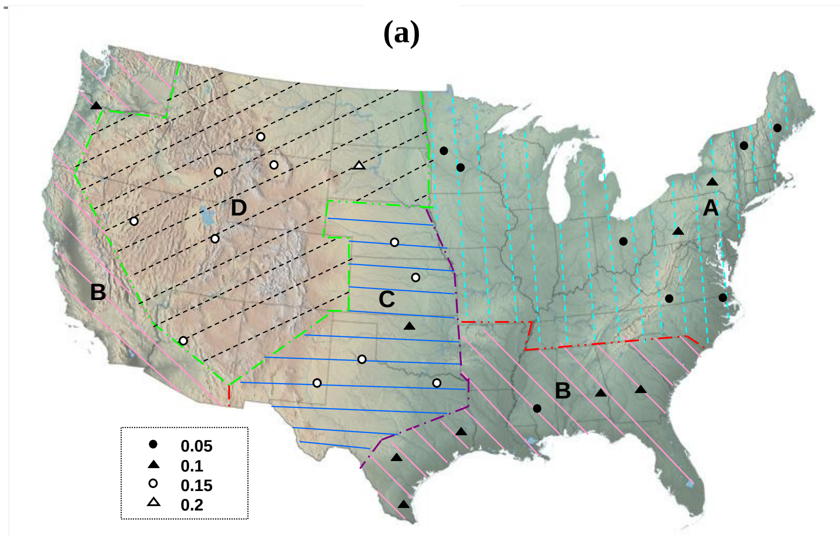
Because snowfall and freeze conditions vary with time, one question is how to determine winter versus non-winter periods. Ground albedo values have been recorded daily or monthly using satellite remote sensing techniques, commonly with a resolution of 10 km across the country. These observations support the conclusion that distinctly higher values of albedo occur during winter snow coverage and freeze than during other periods. Satellite recorded albedo values have been collected in several databases that can be easily accessed (such as NCDC or NSRDB). For any specific pavement site and year of interest, recorded albedo data from these databases at the nearest location can be extracted. The winter period suggested by high albedo values in those databases may then be used to define the winter period for pavement calculations.

Algebraic Difference between Emissivity and Absorption Coefficient

The second important model parameter is the algebraic difference between the pavement emissivity and absorption coefficient. Figure B-9 shows the optimized values of the parameter for the 29 national pavement sites displayed on a national terrain map in both winter (Figure B-9a) and summer (Figure B-9b). Four different values were obtained, 0.05, 0.1, 0.15 and 0.2, but distribution patterns that follow climatic regions can be noted. Four environmental regions that correspond generally to those four values are shown in Figure B-10. Region A covers the northeast and east north central regions and generally experiences a humid climate with long winters. The optimized value for the algebraic difference in this region generally is 0.05. Region B, the southeast areas and part of the south is located in a mesothermal zone with humid sub-tropical climate. An optimized value of 0.1 is common for pavement sites in this region. Region D covers the western part of the country, especially mountain regions and a dry, cold climate is dominant. Here a value of 0.2 was generally obtained in the winter while in the summer a value of 0.15 was obtained. Region C is a transition zone between Regions B and D, and a value of 0.15 was commonly obtained, both winter and summer. Despite several slight deviations, the optimized value for the algebraic difference in most of the pavement sites followed these general trends reasonably well.



(a)



(b)

Figure B-9. Optimized values of the algebraic difference between emissivity and absorption coefficients: a) summer and b) winter.

Previous studies have suggested that the absorption coefficient is mainly affected by the water partial pressure in the air. A linear relationship between absorption coefficients with partial pressure in a clear sky condition have been further developed using linear regression techniques (46). It also has been known that the long-wave emissivity of a pavement is mainly affected by the pavement surface property and environmental conditions such as snow coverage (45). From this perspective, it is not surprising to see that the optimized values of the algebraic difference between the emissivity and absorption coefficients varies from winter to summer at pavement sites in Region D, most likely due to climate effects. As emissivity also is affected by site-specific pavement surface properties, small deviations from the general trends of the climatic regions are reasonable.

With a known pavement location, values of the difference between the emissivity and absorption coefficient for any pavement site in each region can be obtained based on the above observed trends. More realistically, and to consider possible deviations from the general trends caused by different pavement material properties, parameter values obtained from the nearest three pavement sites (of the 29 sites studied in this work) and in the same climatic region, can be averaged to obtain a value for the specific pavement site.

Absorption Coefficients

The third important parameter is the absorption coefficient for down-welling long-wave radiation from the air. Figure B-10 shows the estimated value of the absorption coefficients for the 29 pavement sections. As the absorption coefficient is mainly affected by the water partial pressure in the air, these optimized values are shown on a national relative humidity distribution map (from NCDC) based on average recorded data from 1961 to 1990. The optimized values in both winter and summer are exactly the same, indicating the parameter is less affected by seasonal variation (data not shown). Two values of the absorption coefficient, 0.75 in the east and south (and northwest) coastal regions and 0.7 in the dryer Midwest to west regions were observed.

