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Assessment of Temperature Fluctuations in Asphalt Pavements Due to Thermal Environmental Conditions Using a Two-Dimensional Transient Finite Difference Approach

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October 2002

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The ultimate goal of this study is to lay groundwork for the development of methods and procedures to determine temperature profiles in asphaltic pavements and to provide pavement engineers with computational tools that increase the prediction accuracy of temperatures in asphaltic pavements for reliable pavement design.

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ASSESSMENT OF TEMPERATURE FLUCTUATIONS IN ASPHALT PAVEMENTS DUE TO THERMAL ENVIRONMENTAL CONDITIONS USING A TWO-DIMENSIONAL, TRANSIENT FINITE DIFFERENCE APPROACH

By

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Disclaimer

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PREFACE

Fluctuation in temperatures significantly affects pavement stability and the selection of asphalt grading to be used in pavements. Ability to accurately predict the asphalt pavement temperature at different depths and horizontal locations based on ambient air temperatures will greatly help pavement engineers in performing back-calculations of pavement modulus values. In addition, it will help engineers in selecting the asphalt grade to be used in various pavement lifts. The top pavement layer normally is exposed to greater temperature fluctuations than the layers below it. Knowledge of the temperature distribution in asphalts will allow for a more sophisticated specification of asphalt for lower lifts (through specification of less expensive asphalt binders in lower lifts) and thus provide an economical solution to rising pavement construction costs. The study also will allow for examination of the variability of predicted pavement temperatures on various pavement materials such as dense and open-graded asphalt mixes. This report describes a study conducted at the University of Wyoming by Dr. C. Yavuzturk, assistant professor, and Dr. K. Ksaibati, professor at the Civil and Architectural Engineering Department.

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INTRODUCTION

Thermal environmental conditions, to which pavements continuously are exposed in the construction and repair phases, as well as in use, determine the temperature profile in asphaltic sections. Fluctuations in ambient air temperatures - diurnal and seasonal, intensity of solar radiation, pavement materials and geometry, convective surface conditions, and precipitation significantly impact pavement stability and therefore the long-term success of pavement design.

Accurate prediction of the temperature profile in pavements greatly aids pavement engineers, specifically in the assessment of pavement deflection, in back-calculations of pavement modulus values, in estimations of frost action and frost penetration as well as thaw onset, in calculations of the cooling rates for freshly laid asphalt layers, and in the assessment of diurnal and seasonal heating and cooling effects. The top pavement layer normally is exposed to greater temperature fluctuations than the layers below it. Because of this, detailed knowledge of the temperature distribution in asphalt layers also allows for a more sophisticated specification of asphalt binders for lower lifts through specification of less expensive asphalt binders for lower lifts, and thus it provides an economical solution to rising pavement construction costs. An assessment of the impact of pavement temperature variations on various pavement materials, such as dense and open-graded asphalt mixes, is possible with a higher degree of accuracy.

The Strategic Highway Research Program (SHRP) conducted in the United States and Canada between 1987 and 1992 resulted in a new approach to asphalt mix design (Superpave). The new approach included a grading system called performance grading (PG) that proposes a two-number system intended to insure that the proper asphalt binder is used to resist pavement rutting in hot temperatures and to resist cracking in cold temperatures. The two-numbers in the new approach represent the expected maximum high and low asphalt temperatures based on local climatic data for the hottest and coldest times of the year. A significant number of departments of transportation across the United States and Canada either have already implemented or are in the process of implementing the Superpave design.

However, implementation of Superpave raises questions with respect to pavement temperature estimations since the new performance grading method for asphalt binders appears to modify the asphalt operational temperature range, and thus further limits availability of asphalt that meets the prescribed criteria. One concern associated with this implementation is the cost, since both asphaltic cement and aggregate costs may be higher for Superpave mixes due to limited sources or increased processing than for normal agency mix designs. Also, performance grading requirements either may require modifications in the asphalt or simply further constrain the available crude oil sources. In either case, the cost of asphalt may increase by as much as 30 percent over conventional agency implementations.

The Superpave performance grading requirements for lower asphalt lifts—including the binder and base courses, and the appropriate binder selection for hot mix asphalt recycling, calls for a detailed understanding of the temperature profile in pavements.

Many methods dealing with prediction of temperature gradients in pavements are based on statistical and probabilistic methods developed based on weather and pavement data collected through the Long-Term Pavement Performance Program (LTPP) under SHRP. However, such statistical and probabilistic methods display shortcomings in that they tend to either underestimate high pavement temperatures or overestimate low pavement temperatures raising questions about their accuracy and reliability. More detailed methods using energy balance equations to estimate pavement surface temperatures or numerical models that attempt to predict temperature gradients in asphalt pavements are either steady-state or one–dimensional transient approaches that fail to account for thermal interaction of parallel laid asphalt pavement lifts of varying grades and binders. The uncertainties associated with the Superpave algorithms call for computationally fast tools that can accurately and reliably predict asphalt pavement temperatures at different pavement depths and horizontal locations based on local ambient environmental conditions.

2.0. BACKGROUND AND LITERATURE SURVEY

A literature review was conducted to locate previous work done in the field of modeling temperature distributions in asphalt pavements as a function of thermal environmental conditions. The literature survey was focused on English language works. Also, extensive use was made of the Transportation Research Information Service (TRIS) database of publications, as well as the University of Wyoming library and its connections with libraries across the country.

Pioneering research in the field of asphalt pavement temperatures was done by Barber (1957). Barber attempted to correlate pavement surface temperatures and temperatures at 3.5 inch depths with standard weather report information. The weather parameters used were wind speed, precipitation, air temperature, and solar radiation. The pavement was considered to be a semi-infinite mass in contact with air. Barber observed that pavement temperature fluctuations measured in Hybla Valley, Vir., roughly followed a sine curve with a period of one day. The research and analyses showed that when solar radiation was included in the analyses with air temperature, the sine curve approximation provided reasonable estimates of asphalt surface temperatures.

Straub, et al (1968) studied asphalt pavements in the northern climate of New York. The study considered both 6- and 12-inch thick dense graded pavements at various depths. Measurements of climatic parameters on site were made that influenced pavement temperatures. A computer model was developed to predict pavement temperatures based on air temperature and solar radiation. The study showed that surface temperature measurements must be made at the surface to achieve a good correlation with solar radiation received at the site. Straub stated that temperatures at various depths of an asphalt pavement are independent of the thickness of the asphalt pavement. Results of the study also indicated that solar radiation had a greater effect on pavement surface temperatures than air temperatures, and that snow acted as an insulator while on pavement. The numerical model used by Straub subdivided the asphalt pavement in a column of nodes with a cross sectional area of one sq. ft. The nodes were set at the same depths as the thermocouples had been in the actual test section. Simulation of the model was initiated with guessed temperatures at each node. Energy balance equations for conduction, convection, and radiation were then applied to each node for the initial time step as applicable and a new set of temperatures was calculated for each node. At the next increment of time, the newly determined set of temperatures was used to determine pavement temperatures for the ensuing time step. This iterative process was continued over the time span of study, usually 24 hours. This model was found to provide a good correlation between measured temperatures and those predicted. The sensitivity of the model to the initial conditions used was checked for various depths. It was found that the predicted maximum surface temperatures are not sensitive to the initial input values, but as depth increases the input temperature becomes more critical to the accuracy of the prediction.

Demsey and Thompson (1970) used an approach similar to that of Straub et al., to create a model to evaluate frost action in multilayered pavements. The inputs required for the model included the climatic properties of short-wave and long-wave back radiation, convection, and air temperature. Inputs of thermal and material properties were unit weight, moisture content, material classification, thermal conductivity, and heat capacity of the pavement material. Temperatures predicted by the model were compared with those measured during the AASHO road test and laboratory tests. Some of the input values, such as short-wave radiation, long-wave back radiation, and the convection coefficient, were not measured directly, but were estimated using empirical correlations based on previous research by Geiger (1959), and Vehrencamp (1953). Air temperature values were not available at short enough time increments for use in the model, so intermediate values were approximated by a sine curve through the daily maximum and minimum air temperatures.

Up into the late 1960s, pavement temperature studies had only been conducted in the northern and central latitudes of the U.S. Rumney and Jimenez (1971) filled the gap by conducting a study of pavement temperatures in the Southwest US, near Tucson, Ariz. In this hot desert climate, maximum pavement temperatures are the main concern to pavement engineers. Researchers were looking for a practical tool for predicting maximum surface temperatures. The study collected pavement temperatures at various depths, as well as the corresponding surface temperature and rate of incident solar radiation. From this data a set of correlations were developed that predicted pavement temperatures for a given set of air temperatures and solar radiation intensities. Sets of curves were developed for pavement temperatures at 2- and 4-inch depths.

Pavement temperatures are of concern for pavement engineers in many climates worldwide. In South Africa, the primary consideration was the maximum pavement temperature in the upper levels of a pavement. Williamson (1972) developed a model by adapting a FORTRAN IV model developed by Schenk, Jr. (1963). This model used finite-difference techniques to predict temperatures at various depths over a short period of time, usually a day. Inputs for the model included climatic parameters as well as the thermal properties of the pavement. Series of sensitivity analyses were performed investigating the impact of radiative absorption coefficient, surface emissive power, convection coefficient, thermal conductivity of the pavement material, pavement density, and possible errors in the measurements of incident radiation, initial temperature boundary conditions, and air temperature. Results of the analyses indicated that while variations in the surface absorption coefficient had large effects on temperatures, variations in other items, such as, emissive power, convection coefficient, and thermal conductivity had more marginal effects on temperature. In addition, the model was validated using case studies. Data for model validation was collected from 8-inch thick asphalt pavement and portland cement concrete pavement sections in Pretoria. Actual temperatures and predicted temperatures were plotted versus time for various 24-hour periods. The results showed a good correlation between predicted and measured temperatures. However, neither precipitation nor humidity effects have been considered in the model. Also studied were the differences in temperature of pavements painted white versus naturally-colored asphalt pavements and surface temperatures of cement treated base that were sheltered from direct sunlight versus those exposed.

Christison and Anderson (1972) investigated the response of asphalt pavements to low temperature climatic environments. A computer model was developed that used a numerical finite difference method to predict the thermal regime in pavement systems. Christison and Anderson used the one-dimensional, transient approach in a homogeneous pavement solving resulting energy balance equations with an implicit scheme. Input variables were the meteorological data, such as the air temperature, solar radiation, cloud cover and wind velocity, structural and physical properties including geometry of asphalt pavements, and thermo-physical properties of pavement materials. Comparisons between predicted temperatures throughout the asphalt pavement and measured temperatures showed excellent agreement at the Alberta, Canada, test site.

In Norway, Noss (1973) studied pavement temperatures related to frost penetration in subgrades. Using weather and pavement temperature data collected at the Vormsund Test Road, multivariate regression analyses were performed to predict the difference between air temperature and pavement temperature during cold winters. This boundary condition could then be used to calculate frost depth. The parameters included in regression analyses were 30-year mean air temperature (normal air temperature), relative difference between the normal air temperature and the recorded temperature, precipitation, wind velocity, cloud cover, relative humidity, and absorbed global radiation at the surface. Regression coefficients were calculated for various months.

Southgate and Deen (1969) developed a method of adjusting pavement deflection measurements to a reference mean pavement temperature using a five-day air temperature history. A linear relationship was found between pavement temperatures at a given depth and the sum of the surface temperature and the five-day mean air temperature history. The method was developed using data from Maryland. A model validation was performed using data from Arizona and New York. The study showed that the model worked equally well for additional data sets from radically different climates.

Berg (1974) investigated the computational accuracy of individual energy balance components and total energy balance at the surface of pavement sections constructed with portland cement concrete. Experimental data were obtained from sections located at Lebanon Regional Airport in Lebanon, N.H. The surface energy balance approach includes heat transfer due to incident and reflected short-wave radiation, long-wave radiation emitted by the atmosphere and the earth's surface, convection, conduction into the air and the ground, evaporation and condensation on the surface, and infiltration of moisture into the ground. The study concluded that a surface energy balance approach was not sufficient to estimate frost and thaw depths within 15 percent of the measured depths.

Wilson (1975) used data collected from four pavement sections laid next to the Alconbury By-Pass in the United Kingdom. Modifying heat flow equations developed for predicting temperatures in bridges by Emerson (1968), Wilson used the equations to predict gradients in asphalt pavements. The study also considered solar radiation for cloudless skies. Data collected on one such rare day were compared to the predicted values. Since published values for solar radiation and thermal properties of the pavement materials were used, the model yielded results with limited accuracy. In addition, an empirical approach also was tried. In this, daily pavement temperatures were represented as a sine function. Temperature variation with depth was accounted for by applying a factor that reduced the amplitude of the sine curve with increasing depth. The method provided the greatest accuracy during the warming period at the surface, but had decreasing accuracy with increasing depth.

Spall (1982) designed a modified calorimeter to calculate average thermal conductivity and thermal diffusivity of asphaltic concrete. Each of the calculated properties was then used to predict the transient response of asphaltic concrete when exposed to in-field recycling conditions. The study discretized the two-dimensional transient heat diffusion equation with a heat generation term in cylindrical coordinates for asphaltic concrete samples. The predicted transient response agreed well with measured responses obtained from field tests.

To better quantify the energy transfer experienced by an asphalt pavement during in-place recycling, a laboratory study was conducted by Highter and Wall (1984) to determine thermal properties of various asphalt mixes. During a typical recycling process, an external heat source is applied to the pavement and then approximately the top one inch is scarified and recompacted, and sometimes overlaid with additional pavement. A study by Carmichael et al (1977) attempted to model the temperatures achieved during such a recycling operation. The study found that even a temperature as high as 540°C applied for 30 seconds only changed the temperature to a depth of 16 mm (0.64 in). This simulation was based on estimated values for thermal conductivity, density and specific heat of asphalt pavement. Highter and Wall study endeavored to measure these critical parameters as well as diffusivity of various pavement materials. The research showed that limestone mixes behaved differently from those prepared with lightweight aggregate. For the limestone mixes, thermal conductivity varied as much as 20 percent as the asphalt content was varied between 3.5 percent and 6.5 percent. Little variation of thermal conductivity in the lightweight aggregate mix was observed with comparable changes in asphalt content. Specific heat was approximately 60 percent greater in the lightweight mix than in the limestone mix. Researchers noted that this primarily was due to the difference in unit weights. A significant difference was noted in the diffusivity of the limestone surface course and the limestone base course, apparently due to gradation and aggregate size.

Thomson, Dempsey et al (1987) developed climatic a database for the State of Illinois. This database was derived from weather station records in 23 locations in and near the state. Maps were developed showing areas of equal percent sunshine and wind speed. A table of average weekly high and low air temperatures also was produced. Using this new database, combined with a heat transfer model developed years earlier, several new applications could be made. In one application, pavement temperatures were computed with the heat transfer model and climatic data. A regression analysis was run to establish a relationship between pavement temperatures and Mean Monthly Air Temperatures (MMAT). This information could then be used for selection of the proper asphalt cement modulus value to be used in pavement design.

The heat transfer model together with input from the climatic database produced the dependency of pavement temperatures on MMAT which compared well to published correlations by The Asphalt Institute. The new tools also were used to predict temperature profiles in PCCP for given date, time, and location.

Wolfe et al (1987) suggested a "simple" predictive method based on heat transfer equations to determine the cooling rate of a freshly laid asphaltic mat under a given set of environmental conditions. The method was developed as a decision aid to help pavement engineers decide whether to proceed with construction on a daily basis. Research indicated that the cooling rates of mats of sufficient thickness can be slow enough to permit satisfactory compaction even under rather adverse weather conditions and temperatures.

Huber, et al (1989) adapted a computer program originally created to predict long term permafrost thawing over a period of years. The focus of the research was on studies to develop methods for the prediction of pavement thaw onset, so that the time allowable for use of heavy trucks for logging during the winter could be maximized. In the original program by Hildebrande and Haas (1983), the energy balance at the surface was modeled using so-called N-factors rather than surface temperatures. N-factors represent the ratio of daily mean air temperatures to daily mean pavement temperatures. Researchers were interested in predictions over shorter time spans, hours rather than months, so they adapted the program for input of pavement temperatures. Pavement temperature data were scarce for Saskachewan, so local data were used from a 1975 study by the Saskachewan Highway and Transportation Department. Temperatures were available on a bi-hourly basis. Thermal properties for the various layers were assigned for the thawed and frozen conditions. These values were modified until a good correlation with measured pavement and subsoil temperatures was obtained with the model.

Hsieh et al (1989) developed computer models for predicting temperatures in concrete pavements and rain water infiltration into soil and subgrades due to weather changes. The models use an implicit finite difference scheme that employs spatial factorization to implement the solution as an alternating-direction implicit sequence. The model utilizes a series of TMY (Typical Meteorological Year) weather databases pertaining to various climate conditions. The significance of the study is that a three-dimensional numerical modeling approach was used coupled with moisture diffusion into pavements. An experimental validation of the model was attempted using data from sunny and cloud covered days in Miami and Orlando, Fla.

Another area of interest to researchers was the cooling of fresh hot mix asphalt pavement. This area was of particular importance to Saskatchewan Highways and Transportation because of the short paving season in the northern latitudes. Engineers frequently struggle with whether or not to allow paving to proceed, either due to marginal weather conditions or the specified cut-off date has passed. In an attempt to aid the engineers in making these decisions, White, et al (1990) developed a method to predict available compaction times that could be used in the field. Using the TEMPR2 computer program developed by Jordan and Thomas (1976) and through dimensionless analysis, the sensitivity of heat flow variables were tested. The study showed that the most significant factors were initial mix temperature and lift thickness. Other important variables were wind speed, thermal conductivities, thickness of the existing pavement, ambient temperature, and incident solar radiation. A series of charts were developed from which the allowable compaction time could be estimated for various combinations of the variables.

Studies also have been conducted on rigid pavements. While not the focus of this report, they are included for completeness. Choubane and Tia (1992) measured pavement temperatures at various depths in rigid pavements in Florida. A quadratic equation was developed that is used to predict temperature profiles in portland cement concrete pavements.

The advent of the Strategic Highway Research Program steered research in a slightly different direction. The performance-type specifications developed for asphalt cements required that a certain grade of asphalt binder perform over a given range of temperatures. For pavement engineers, knowing the upper and lower temperatures a pavement would be exposed became important. Solaimanian and Kennedy (1993) made an effort to develop a simple way for pavement engineers to determine these critical temperature extremes. Solaimanian and Kennedy study indicated that the difference between maximum pavement surface temperatures and maximum air temperatures were a function of latitude. A parabolic equation was developed that describes this relationship well. Using a known value of latitude, the maximum expected surface temperature could be approximated. The study also recommended using the lowest expected air temperature as the lowest expected pavement temperature for design. A third order polynomial corollary equation was suggested to predict pavement temperatures at various depths.

Another study to predict effective asphalt layer temperatures was conducted by Inge and Kim (1995), who developed a database approach for the estimation of asphalt concrete mid-depth temperature. The method represents improvements over the AASHTO method for the temperature correction procedure for asphalt concrete deflections in that air temperatures for the previous five days are not needed allowing for quicker computations, and heating and cooling cycles of asphalt pavements are taken into account. The research also studied an alternative temperature prediction model known as the BELLS equation to validate temperature prediction at on-third asphalt depths.

Voller et al (1998) developed a computer tool to predict the time-dependent thermal profile in an asphalt concrete lift during pavement construction. The key feature of the computer model was that the thermal predictions were directly related to the compaction characteristics of an asphalt lift using a asphalt thermal properties database. The goal of the research was to develop a tool that can be used to determine optimum strategies for paving operations, particularly in cold climates. The proposed thermal model uses the one-dimensional, transient heat diffusion equation and subdivides the asphalt pavement into two regions: an asphalt lift and a ground base at the interface of which a constant conduction heat flux is assumed. The numerical model imposes a radiative and convective heat exchange boundary condition at the pavement surface while the bottom surface in contact with the earth is treated as an insulated boundary. The model requires 24-hour weather data for input as well as input of the thermal properties of the pavement materials.

Lukanen et al (1998) suggested a probabilistic method for asphalt binder selection based on pavement temperatures. The Lukanen et al study developed an empirical prediction model based on simple regression analysis to relate the seven-day average high air temperature to the seven-day average high pavement temperature. The analyses used data from SHRP obtained in Canada and the US as well as data from LTPP-SMP. Temperature prediction of the empirical model is then compared to existing prediction relationships including an asphalt pavement heat flow model.

Mohseni (1998) proposed revisions to the SHRP performance grading system for asphalt binder selection, specifically for low temperature applications. The study, based on data from Long Term Pavement Performance Study's Seasonal Monitoring Program (LTPP-SMP), presents revised models for determining the low- and high-temperature component of Superpave performance-based binders. The study also compares existing models and resulting performance grades with the proposed approach.

An interesting study was conducted by Bosscher et al (1998) on six test sections on US-53 in Trempealeau County, Wis., by using different performance-graded asphalt binders to validate the Superpave pavement temperature algorithm and the binder specification limits. The analysis was focused on development of a statistical model for estimation of low and high pavement temperatures from meteorological data. The model was then compared to the Superpave recommended model and to the more recent model recommended by the LTPP program. Although the temperature data analyses indicated a strong agreement between the new statistical model and LTPP model for the estimation of low pavement design temperatures, LTPP and Superpave models both underestimated the high pavement design temperature at air temperatures higher than 30°C. The temperature data analyses also showed that there are significant differences between the standard deviation and of air temperatures and the standard deviation of pavement temperatures. The study raised questions about the accuracy of the reliability estimates used in the current Superpave recommendations.

3.0. OBJECTIVE OF THE STUDY

The objective of this research is to develop a method to predict temperature fluctuations at various depths and lateral locations in asphalt pavements. A two-dimensional, transient finite difference model of a pavement section is proposed that subdivides the pavement into vertical and horizontal control cells. The model is capable of predicting pavement temperatures at various depths and horizontal expansions as a function of thermal environmental conditions. Temperature predictions of the proposed model thus attempts to account for the lateral thermal interaction between pavement lifts of different materials, not only in the vertical, but also in the horizontal directions. The ultimate goal of the study is to lay groundwork for the development of methods and procedures to determine temperature profiles in asphaltic pavements and to provide pavement engineers with computational tools that increase the prediction accuracy of temperatures in asphaltic pavements for reliable pavement design.

4.0. METHODOLOGY

The two-dimensional finite-difference approach used to predict temperatures in asphalt pavements is described in detail below:

4.1. Energy Balance in Asphaltic Pavements

The temperature profile in an asphaltic pavement is affected directly by the thermal environmental conditions to which it is exposed. The primary modes of heat transfer are incident solar radiation, thermal and long-wave radiation between the pavement surface and the sky, convection due to heat transfer between the pavement surface and the fluid (air or water) that is in contact with the surface, and conduction inside the pavement as shown in Figure 1.

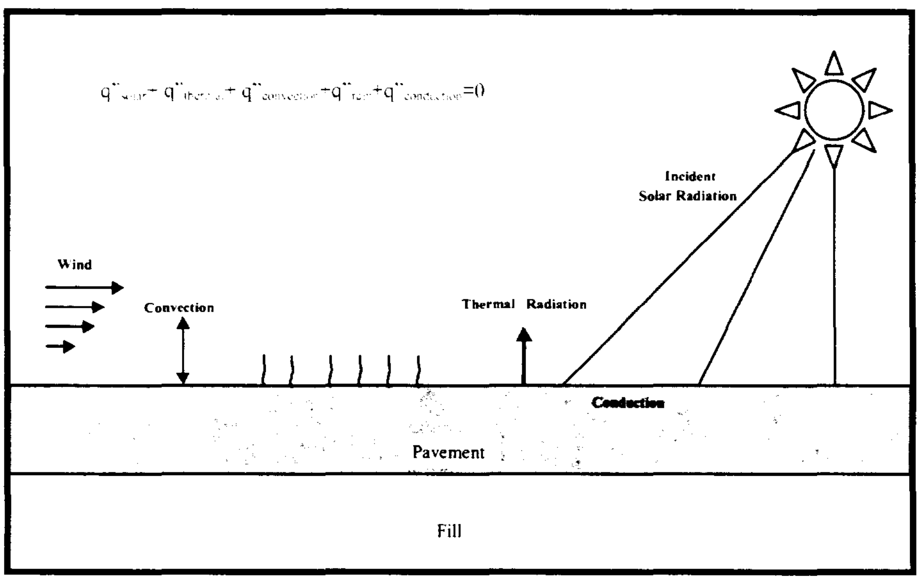

Figure 1. Energy balance on Asphalt Surface.

The intensity of solar radiation (direct and diffuse) is dependent on diurnal cycles, the location of the sun in the sky and the incident angle between the surface and sun's rays. The solar radiation results in direct and diffuse heat gain on the pavement through absorption of solar energy by the pavement. The convection heat flux is a function of fluid velocity and direction, and it is affected primarily by wind velocity and direction on the surface. As the convection heat transfer coefficient increases due to higher velocities and opportune wind directions, the convective heat flux also increases. Thus, at relatively high wind velocities a convective cooling of the surface occurs when the temperature of the wind is lower than the temperature of the pavement surface. The direction of the heat transfer due to thermal and long-wave radiation is away from the pavement since deep sky temperatures typically are significantly lower than pavement surface temperatures.

The surface energy balance on a pavement requires that the sum of all heat gains through the surface of the pavement must be equal to the heat conducted in the pavement. The direction of the heat flux due to convection and thermal radiation is a function of the temperature difference between the pavement surface and the bulk fluid/sky temperatures. In cases where the sky temperature and the bulk fluid temperature are lower than the pavement surface temperature, a cooling of the surface occurs while the surface might simultaneously be heated through incident solar radiation. Thus, depending on the magnitudes of individual heat fluxes, a heating or a cooling of the pavement takes place. An adiabatic bottom surface can be assumed for sufficiently thick pavements stipulating no heat transfer between the pavement and sub-grade layers. Similarly, side surfaces of the pavement (pavement edges) are considered to be adiabatic for sufficiently large horizontal expansions since spatial temperature changes in the vertical direction will be much greater than horizontal changes at pavement edges, and any heat transfer through pavement edge surfaces can be neglected. In this study, a pavement of 730 cm width approximating a two-lane pavement of 50 cm depth and infinitely long length is considered. The length of the pavement is of interest since it affects directly the convective heat flux on the surface.

4.2. The Finite Difference Mesh

Representation of the finite difference mesh used in the model is shown in Figure 2. A uniform square nodal spacing of 2.5 cm in x and z-directions has been used. In the z direction, the domain corresponds to the top of the pavement and bottom of the pavement or the base of the underlying fill material. A pavement of 730 cm horizontal expansion and 50 cm vertical depth is considered resulting in 292 cells in x and 20 cells in z directions. Thus, the domain of interest is subdivided into 5,840 cells for each of which an energy balance equation is developed.

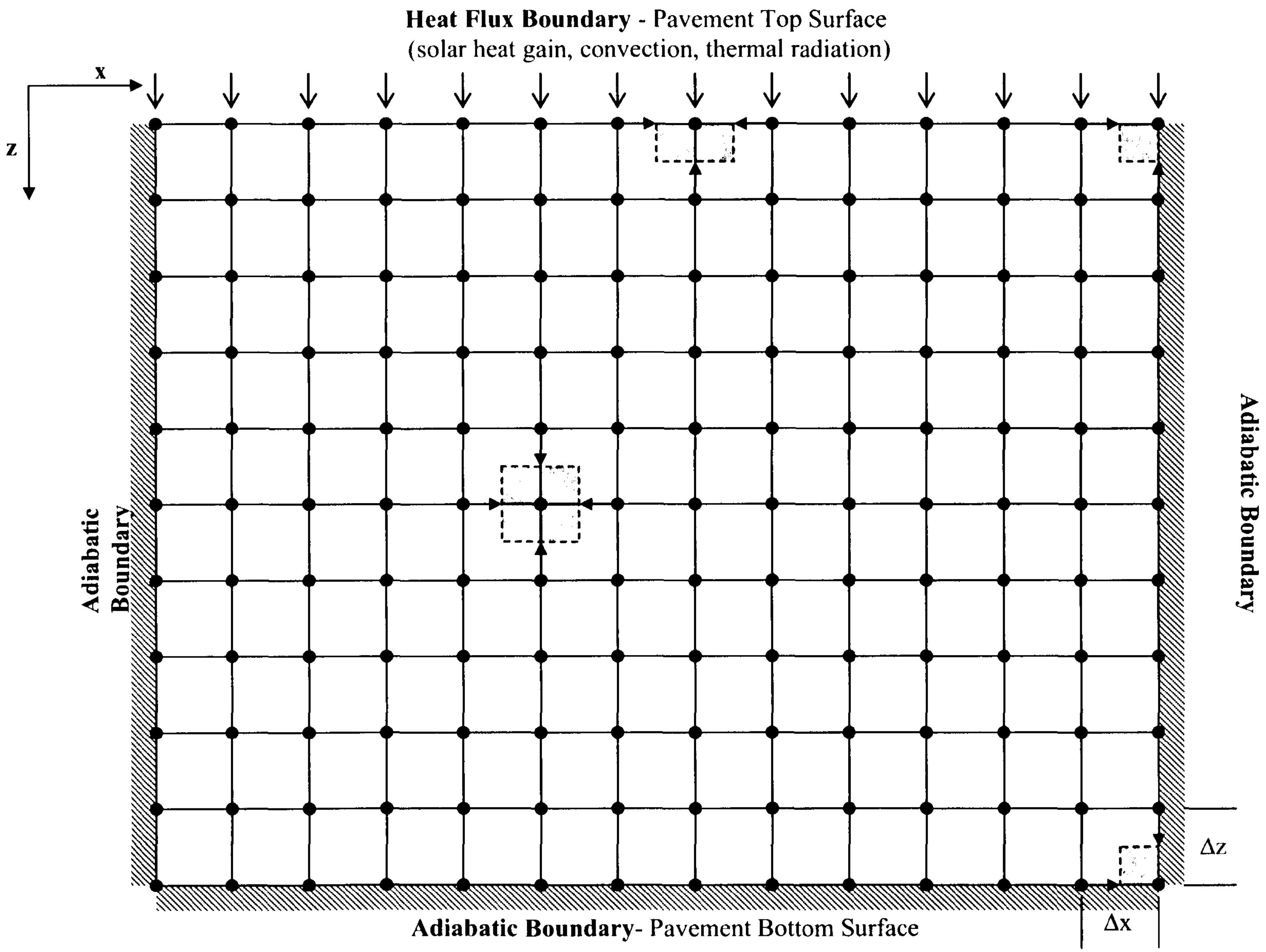

Figure 2. Finite Difference Nodal Network.

4.3. Two-Dimensional, Numerical Approach

The time-dependent heat transfer in the pavement is represented in two-dimensional cross-section using the Cartesian coordinate system. The applicable transient two-dimensional heat transfer equation is expressed as:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where α is the thermal diffusivity of the material, T the temperature, x and z are the spatial coordinates and t is the time.