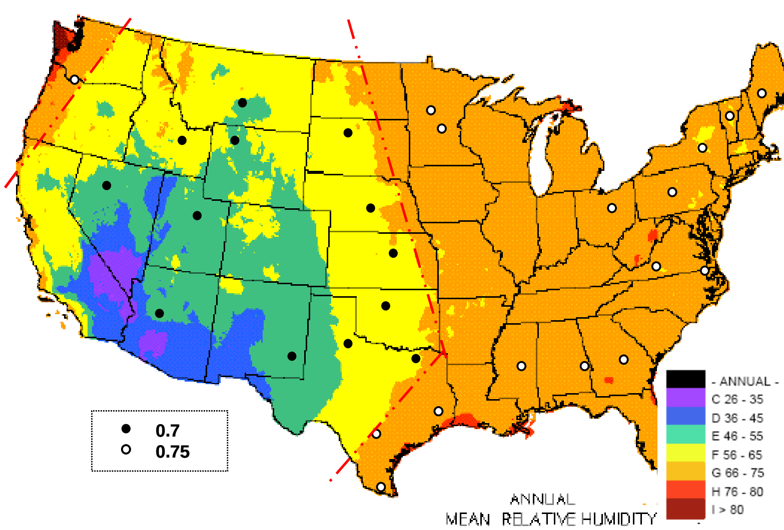


Figure. B-10 Optimized values of absorption coefficients.

VALIDATION OF THE PAVEMENT CALCULATION MODEL

To demonstrate the process of obtaining hourly climatic data input and model parameters and to validate the proposed pavement temperature models, two distinct LTPP SMP sites were selected for inclusion in this study: pavement 48-1068 in Lamar, Texas and pavement 27-1028 in Otter Tail, Minnesota. Pavement temperatures at those two pavement sites were calculated based on the above proposed procedures and then compared to field measured temperatures. The average absolute error between hourly predicted temperatures and measured temperatures was used to indicate the accuracy of model prediction.

Lamar Texas, Pavement 48-1068

As a complete record of measured hourly pavement temperatures was only available in 1994 in the LTPP database for pavement site 48-1068, pavement temperatures in 1994 were modeled and then compared to the measured data. The calculation started with collecting hourly climatic data, including hourly solar radiation, hourly ambient air temperature and hourly wind speed. In the NSRDB, hourly solar radiation data were listed by state and site name. Although solar radiation data for the Lamar site were not available, solar radiation data from a nearby site (Denison, 62 miles from Lamar) were available and were used instead. Daily maximum and minimum air temperatures recorded at the LTPP database were extracted and then were further processed using the imputation methods described above to obtain hourly air temperature data. Daily wind speed data at the pavement site were directly obtained from the LTPP database (Virtual Weather Station).

Values of model parameters were then estimated from the parameter map with proper interpolation. For pavement 48-1068, an albedo value of 0.2 (determined from the albedo value for the nearest pavement site), a value for the algebraic difference between emissivity and absorption coefficients of 0.15 (determined by the values at nearest site), and an absorption coefficient of 0.7 were obtained from this process. For Texas, these model parameters are taken to be constant throughout the year.

With estimates for these model parameters determined, pavement temperatures were calculated using the numerical simulation model. Figure B-11(a) shows the comparison of the calculations to the field measured temperatures over the one-year study period at three pavement depths: 25 mm, 128 mm, and 232 mm. Computation showed that the average absolute error between the measured and predicted temperatures was about 2.4 ^{o}C at 25 mm below the surface, 2.0 ^{o}C at 128 mm below the surface and 2.2 ^{o}C at 232 mm below the surface respectively. While the model cannot exactly reproduce the measured pavement temperature profiles, it really does quite well.

Otter Tail Minnesota, Pavement 27-1028

As a complete record of measured hourly pavement temperatures was available in the LTPP database at this site only from April 1996 to March 1997, pavement temperatures during that period were modeled and then compared to measured data to validate the model. The procedure to obtain hourly climatic data and model parameters are quite similar in pavement 27-1028 as in pavement 48-1068, except that two sets of model parameters need to be used as model parameters in winter time differ from the values obtained in summer time. The parameter values used for the winter were: albedo 0.35, algebraic difference between emissivity and absorption coefficients 0.05, and the absorption coefficient 0.75. In the summer, those parameters differ significantly from the winter values: albedo 0.2, difference between emissivity and absorption coefficients 0.05, absorption coefficient 0.75. The winter time period, when the winter set of parameter need to be used, can be determined directly as the time when typical high albedo value was recorded in NSRDB. At Fergus Falls (32 miles away from Otter Tail) from 1996 to 1997, high albedo value was obtained at Jan-1996 and Jan-1997. One month winter period at Jan-1997, when winter set of model parameters should be used, can hereby be determined in the calculation period from Apr-1996 to Mar-1997.