The partial differential equation (1) is discretized using an explicit finite difference method. The geometry and notation of the finite difference cells in the x-z Cartesian coordinate plane are shown in Figure 2.

Using an energy balance approach, the nodal equations are formulated for each cell. The resulting general form of the explicit finite difference equation is:

$$\sum_{i=1}^{4} q''^{(t-\Delta t)}_{i} A = V\rho c_p\left(\frac{T_{(x,z)}^{\ t}-T_{(x,z)}^{\ (t-\Delta t)}}{\Delta t}\right) \tag{2}$$

where, $q_i''^{(t-\Delta t)}$ is the heat flux across the cell face i at the previous time step, A is the cell face area with a unit depth, V is the cell volume (assuming a unit depth), ρ is the average density of the cell material, c_p is the average specific heat capacity of the cell material, $T_{(x,z)}^{\ t}$ is the nodal temperature at the current time step, $T_{(x,z)}^{\ t-\Delta t}$ is the nodal temperature at the previous time step, and Δt is the time step. The heat flux, q'', for conduction into node *(x,z)* during a given time step is expressed by Fourier's Law in discrete form as:

$$q''_{i\rightarrow(x,z)} = k\frac{(T_i - T_{(x,z)})}{\ell} \qquad (3)$$

where subscript *i* denotes a neighboring node, *k* is the average thermal conductivity of the pavement material between nodes *i* and *(x,z)*, and ℓ is the distance between nodes *i* and *(x,z)*.

The stability criterion for the explicit method in two-dimensional problems is given through:

$$\frac{\alpha\Delta t}{\ell^2} \leq 0.25 \qquad (4)$$

Thus, the stability criterion requires two-minute time intervals for transient progression using typical heat diffusivity values of asphaltic materials.

4.4. Boundary Conditions

The boundaries of the model domain are treated as flux-type conditions as shown in Figure 1. The temperature at each boundary node is given by the energy balance equation (Equation 2), where q_i'' represents the appropriate external flux and conduction flux from adjacent nodes.

Lines of symmetry on the left- and right-hand boundaries are, by definition, zero-flux conditions. Heat flux at the pipe surface nodes represents convection from the heat transfer fluid. Heat flux at each top surface node ($q''_{(x,1)}$) is given by:

$$q''_{(x,1)} = q''_{solar} + q''_{thermal} + q''_{convection} + q''_{rain,sensible} + q''_{rain,latent} \quad (5)$$

where q''_{solar} is the solar radiation heat flux, $q''_{thermal}$ is the thermal radiation heat flux, $q''_{convection}$ is the convection heat flux, $q''_{rain,sensible}$ is the sensible heat flux from falling rain, and $q''_{rain,latent}$ is the latent heat flux from evaporating and/or condensing water. The bottom surface is treated either as an insulated surface of zero flux condition. Each of the heat flux terms is further described below.

4.4.1. Solar Radiation Heat Flux

Solar radiation heat flux (q''_{solar}) is the net solar radiation absorbed by the pavement surface and is given by:

$$q''_{solar} = \alpha I \quad (6)$$

where I is the solar radiation incident on the pavement surface and α is the absorptivity coefficient for the pavement material. The absorptivity coefficient is corrected for solar incidence angle (θ) dependence using an empirical correlation given by Duffie and Beckman (1991). The model also accepts solar radiation in the form of beam (I_b) and diffuse (I_d) components, in which case I is computed from:

$$I = I_b \cos\theta + I_d \quad (7)$$

The angle of incidence (θ) of the sun's rays can be computed at each time step from correlations given by Spencer (1971), Duffie and Beckman (1991), and ASHRAE (1997). The computation of the angle of incidence was not required in the end since measured values of solar fluxes were available through weather data.

4.4.2. Thermal Radiation Heat Flux

This heat transfer mechanism accounts for heat flux at the pavement top surface due to thermal or long-wave radiation. This model uses a linearized radiation coefficient (h_r) defined as:

$$h_r = 4\varepsilon\sigma\left(\frac{T_{(x,z)} + T_2}{2}\right)^3 \quad (8)$$

where ε is the emissivity coefficient of the pavement material, σ is the Stefan-Boltzmann constant, $T_{(x,z)}$ is the surface node temperature in absolute units, and T_2 represents the sky temperature in absolute units. T_{sky} is computed from the relationship given by Bliss (1961). The thermal radiation heat flux at each node ($q''_{thermal}$) is then computed by:

$$q''_{thermal} = h_r (T_2 - T_{(x,z)}) \quad (9)$$

4.4.3. Convection Heat Flux at the Pavement Surfaces

This mechanism accounts for heat transfer at the pavement top surface due to free and forced convection. The convection coefficient (h_c) is a function of the Nusselt Number (Nu). Several empirical formulations exist for determining the convection coefficient for different geometries. For a pavement surface, correlations for a horizontal flat plate are the most applicable.

In free convection heat transfer, Nu is a function of the Rayleigh Number (Ra). In external free convection flows over a horizontal flat plate, the critical Rayleigh Number is about 10^7. Therefore, two empirical relations for the Nusselt number are used in the model, as described by Incropera and DeWitt (1996), for free convection from the upper surface of a heated or cooled plate:

$$\mathrm{Nu} = 0.54\mathrm{Ra}^{\frac{1}{4}} \qquad (10^4 < \mathrm{Ra} < 10^7;\ \text{laminar flow}) \qquad (10a)$$

and

$$\mathrm{Nu} = 0.15\mathrm{Ra}^{\frac{1}{3}} \qquad (10^7 > \mathrm{Ra} > 10^{11};\ \text{turbulent flow}) \qquad (10b)$$

The convection coefficient (h_c) for free convection can then be determined from:

$$h_c = \frac{\mathrm{Nu}\ k}{L} \qquad (11)$$

where k is the thermal conductivity of air evaluated at the film temperature (as with the other thermal properties of air) and L is the characteristic length described for horizontal flat plates as the ratio of the area to the perimeter (Incropera and DeWitt, 1996).

In forced convection heat transfer, Nu is correlated to the Reynolds (Re) and Prandtl (Pr) Numbers. For external forced convection over a flat plate (i.e. the pavement surface), the critical

Reynolds Number is approximately 10^5. Therefore, two empirical relations for the Nusselt number are used in the model, as described by Incropera and DeWitt (1996), for forced convection over a flat plate:

$$\mathrm{Nu} = 0.664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}} \quad \text{(laminar flow regime)} \qquad (12a)$$

$$\mathrm{Nu} = 0.037\,\mathrm{Re}^{\frac{4}{5}}\,\mathrm{Pr}^{\frac{1}{3}} \quad \text{(mixed and turbulent flow)} \qquad (12b).$$

The convection coefficient (h_c) for forced convection can then be determined by Equation 11 with the characteristic length value described as the ratio of the length (parallel to the wind direction) to the perimeter.

Finally, the convection heat flux at each pavement surface node ($q''_{convection}$) is computed by:

$$q''_{convection} = h_c (T_{air} - T_{(x,z)}) \qquad (13)$$

where T_{air} is the dry-bulb air temperature and h_c is taken as the maximum of the free convection coefficient and the forced convection coefficient. This practice of choosing the larger of the free and forced convection coefficients is recommended by Duffie and Beckman (1991) and McAdams (1954) and is used in the absence of additional experimental evidence regarding combined free and forced convection.

4.4.4. Heat Flux Due to Rain

This heat transfer mechanism includes sensible and latent effects. This model uses a simple mass/energy balance on water at the pavement surface to account for heat and mass transfer. The thermal properties of water are computed from correlations given in the Handbook of Chemistry and Physics (CRC, 1980).

The sensible heat flux due to falling rain at each pavement surface node (q''_{rain}) is given by:

$$q''_{rain} = \dot{m}''_{rain} c_p (T_{air} - T_{(x,1)}) \qquad (14)$$

where $\dot{m}''_{rain}$ is the rainfall or snowfall rate in water equivalent mass per unit time per unit area and c_p is the specific heat capacity of water at the air temperature.

Latent heat transfer is considered only if the air temperature or the pavement surface temperature is above 33°F (0.55°C). Accumulation of rain is not considered; rainfall is assumed to drain instantaneously from the pavement surface, forming a thin film from which evaporation occurs.

This model uses the j-factor analogy to compute the mass flux of evaporating water at each pavement surface node ($\dot{m}''_w$):

$$\dot{m}''_w = h_d (w_{air} - w_{(x,1)}) \qquad (15)$$

where h_d is the mass transfer coefficient, w_{air} is the humidity ratio of the ambient air, and $w_{(x,1)}$ represents the humidity ratio of saturated air at the surface node. The mass transfer coefficient (h_d) is defined using the Chilton-Colburn analogy as:

$$h_d = \frac{h_c}{c_p \mathrm{Le}^{\frac{2}{3}}} \qquad (16)$$

where h_c is the convection coefficient defined previously, c_p is the specific heat capacity of the air evaluated at the pavement-air film temperature, and Le is the Lewis number. Le is computed as:

$$\mathrm{Le} = \frac{\alpha}{D_{AB}} \qquad (17)$$

where α is the thermal diffusivity of the air and D_{AB} represents the binary diffusion coefficient, each evaluated at the pavement-air film temperature. The heat flux due to evaporation ($q''_{evaporation}$) is then given by:

$$q''_{evaporation} = h_{fg}\dot{m}''_{w} \quad (18)$$

where h_{fg} is the latent heat of vaporization and is computed from the relationship given by Irvine and Liley (1984).

Although the discussed heat transfer algorithm due to rain is incorporated into the two-dimensional finite difference code in the simulation results presented here, the heat transfer due to rain is not simulated because of insufficient and inconsistent rain data in the weather information.

4.5. Climate and Pavement Data

Two sets of climate data were used for preliminary model validation and to assess model performance as compared to the Superpave algorithms for determining the maximum and minimum asphalt temperatures. For preliminary model validation, SHRP and LTPP climate and pavement data have been used. For comparison of the two-dimensional finite difference model to the Superpave algorithms, typical meteorological year (TMY) weather data were input.

4.5.1. SHRP and LTPP-SMP Climate and Pavement Data

The climate and pavement data used in this study for preliminary validation of the numerical model were extracted from the data archives of the Seasonal Monitoring Program (SMP) conducted under the Long-Term Pavement Performance Program. The SMP established a number of data collection sites in the United States and Canada to evaluate the thermal seasonal response of asphaltic pavements. These sites included weather stations and pavement temperature sensors to log climate and pavement data on an hourly basis.

4.5.2. Typical Meteorological Year (TMY) Climate Data

A Typical Meteorological Year (TMY) weather data file is a data set of hourly values of solar radiation and meteorological elements for a one-year period. It consists of months selected from individual years and summarized to form a complete year. The intended use is for computer simulations of solar energy conversion and building systems, and it provides a standard for hourly data for solar radiation and other meteorological elements. The TMY weather file represents conditions judged to be typical over a long period of time, such as 30 years.

The TMY weather files were derived from the National Solar Radiation Data Base (NSRDB), which was completed by the National Renewable Energy Laboratory (NREL). The NSRDB contains hourly values of measured or modeled solar radiation and meteorological data for 239 stations for the 30-year period from 1961 to 1990. The NSRDB accounts for any recent climate changes and provides more accurate values of solar radiation due to a better model for estimating values (more than 90 percent of the solar radiation data in both data bases are modeled), more measured data including direct normal radiation, improved instrument calibration methods, and rigorous procedures for assessing quality of data. The TMY weather files were created using similar procedures that were developed at Sandia National Laboratories by Hall et al (1978). The Sandia method is an empirical approach that selects individual months from different years from the period of record. For example, in the case of the NSRDB which contains 30 years of data, all 30 Januarys are examined, and the one judged most typical is selected to be included in the TMY. The other months of the year are treated in a like manner, and then the 12 selected typical months are concatenated to form a complete year. The 12 selected typical months for each station were chosen from statistics determined by using five elements: global horizontal radiation, direct normal radiation, dry bulb temperature, dew point temperature, and wind speed. These elements are considered the most important for simulation of solar energy conversion systems and building systems.

For other elements in the TMYs, the selected months may or may not be typical. Cloud cover, which correlates well with solar radiation, is probably reasonably typical. Other elements, such as snow depth, are not related to the elements used for selection; consequently, their values may not be typical.

4.6. Implementation of the Numerical Code

Implementation of the numerical code is done using FORTRAN 90 programming language. The executable code was developed using the COMPAQ Visual FORTRAN compiler. The source code comprises three sub-modules that sequentially interface to input pavement and weather data, to determine pavement asphalt temperatures, and to properly output pavement temperature response.

4.7. Analysis Procedure

4.7.1. Preliminary Model Validation

SHRP and LTPP climate and pavement database contains a large number of weather and pavement data from numerous locations across the USA and Canada. An investigation on the raw data sets has revealed a number of problems with individual weather and pavement data and problems related to matching the collected weather data with the pavement temperature data. In many instances, asphalt temperatures were measured at distances well away from the weather station locations. It is therefore somewhat difficult to obtain a fully satisfactory model validation since it is unreasonable to use weather data as input in the numerical model that was collected, at times, several miles away from the road segment where asphalt temperatures were measured. In addition, some data sets contained significant gaps (some as long as three months) that possibly were the result of failing data acquisition equipment at the site. The lengths of weather and pavement data also were different. Some weather data sets contain weather information that was collected much longer than the corresponding pavement data. Because of this, both data sets had to be carefully synchronized so simulation results (model predicted pavement temperatures generated based on the weather data) can be compared properly to the measured pavement temperatures. Nonetheless, an attempt has been made when using the SHRP and LTPP data sets to identify asphalt segments closest to the weather stations. Three such locations were found in Alabama, Delaware, and Virginia. The simulation results for the three locations are presented and discussed below.

4.7.2. Comparison to Superpave Algorithms

It is of interest to investigate, compare, and assess the performance of the proposed two-dimensional finite difference model relative to Superpave algorithms, a commonly accepted standard in asphalt engineering. Superpave binder specification is based directly on the climate in which the pavement will serve providing a realistic correlation between climatic conditions at a given location and pavement performance. Superpave algorithms allow for the distinction between various binder grades through specification of maximum and minimum asphalt temperatures at which the requirements must be met. Superpave defines the high pavement design temperature at a depth of about 20mm (0.8 inches) below the pavement surface, and the low pavement design temperature at the surface of the pavement. The following correlations are proposed based on a pavement solar absorption of 0.9, radiation transmission through air of 0.81, an atmospheric radiation of 0.7 and an average wind speed of 4.5 m/s (15 ft/s).

For maximum pavement temperature:

$$T_{20mm} = (T_{Air} - 0.00618Lat^2 + 0.2289Lat + 42.2)(0.9545) - 17.78 \qquad (19)$$

where,

Lat = the latitude of the location,

T_{Air} = the seven-day average high air temperature in □C.

For minimum pavement temperature:

$$T_{Surface} = -1.56 + 0.72T_{Air} - 0.004Lat^2 + 6.26\log_{10}(H + 25) - z(4.4 + 0.52\sigma^2)^{1/2} \qquad (20)$$

where

Lat = the latitude of the location,

T_{Air} = the low air temperature,

H = depth to surface in mm,

z=2.055 for 98% reliability,

σ = standard deviation of the mean low air temperature.

The comparative analyses are performed by simulating thermal behavior of a pavement of known thermal properties and comparing the pavement temperatures predicted by the numerical model proposed here to maximum and minimum pavement temperatures determined through the Superpave algorithms. The results are expected to be strongly dependent on the weather files used. Therefore, identical weather data are used to produce maximum and minimum pavement temperatures by both the Superpave algorithms and the numerical pavement model presented here.

5.0. SIMULATION RESULTS

5.1. Preliminary Model Validation

Preliminary validation of the numerical model is attempted using three different climate and pavement data sets obtained from the LTPP seasonal monitoring program data archives. The weather and pavement data are of actual acquisitions obtained through weather stations and temperature measurements made on highway sections in the states of Alabama, Delaware, and Virginia.

5.1.1. Model Validation using Alabama LTPP Data

The Alabama LTPP pavement temperature data was collected at Section 0101 with the corresponding weather station number 0101, both located approximately at N 32.6 degrees latitude and W 85.3 degrees longitude between 7/24/1995 starting at 1700 hours and 10/10/1996 ending at 1700 hours. The ambient air dry bulb temperature and the total solar radiation intensity incident on the pavement are shown in Figures 3 and 4 below.

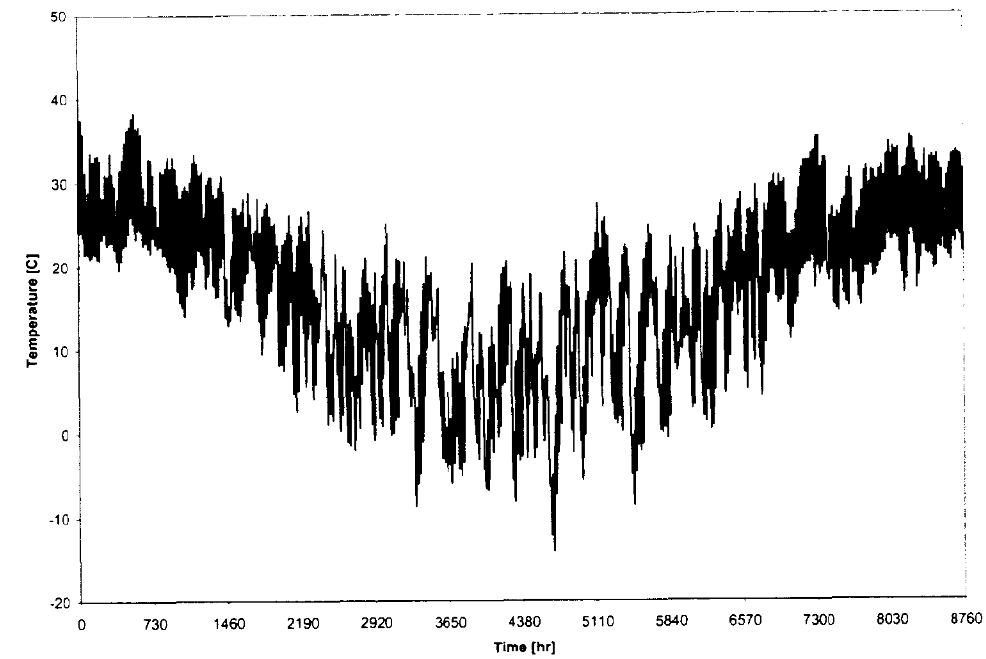

Figure 3. *AL LTPP Ambient Dry Bulb Temperatures*

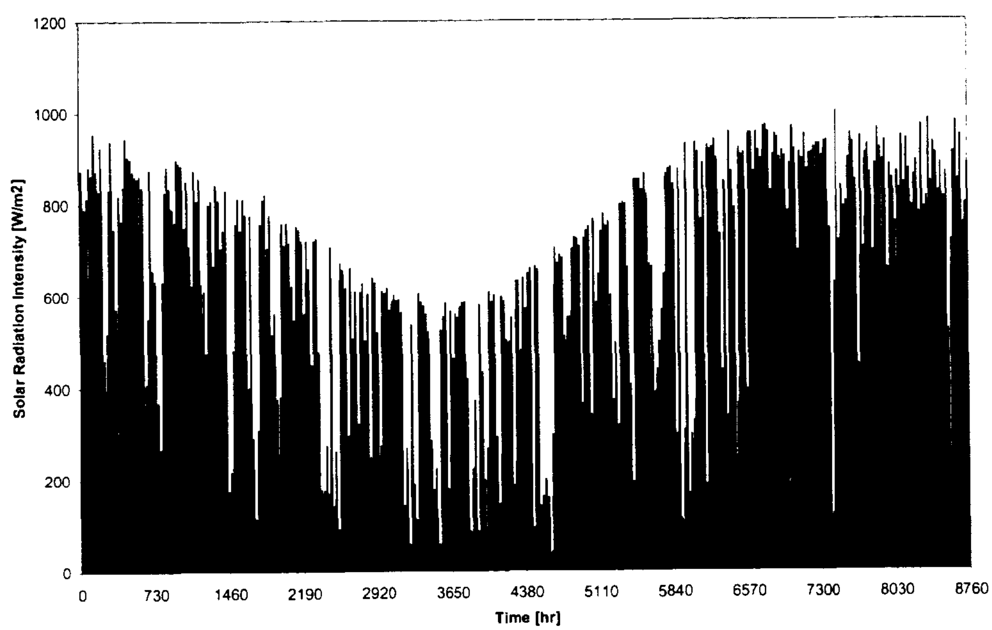

Figure 4. *AL LTPP Global Solar Radiation*

The surfacing of the asphalt is plant mix pavement (PMP) in the top lift of 1.4 inches (35mm) and PMP in the bottom lift of 5.2 inches (132mm). Asphalt temperatures are recorded at 18 different depths of the pavement between the surface and as deep as 25 inches (635mm). The pavement data set is not continuous and contains a large gap of almost three months between 9/11/1995 and 12/11/1995. The two-dimensional finite difference model is run using the corresponding weather data and a comparison plot between the actually measured and predicted asphalt surface temperatures is provided in Figure 5.

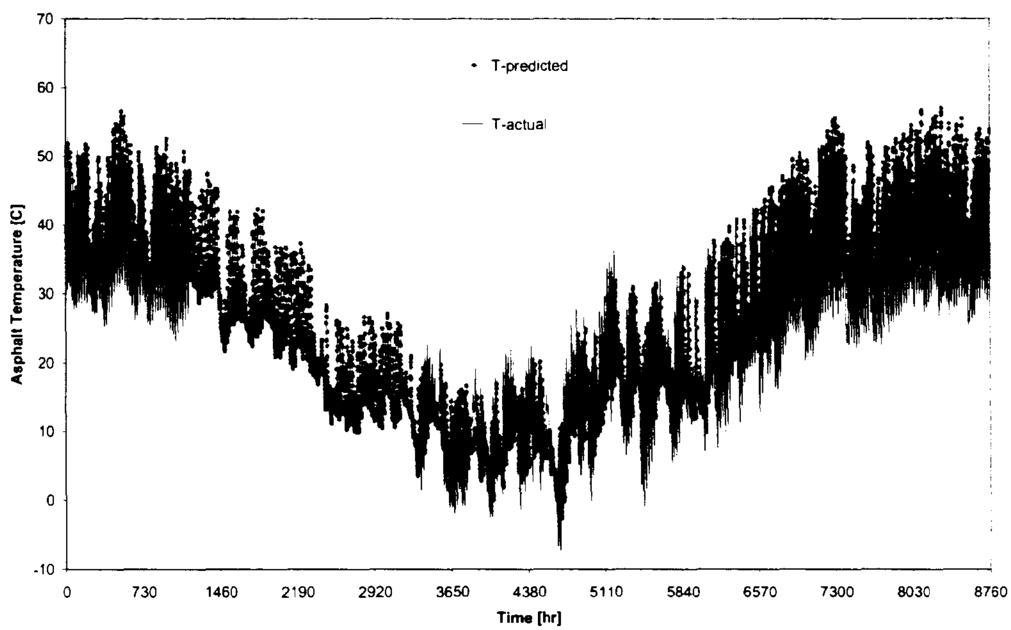

Figure 5. Comparison of actually measured and model predicted asphalt surface temperatures using AL LTPP data.

In Figure 5, note that, since continuous weather data was available the model simulation is continued although no corresponding comparative measured pavement temperature was available. The continuation of the model simulation was necessary to account for the thermal history in the asphalt pavement. Figure 5 shows the temperature comparison on an hour-by-hour basis starting on 7/24/1995 and continuing for a full year (8,760 hours). Despite uncertainties due to weather as well as pavement data, the predicted temperatures show an excellent agreement to the field-measured temperatures. The maximum and minimum predicted asphalt surface temperatures of 57.0 °C and -3.5 °C respectively deviate only little from measured asphalt surface temperatures of 53.6 °C and -7.4 °C.

5.1.2. Model Validation using Delaware LTPP Data

The Delaware LTPP pavement temperature data was collected at Section 0102 with the corresponding weather station number 0100, both located approximately at N 38.8 degrees latitude and W 75.4 degrees longitude between 11/18/1995 starting at 1800 hours and 5/9/1996 ending at about 4100 hours. The ambient air dry bulb temperature and the total solar radiation intensities incident on the pavement are shown in Figures 6 and 7 below.

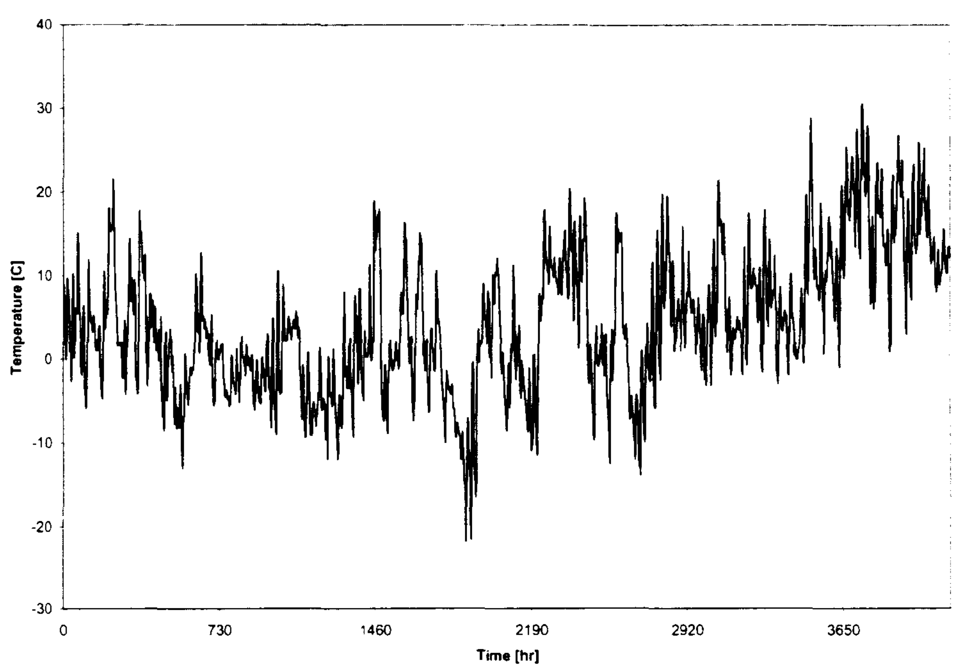

Figure 6. *DE LTPP Ambient Dry Bulb Temperatures*

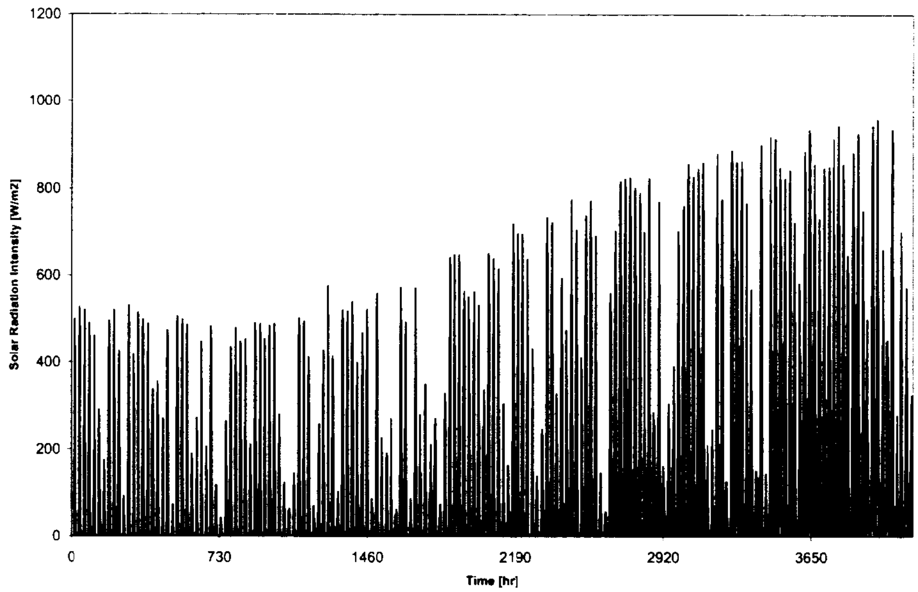

Figure 7. *DE LTPP Global Solar Radiation*

The asphalt surface is one inch (25mm) plant mix wearing course (PMWC) underlain by 1.5 inches (38mm) of PMP. The bottom lift is 3 inches (76mm) of also PMP. Asphalt temperatures are recorded at 18 different pavement depths between the surface and as deep as 25 inches (635mm). The pavement data set is not continuous but contains only a short gap of two hours between 1/15/1996 and 1/16/1996. The two-dimensional finite difference model is run using the corresponding weather data and a comparison plot between the actually measured and predicted asphalt surface temperatures as shown in Figure 8.

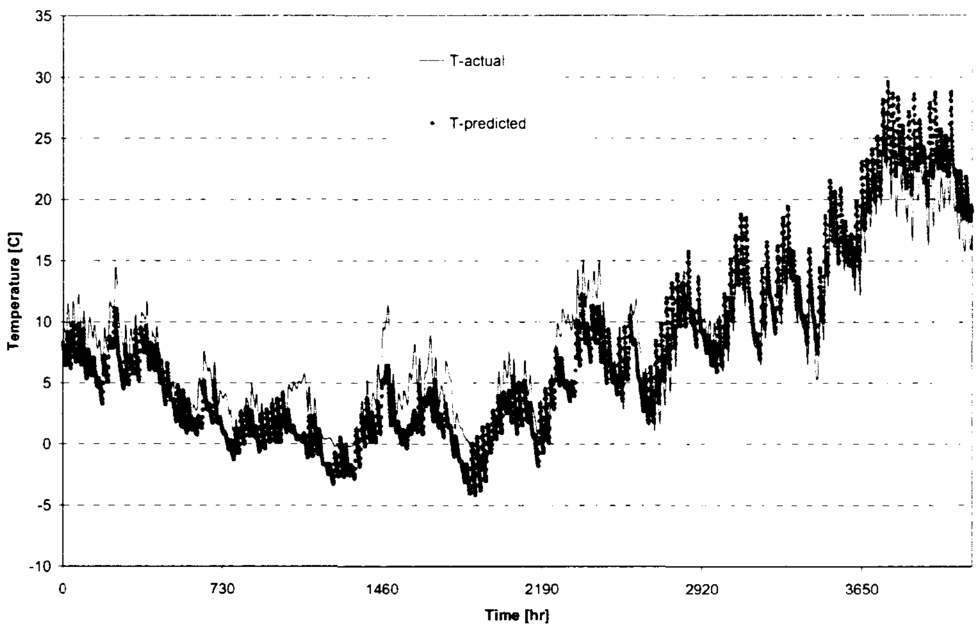

Figure 8. Comparison of actually measured and model predicted asphalt surface temperatures using DE LTPP data.