With estimates for these model parameters determined, pavement temperatures were calculated using the numerical simulation model. Figure B-11(b) shows the comparison of the calculations to the field measured temperatures at three pavement depths: 25mm, 115 mm and 205 mm. Computation showed that the average absolute error between the measured and predicted temperatures was 1.8 ^{o}C at 25 mm below the surface, 2.0 ^{o}C at 115 mm below the surface and 1.9 ^{o}C at 205 mm below the surface respectively, indicating good prediction accuracy of the calculation model.

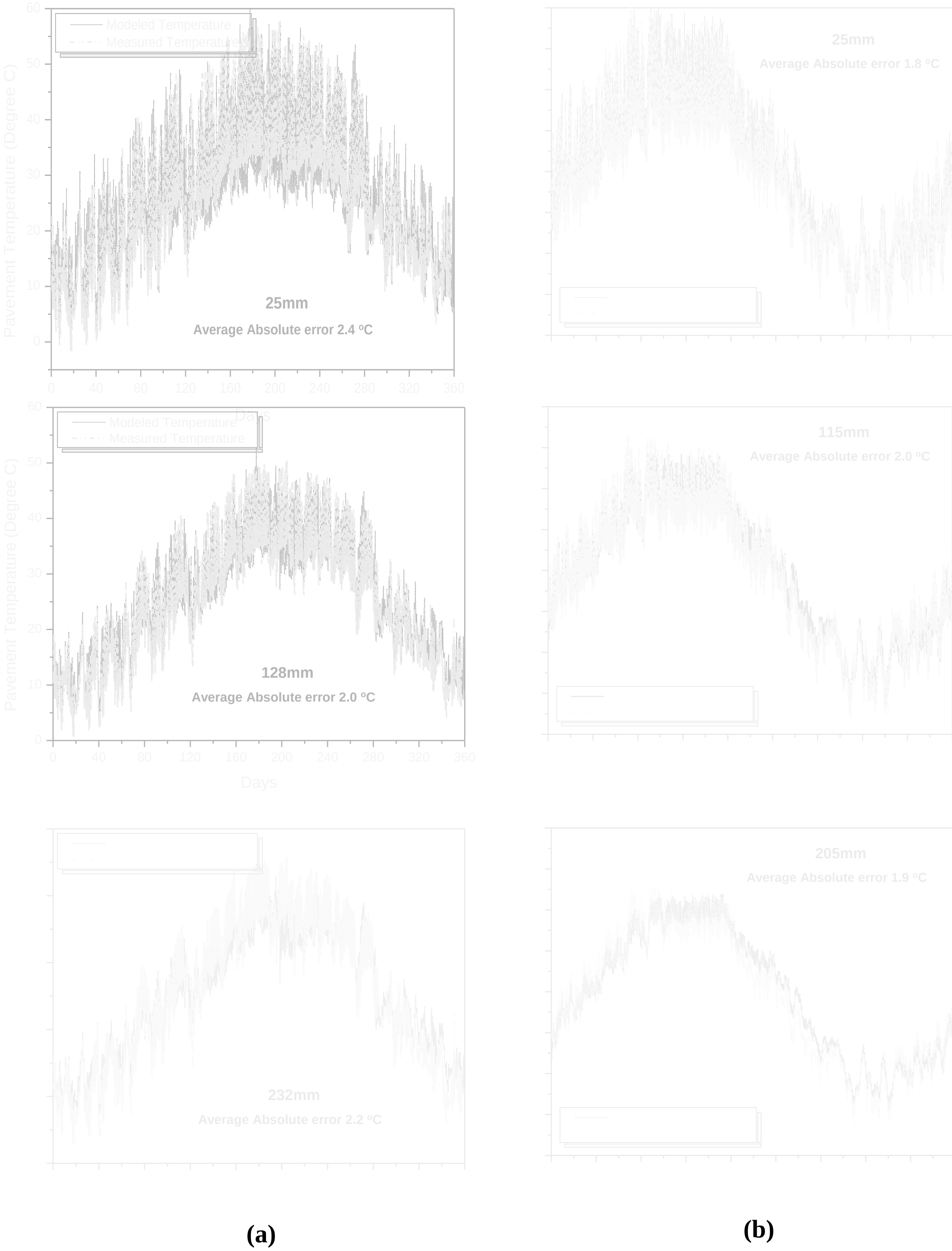


Figure B-11. Comparison of model predicted annual hourly pavement temperature and field measurement in both a) 48-1068 and b) 27-1028 at three depths.

SUMMARY

An accurate model for pavement temperature prediction is critical in the study of pavement material properties as well as their change over time, for example, prediction of binder oxidation and thermal cracking in pavement. In this work, a one-dimensional numerical model was developed to predict pavement temperature based on heat transfer fundamentals. The model employs commonly available hourly solar radiation, daily average wind speed, and imputed hourly air temperature based on site-specific daily pattern derived using time series analysis as climate input data. Three key site-specific model parameters were identified and national distribution of their values correlate with climatic patterns, suggesting possible interpolation strategies based on climate. The temperature model, proposed data sources and methods provided calculations that agreed well with experimental measurements, suggesting a general approach to predicting pavement temperature nationwide with acceptable accuracy.