The temperature comparison is performed on an hour-by-hour basis starting on 11/18/1995 and continuing for a total of 4,155 hours (about six months). Again, despite uncertainties due to weather and pavement data, the predicted temperatures show a very good agreement to the field-measured temperatures. For the simulation time segment, the maximum and minimum predicted asphalt surface temperatures of 29.6 °C and -4.1 °C respectively deviate only slightly from measured asphalt surface temperatures of 28.7 °C and -1.9 °C.

5.1.3. Model Validation using Virginia LTPP Data

The Virginia LTPP pavement temperature data was collected at Section 0113 with the corresponding weather station number 0100, both located approximately at N 36.7 degrees latitude and W 79.4 degrees longitude between 10/8/1997 starting at 1400 hours and 5/19/1998 ending at 1600 hours.

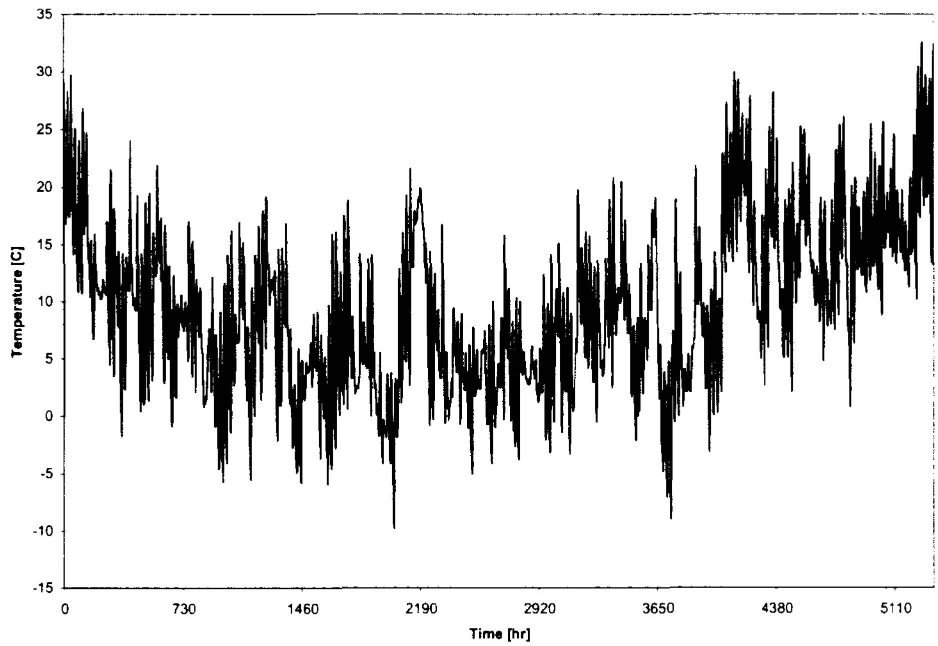

Figure 9. *VA LTPP Ambient Dry Bulb Temperatures*

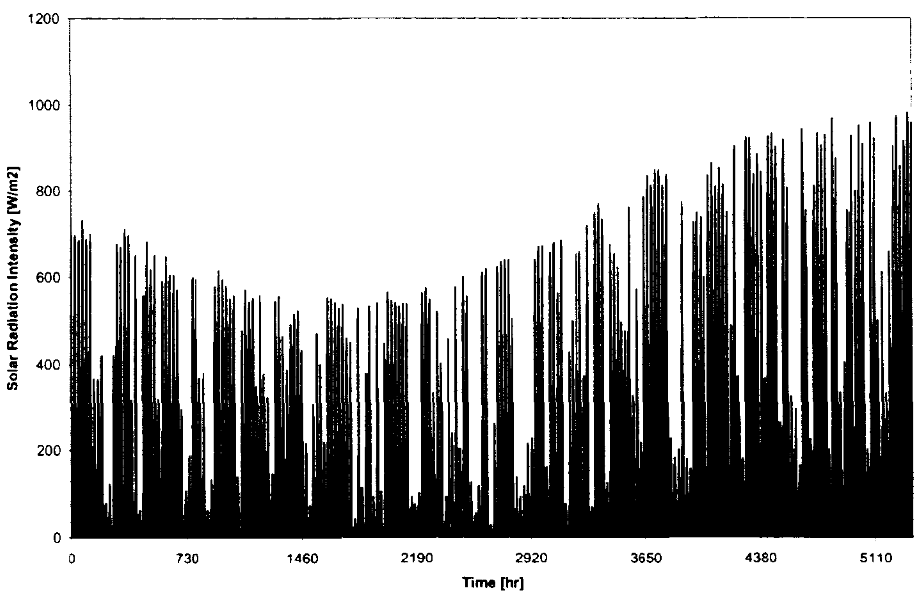

Figure 10. *VA LTPP Global Solar Radiation*

Surfacing of the asphalt is PMP in the top lift of 1.7 inches (43mm) and PMP in the bottom lift of 2.3 inches (58mm). Asphalt temperatures are recorded again at 18 different depths of the pavement between the surface and as deep as 24 inches (610mm). The pavement data set again contained significant gaps so that only a continuous data segment of 5351 hours starting on 10/8/1997 is used for validation. The two-dimensional finite difference model is again run using the corresponding weather data and a comparison plot between the actually measured and predicted asphalt surface temperatures is shown in Figure 11.

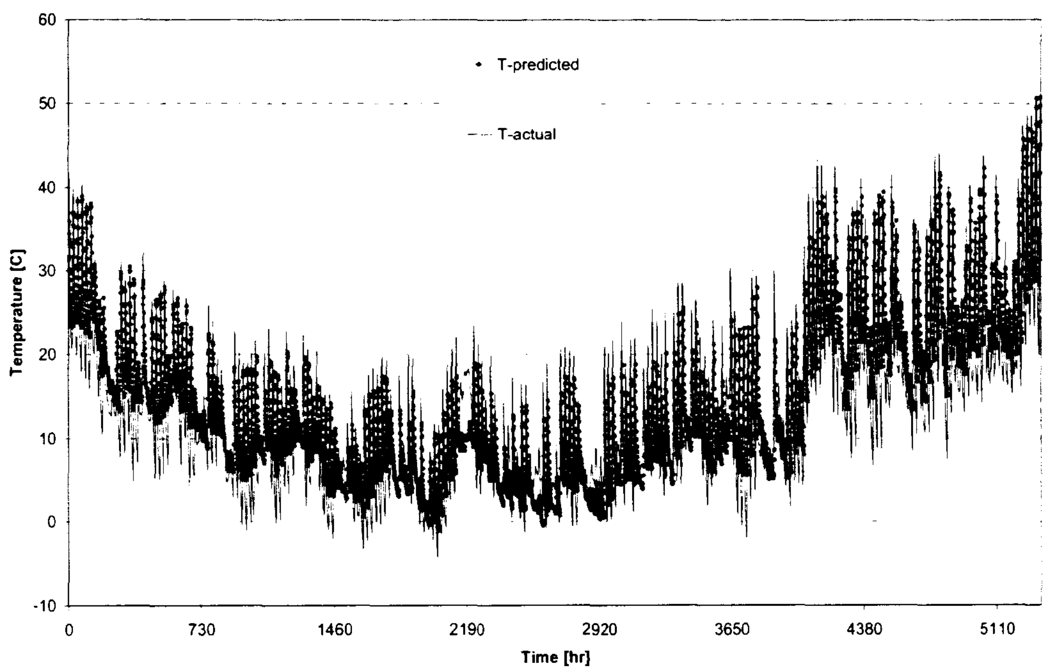

Figure 11. Comparison of actually measured and model predicted asphalt surface temperatures using VA LTPP data.

For the comparison segment, the predicted temperatures again show an agreement with the field-measured temperatures. The maximum and minimum predicted asphalt surface temperatures are 50.6 °C and -1.1 °C respectively, while the measured asphalt surface temperatures are 51.1 °C and -4.4 °C.

5.2. Comparison to Superpave Algorithms

A comparison to the suggested Superpave algorithms for determining asphalt surface temperatures and asphalt temperatures at a depth of 20mm is performed to assess performance of the numerical model. For this comparison, Typical Meteorological Year Weather files for Bismarck, N.D.; Cheyenne, Wyo.; Denver, Colo.; Great Falls, Mont.; Omaha, Neb.; and Phoenix, Ariz., are used to cover a variety of major climates in the western U.S.

Simulations were performed using typical thermal properties for asphalt. The computational time for each one-year hour-by-hour simulation was approximately seven minutes on a Pentium III 500MHz single processor workstation. The input parameters for the thermal properties of asphalt used in the simulations of the comparative analyses are provided in Table 1. Results of the hour-by-hour yearly simulations are provided in Table 2. Figures 12, 13 and 14 show a summary of pertinent TMY weather input parameters and predicted hourly temperature data at the asphalt surface and at a depth of 20mm for Denver, Colo. The most significant weather parameters for this study include hourly ambient air temperatures and global solar radiation intensities. The wind flow conditions, such as wind velocity and direction are assumed to have secondary impact on the asphalt temperatures. Simulation results for the additional climate regions are provided in Appendix A.

TABLE 1. Input Parameters for the Thermal Properties of Asphalt used in the Simulations of the Comparative Analyses

Thermal Conductivity k	1.3 W/m-K
Volumetric Specific Heat ρC_p	2,000 kJ/m^3-K
Length of Asphalt Segment L	Infinitely long
Emmissivity ε	0.81
Absorptivity α	0.95
Orientation of Asphalt from North	0 degrees

TABLE 2. Results of the hour-by hour yearly simulations and Comparison to Superpave Algorithms

Location	**Maximum and Minimum Ambient Air Temperatures in the TMY weather data [°C]**	**Maximum Global Solar Radiation Intensity in the TMY weather data [W/m^2]**	**Numerical Model Predictions- T_{max}/T_{min} [°C]**	**Superpave Algorithm- T_{max}/T_{min} [°C]**	**Performance Grade (*Model*/Superpave)**
Bismarck, N.D.	38/-40	1025.3	51/-27	55/-33	55/-33 (*52-28*/58-34)
Cheyenne, Wyo.	33/-29	1021.4	50/-17	53/-24	53/-24 (*52-22*/58-28)
Denver, Colo.	35/-29	1022.8	55/-14	55/-16	55/-16 (*58-16*/58-16)
Great Falls, Mont.	36/-26	1046.1	50/-23	54/-21	54/-21 (*52-28*/58-22)
Omaha, Neb.	36/-24	989.4	55/-18	56/-20	56/-20 (*58-22*/58-22)
Phoenix, Ariz.	46/-2	1095.6	67/-3	67/0	67/0 (*70-10*/70-10)

The results of the comparative analyses show a reasonable agreement between the predicted temperatures of the numerical model and the Superpave algorithms. Although the numerical model appears to somewhat underpredict the maximum and minimum asphalt design temperatures relative to Superpave algorithm, there is good agreement in the majority of the six cases considered. In cases of Denver, Colo.; Omaha, Neb.; and Phoenix, Ariz., the maximum expected asphalt temperatures at a depth of 20mm are predicted equally to Superpave while the largest deviation in maximum temperatures is no more than 4 °C. The minimum asphalt surface temperatures are in general predicted almost within 2 °C. The largest deviations are observed in simulations for Bismarck, N.D., and Cheyenne, Wyo.

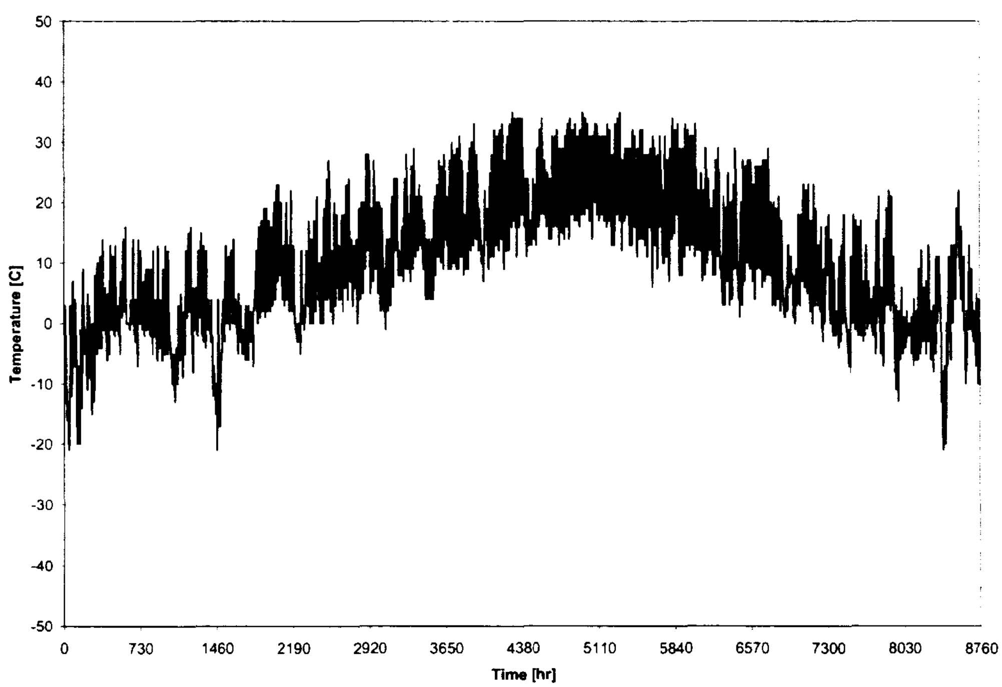

Figure 12 *Denver, Colo., TMY Ambient Dry Bulb Temperatures*

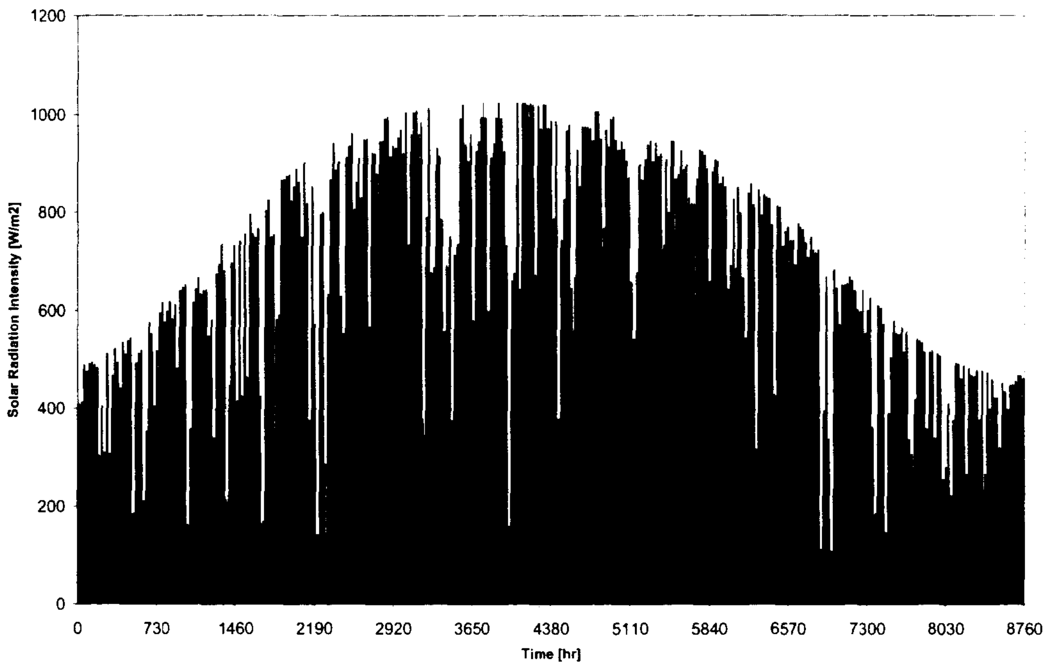

Figure 13 *Denver, Colo., TMY Global Solar Radiation*

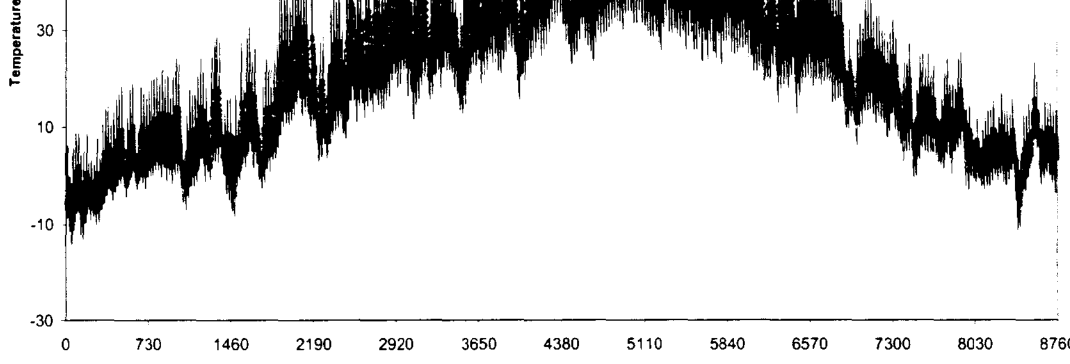

Figure 14 *Denver, Colo., Asphalt Temperature Predictions*

5.3. Sensitivity Analyses

Strong dependence of the predicted asphalt temperatures exists on the thermal properties of asphalt materials. Series of sensitivity analyses are conducted to quantify and assess this dependence. Using the TMY weather data for Denver, Colo., repeated predictions of asphalt temperatures are obtained for a range of values for asphalt thermal conductivity, volumetric specific heat, length of asphalt segment, emmissivity and asphalt segment orientation from North. A sensitivity analysis modulating asphalt absorptivity was deemed unnecessary since typical asphalt materials in upper lifts have relative high absorptivity values of about 0.95. The range of asphalt thermal properties values are selected to include most common asphalt materials covering a significantly large range of materials. The thermal conductivity was modulated between 0.5 W/m-K and 2.5 W/m-K while volumetric heat capacities were varied between 500,000 J/m^3-K and 2,500,000 J/m^3-K.

Results of the sensitivity analyses are shown in the Figures 15 through 26. Since pertinent sections of the hourly temperature predictions are around the times when the maximum asphalt temperature at a depth of 20mm and a minimum temperature at the asphalt surface are observed hourly temperatures predicted within a week (168 hours) of the maxima and minima are shown.

5.3.1. Sensitivity to Thermal Conductivity of Asphalt Material

Sensitivity to thermal conductivity is shown in Figures 15 and 16 The minimum and maximum temperatures at the asphalt surface change by 6.6°C and 0.9°C respectively when the thermal conductivity of the asphalt material is changed between 0.5 W/m-K and 2.5 W/m-K. As the thermal conductivity increases the predicted temperature at the surface of the asphalt decreases due to higher rate of heat dissipation off the surface.

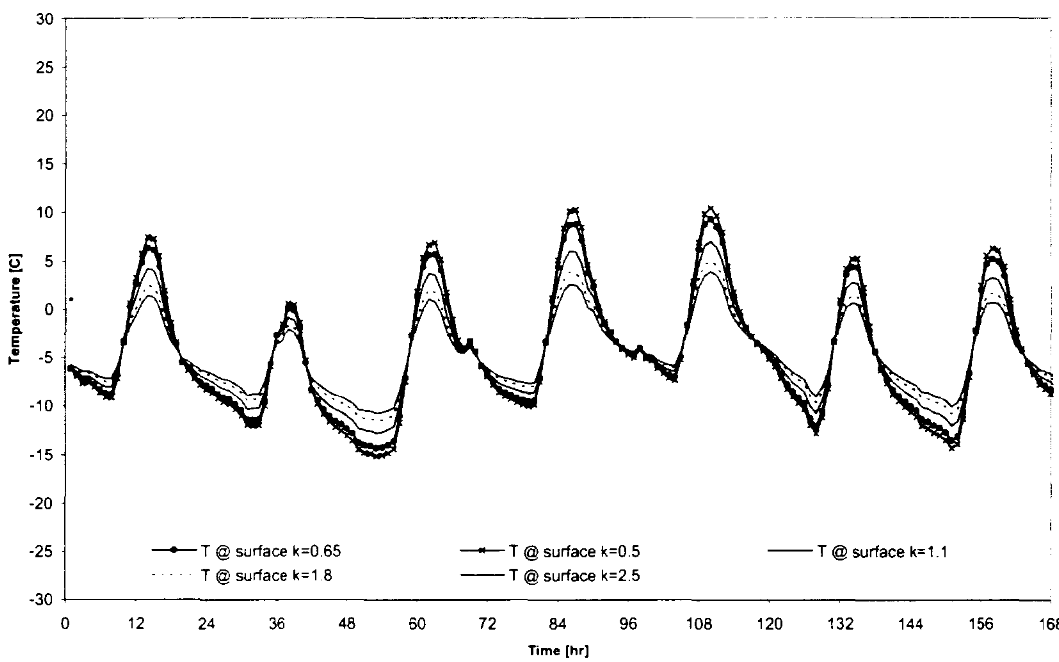

Figure 15 *Sensitivity of Temperature Predictions to Thermal Conductivity of Asphalt Material using Denver, Colo., minimum Temperatures Predictions.*

The differential maximum asphalt temperature variation at a depth of 20mm is, as expected, significantly less than at the surface because heat transfer inside the asphalt material is only due to pure conduction, whereas convective cooling dominates at the surface resulting in higher rates of heat transfer and larger temperature fluctuations. The temperature change at the asphalt surface is about 3.3°C for every 1 W/m-K change in the thermal conductivity of the asphalt material. The temperature change is only 0.45°C for every 1 W/m-K at the 20mm depth. Due to the thermal mass of the asphalt a slight time shift is observed as to when the maximum temperature is reached at varying values of thermal conductivity. This time shift, as expected, is not observed at the asphalt surface since the energy balance boundary condition assumes a infinitesimally small control volume without a thermal mass.

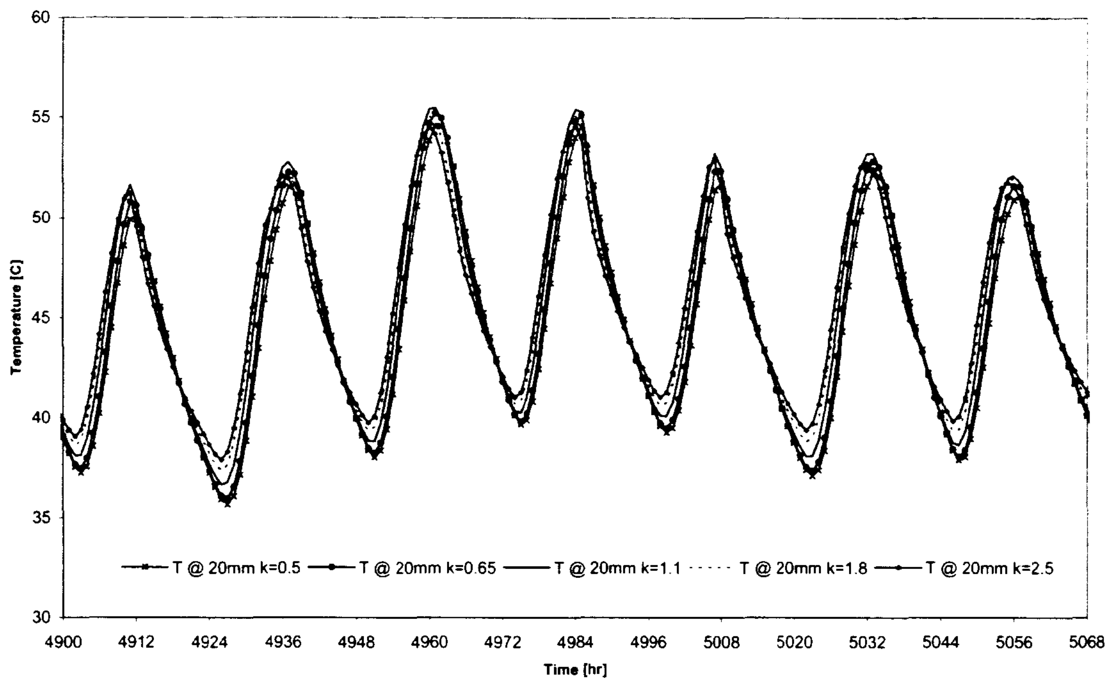

Figure 16 *Sensitivity of Temperature Predictions to Thermal Conductivity of Asphalt Material using Denver, Colo., maximum Temperatures Predictions.*

5.3.2. Sensitivity to Volumetric Specific Heat Capacity of Asphalt Material

Sensitivity to volumetric specific heat capacity is shown in Figures 17 and 18. Sensitivity of the temperature predictions to the volumetric specific heat capacity of the asphalt material is significantly higher than to the thermal conductivity. As expected, the temperature changes in sections of asphalt where the heat transfer is due to pure conduction are much larger than at the surface. The minimum and maximum temperatures at the asphalt surface change by only 10.2°C and 17.6°C respectively when the thermal conductivity of the asphalt material is changed between 500,000 J/m^3-K and 2,500,000 J/m^3-K. As the volumetric specific heat capacity of the asphalt material is increased the predicted asphalt temperatures decrease because asphalt materials with higher volumetric specific heat capacity values can store more energy per unit volume resulting in lower temperatures.

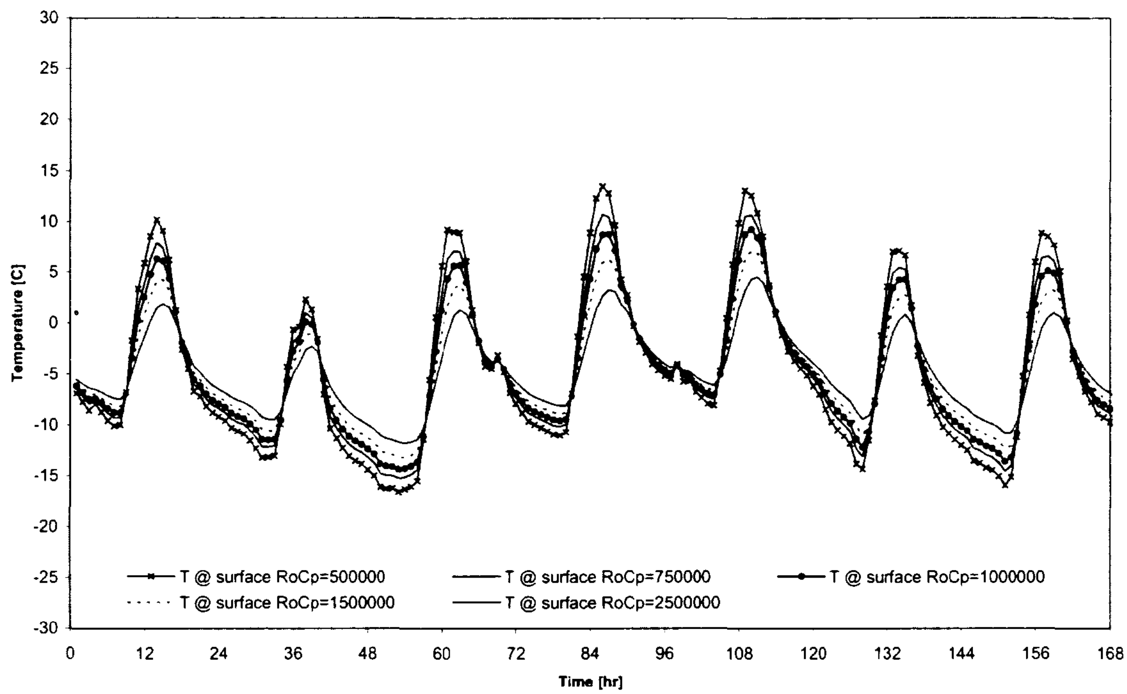

Figure 17 *Sensitivity of Temperature Predictions to Volumetric Specific Heat Capacity of Asphalt Material using Denver, Colo., minimum Temperatures Predictions.*

The temperature change is much higher inside the asphalt material than at the surface of it due to no-thermal mass boundary condition at the asphalt surface. Because of the thermal mass of the asphalt material a significant time shift of about three hours is observed in the maximum temperature predictions between 500,000 J/m^3-K and 2,500,000 J/m^3-K. The temperature change at the asphalt surface is estimated to be about 0.5°C for every 100,000 J/m^3-K change in the volumetric specific heat capacity of the asphalt material. The temperature change is only 0.9°C for every 100,000 J/m^3-K at the 20mm depth.

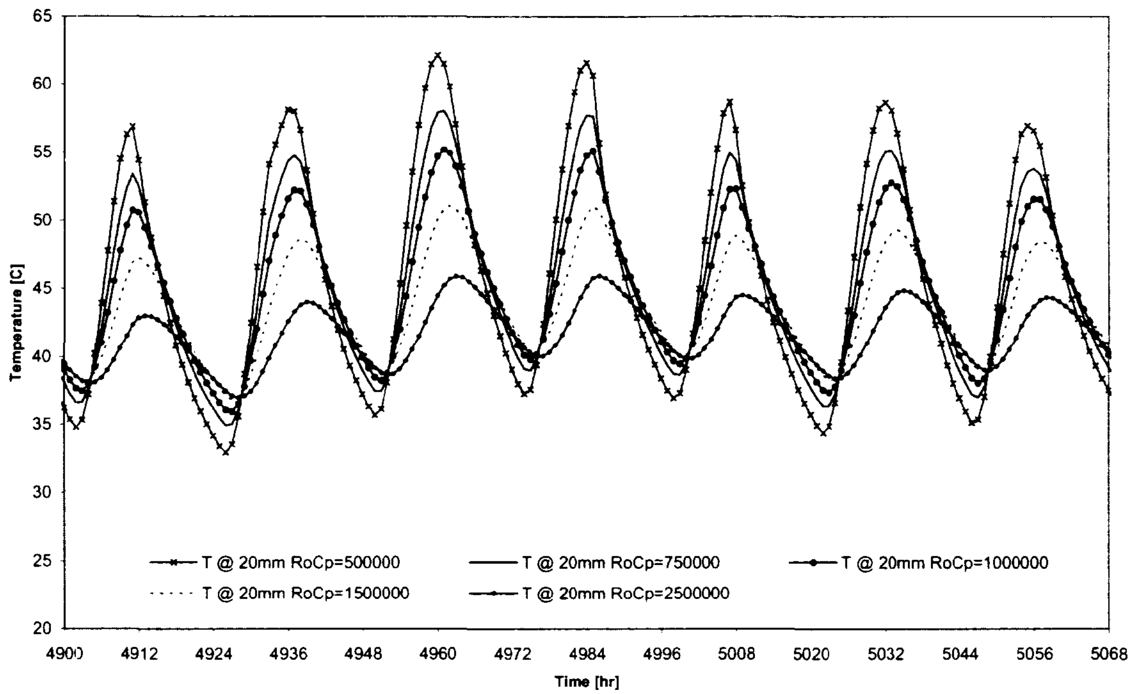

Figure 18 *Sensitivity of Temperature Predictions to Volumetric Specific Heat Capacity of Asphalt Material using Denver, Colo., maximum Temperatures Predictions.*

5.3.3. Sensitivity to Length of Asphalt Segment

Sensitivity to the length of the asphalt segment is given in Figures 19 and 20. The minimum temperatures at the asphalt surface change by 1.5°C when the length of the asphalt segment is assumed to be 1 m long. The maximum temperature changes significantly by about 7.2°C when an infinitely long segment is considered. The significance of asphalt length is related to the amount of heat transfer off the asphalt surface. The longer the asphalt segment is the more heat is transferred off it because the air flow (wind over the asphalt surface) in longer segments reaches a turbulent fluid flow regime allowing for increased rates of heat transfer resulting in lower temperatures due to increased cooling. However, this impact appears to be relatively small.

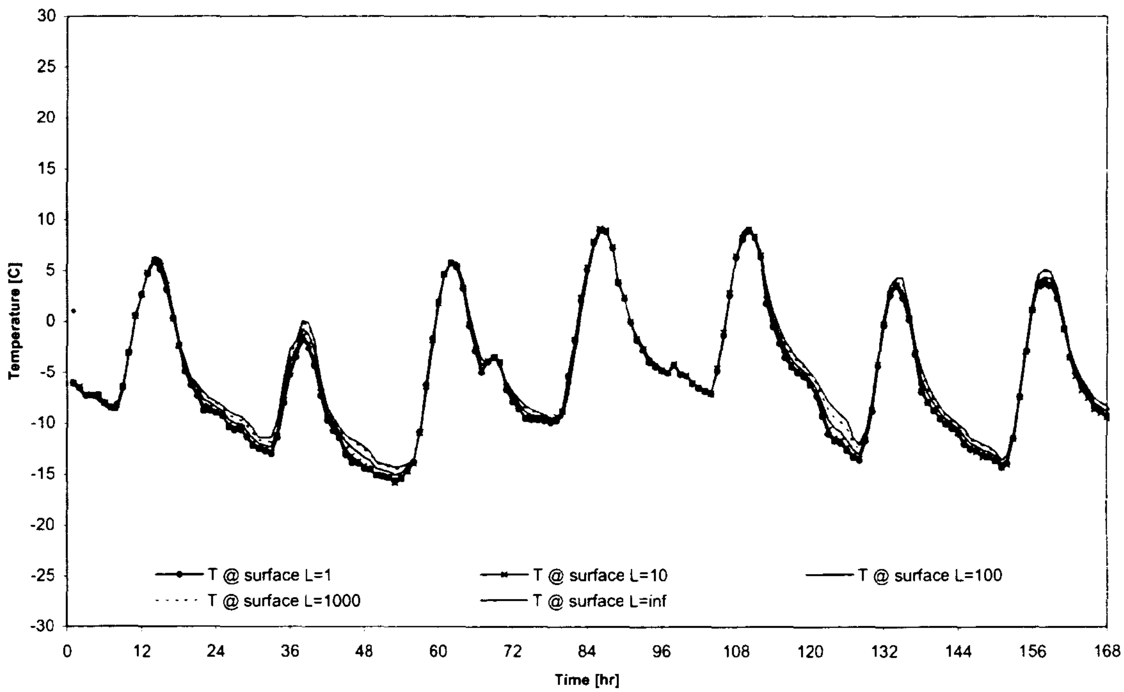

***Figure 19** Sensitivity of Temperature Predictions to the Length of Asphalt Segment using Denver, Colo., minimum Temperatures Predictions.*

The length of the asphalt appears to impact the maximum predicted temperatures at a depth of 20mm in a significant way. There are however upper and lower critical values in the length at which point on the changes become insignificant. The difference in maximum temperature between an asphalt segment of a length of 1,000m and a segment that is infinitely long is only about 1°C. At the lower critical limit, the temperature change is less than 0.4°C when the length of the asphalt segment is modified between 1m and 10m. When an asphalt length of 100m is considered the temperature change becomes about 3.6°C compared to the 10m and the 1,000m segments. The lower temperature predictions at a depth of 20mm for short asphalt lengths is due to the fact that the total energy incident up the surface is significantly less than the total energy incident upon the longer segment while the solar radiation intensity per unit area of the asphalt remains constant. The segment that receives more energy subsequently cools off slower.

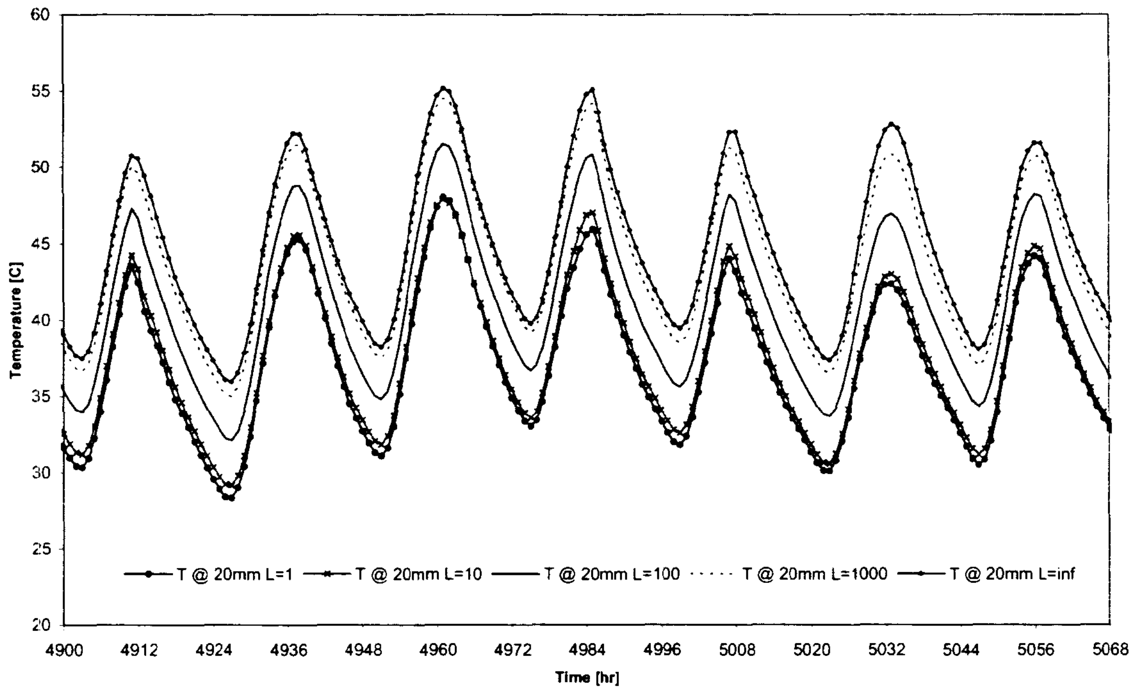

Figure 20. *Sensitivity of Temperature Predictions to the Length of Asphalt Segment using Denver, Colo., maximum Temperatures Predictions*

5.3.4. Sensitivity to Emmissivity of Asphalt Material

Sensitivity to the emmissivity of the asphalt material is given in Figures 21 and 22. The minimum temperature at the asphalt surface changes by 3.9°C when the emmissivity of the asphalt material is modulated between 0.5 and 0.95. A higher temperature is predicted at lower emmissivities because the asphalt surface radiates less energy resulting in higher temperatures.

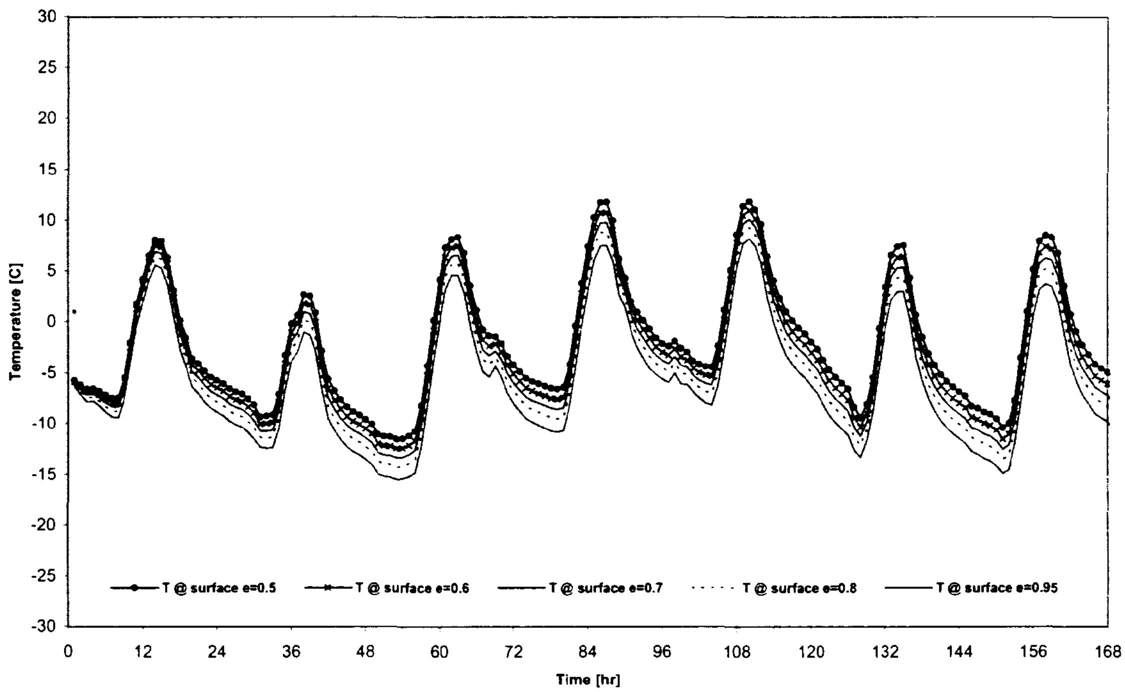

Figure 21. *Sensitivity of Temperature Predictions to Emmissivity of Asphalt Material using Denver, Colo., minimum Temperatures Predictions*

However, the maximum temperature change at the 20mm depth is about 8.7°C when the emmissivity of the asphalt material is modulated between 0.5 and 0.95 while, as expected, higher temperature predictions are observed for low emmissivity values. The maximum temperatures change by about 1.9°C for every 0.1 increment in the emmissivity value while the minimum temperatures change by about 1°C for every 0.1 change in the emmissivity.

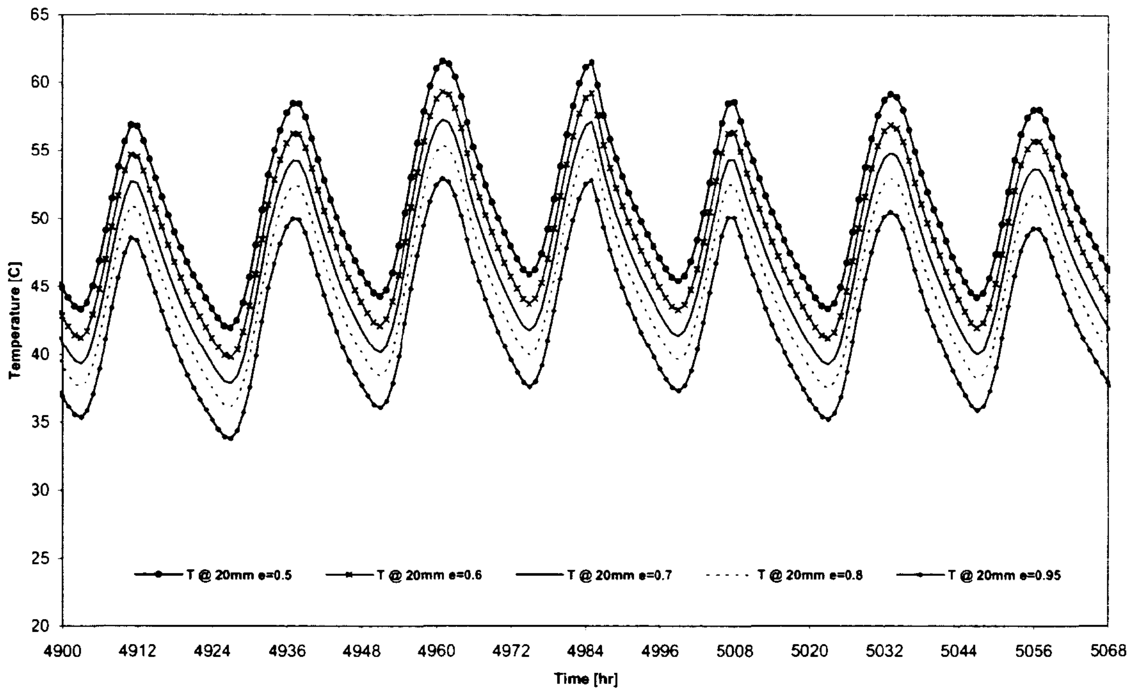

Figure 22 *Sensitivity of Temperature Predictions to Emmissivity of Asphalt Material using Denver, Colo., maximum Temperatures Predictions*

5.3.5. Sensitivity to Orientation of Asphalt Segment

The relative position of the asphalt segment with respect to the wind direction influences the amount of convective heat transfer off the asphalt surface and thus impacts the minimum and the maximum asphalt temperatures. A series of sensitivity analyses are performed assuming an asphalt segment orientation of 0 degrees from north, a segment lined up along the north and south; 45 degrees from north, lined up along northeast and southwest; 90 degrees from north, lined up along west and east; and 135 degrees from north, lined up along northwest and southeast. All other orientations from North are thus considered. The results of the sensitivity analyses are provided in Figures 23 and 24. The change in the minimum and maximum asphalt temperatures are about 0.4°C and 1.0°C respectively.

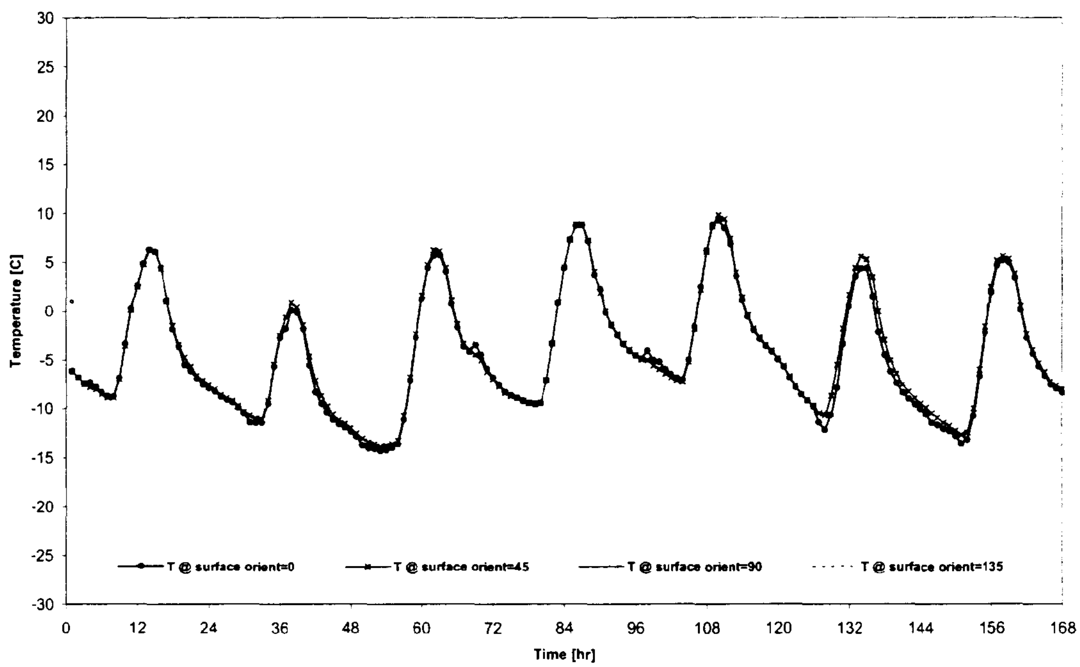

Figure 23. *Sensitivity of Temperature Predictions to Orientation of Asphalt Segment using Denver, Colo., minimum Temperatures Predictions*

It should be noted that it is highly likely for the wind direction to change significantly in short time steps, at times in time intervals shorter than an hour, based on local weather conditions the changes in maximum and minimum asphalt temperature can vary accordingly. In addition, solar radiation intensity at a given hour that is a significant factor in determining the amount of total energy incident upon the asphalt segment, clearly impacts asphalt temperatures in interaction with hourly wind conditions in either reinforcing the increase of asphalt temperatures (high solar radiation and low wind conditions) or reducing the increase of asphalt temperatures (high solar radiation occurring simultaneously with high wind conditions) so temperature variations may strongly fluctuate. Therefore, the impact of asphalt segment orientation must be assessed in direct consideration with local wind conditions.

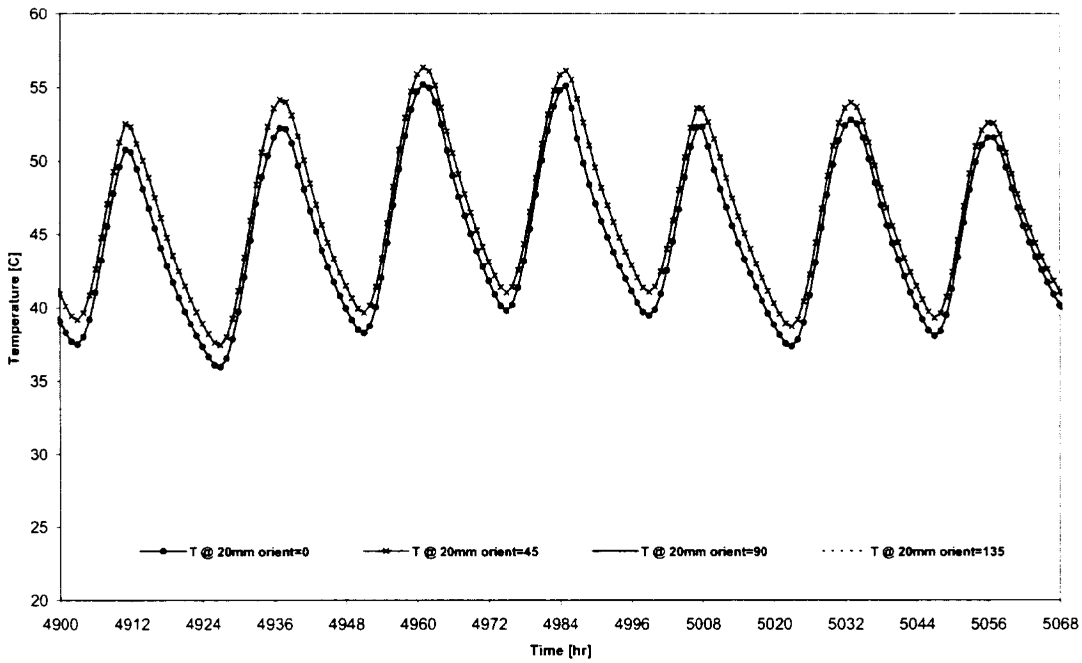

Figure 24 *Sensitivity of Temperature Predictions to Orientation of Asphalt Segment using Denver, Colo., maximum Temperatures Predictions*

6.0. CONCLUSIONS AND DISCUSSION

A two-dimensional finite difference model is presented that is capable of determining temperatures on an hour-by-hour basis at any arbitrary point in an asphalt pavement. The model considers thermal ambient conditions, such as the ambient dry bulb temperature, global solar radiation intensity, pavement geometry and orientation, ambient wind conditions and pavement thermal properties. A preliminary validation of the numerical model was performed using actual weather and pavement data from SHRP and LTPP-SMP databases. To aid asphalt engineers in pavement design, temperature predictions at pavement surface and at a depth of 20mm using typical meteorological year weather data were compared to Superpave algorithms that are commonly used in the design of highway pavements. In addition, a series of sensitivity analyses are conducted to assess the influence of pertinent design variables such as asphalt material thermal properties, pavement geometry and orientation on temperature predictions of the numerical model. The results of the analyses allow for the following conclusions:

1) The proposed numerical model provides a powerful tool in determining asphalt pavement behavior. The model allows for an hour-by-hour calculation of the pavement thermal response in the form of pavement temperatures using primary weather data for varying asphalt materials. The various lifts of asphalt materials can be entered into the model approximating layer geometry in 25mm grid increments in the direction normal to the asphalt surface through specification of thermal properties of asphalt materials (thermal conductivity, volumetric specific heat capacity and emmissivity). This allows for the determination of temperature responses at different lifts. In addition, the model allows for specification of different asphalt materials in the horizontal direction. Thus, it

is possible to define varying materials in each highway lane and in different lifts. This is a significant improvement over Superpave algorithms developed using analytical curve fitting techniques based on observed asphalt performance data.

2) The numerical model predictions are strongly dependent on climate data in addition to accurate knowledge of the thermal properties of pavement materials. The weather and pavement data used for preliminary validation of the numerical model contained significant inconsistencies, specifically in respect to large amounts of missing field collected measurements. Although an effort was made to use continuous weather data, gaps in measurements cause a loss in the history terms of the temperature response of the pavement resulting in erroneous maximum and minimum temperature predictions. Also, a large number of weather stations dedicated to collecting climate data at different pavement segments were well removed by some significant distances from the pavements. Thus the pavement segments, in some cases, were exposed to somewhat different ambient thermal conditions as they were presumed to have been. It is therefore important to use high quality weather data for the field validation of the numerical model. In addition, information with respect to sloping angles (tilt angles of the pavement surface from the horizontal) of the pavement segments was not known. Nevertheless, a comparison between actually measured and predicted pavement temperatures showed good agreement.

3) A comparison between numerical model predictions and the Superpave algorithms have shown satisfactory results considering further improvements can be made to the numerical model and weather data used. In general, the numerical model underestimated the maximum and minimum asphalt temperatures when compared to

Superpave. However, differences in predicted temperatures and Superpave recommendations were on average approximately 2°C for the maximum asphalt temperatures and less than 4°C for the minimum asphalt temperatures.

4) Asphalt temperature predictions appear to be significantly more sensitive to changes in volumetric specific heat capacity of the asphalt material than to its thermal conductivity. The volumetric heat capacity of the pavement thermal mass (the product of asphalt density and specific heat capacity of the material) strongly influences thermal behavior of the pavement where heat transfer is dominated by pure conduction. On the other hand, the minimum asphalt temperature at the surface of the pavement primarily is dependent on ambient flow conditions (wind speed and direction), since convective cooling affects dominate the heat transfer at the surface. Theoretically, the higher the wind speed is, the higher the convection heat transfer coefficient at the asphalt surface, resulting in lower surface temperatures. A significant amount of energy received by the asphalt surface is due to incident solar radiation although some convective heat gains occur at times when the ambient air temperature is greater than the asphalt surface temperature.

5) The impact of the orientation of asphalt pavement is relatively small. Analyses have indicated that the maximum temperature change to be well within 1°C. This impact is strongly dependent on local wind conditions, specifically the wind direction. In analyses where longer asphalt segments were considered coupled with suitable local prevailing wind directions along the length of the pavement the effects of convective cooling at the asphalt surface were noticeable yielding lower average surface temperatures. The rate of convection heat transfer increased because air flow sweeping

the asphalt surface had reached turbulent flow conditions resulting in a significantly larger convection heat transfer coefficients. On the other hand, for shorter pavement segments or when the local prevailing wind direction was perpendicular to the shorter pavement section, the effects of convective cooling of the surface were less pronounced, yielding higher asphalt temperatures.

Nevertheless, it should be noted that dependence of temperature predictions on wind direction and velocity is of more importance on pavement surfaces exposed to light traffic conditions, where there might be the chance of encountering laminar flow regimes at suitably low wind velocities. During typical traffic conditions, the wind velocity and direction near the pavement surface will be dominated by vehicle traffic. Thus, in practice, it is reasonable to expect a continuously turbulent flow regime near the pavement surface independent of the wind conditions.

6) The impact of emmissivity of the asphalt material was significantly higher in summer months when the maximum asphalt temperatures were reached than during winter months when minimum asphalt temperatures are determined. The higher the emmissivity of the asphalt material the lower the maximum and minimum temperatures, since the pavement is capable of dissipating more energy at higher emmissivities. Temperature changes in the summer are nearly twice as large as in the winter months. The asphalt rejects less energy in the winter since there is a smaller temperature differential between the sky and the asphalt surface. This temperatures differential is much larger during summer months where the asphalt pavement is heated considerably through solar radiation.

7.0. RECOMMENDATIONS FOR FURTHER WORK

The following recommendations are made for further research to improve numerical model predictions to determine the maximum and minimum asphalt temperatures using local typical meteorological year weather data:

1) Improvements to the two-dimensional numerical model are of interest through additional field validations using high quality weather data. This may be accomplished through a specially designed pavement segment with a fully dedicated weather station nearby that would reflect the true ambient thermal conditions of the pavement. Although the numerical model currently includes the capability to consider thermal effects of rain precipitation, insufficient rain data were available in the weather data. A dedicated weather station coupled with a specially designed test segment would allow for a more reliable field validation.

2) A finer, possibly adjustable, node spacing would allow for a more accurate geometry implementation for each asphalt lift. The drawback of a finer node implementation is that the computational time of the numerical calculation will increase. However, considering that the computational time of the code already is relatively short, added computational time would not burden the functions of the pavement engineer in the field.

3) The numerical model currently assumes a horizontal pavement surface where only the orientation of the horizontal surface from the north can be modified. The tilt angle of the pavement surface with respect to the horizontal is of interest since this would impact the incident angle of the solar radiation. A pavement surface oriented toward the south with appreciable tilt angle from the horizontal will have a much larger solar radiation during summer days than a surface that might be oriented toward north with the same tilt angle.

4) The numerical model assumes an adiabatic bottom surface through which no heat transfer is occurring. This is a reasonable assumption when asphalt is laid on ordinary earth and gravel sub-grades. However it is not applicable for pavements laid on bridge decks where an adiabatic bottom surface cannot be assumed due to convective cooling of the exposed bottom of the bridge deck. This convective cooling primarily is responsible for bridge deck icing during seasons when low ambient air temperatures are encountered along with high wind conditions. Therefore, it is of interest to expand the model to be used for pavement design on bridge decks.

5) The two-dimensional finite difference model should be expanded to the third dimension so temperature changes can be assessed between pavement segments along the length of the pavement. A three-dimensional modeling also would allow for accurate assessment of pavements including pavement thermal responses at bankments and slopes.

6) The effects of snow cover and freezing rain on pavement surfaces, and freezing inside the asphalt material, impact the maximum and minimum asphalt temperatures considerably. The

snow cover typically has an insulating effect on the surface reducing the amount of convective heat losses through the pavement. The mechanisms of heat transfer through layers of mushy zones cannot be simulated through simple energy balance boundary conditions on the pavement surface. The numerical model should be extended to include the effects of snow, mushy zones and rain for a more realistic prediction of pavement temperatures allowing for more accurate and reliable pavement designs.

7) Finally, the two-dimensional finite difference code is in the form of a research tool and requires recompilation of the FORTRAN source on a specialized compiler for every modification in pavement thermal properties and geometry. An improved graphical user interface that uses Windows programming techniques is required so changes can be entered by the user on-the-fly without reliance on special programming tools.

8.0. REFERENCES AND BIBLIOGRAPHY

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APPENDIX A

Figure A1. Bismarck, ND TMY Ambient Dry Bulb Temperatures

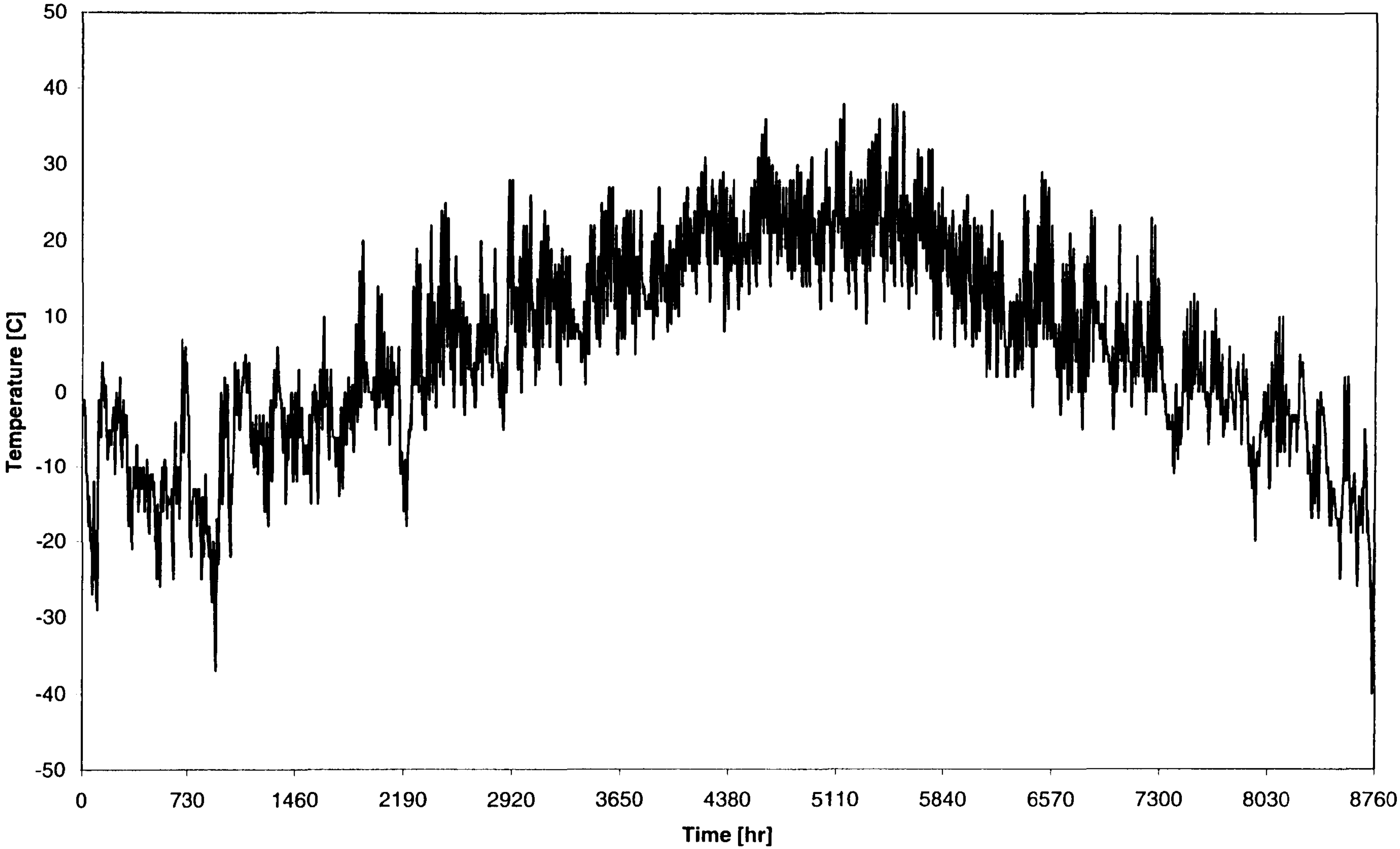


Figure A2. Bismarck, ND TMY Global Solar Radiation

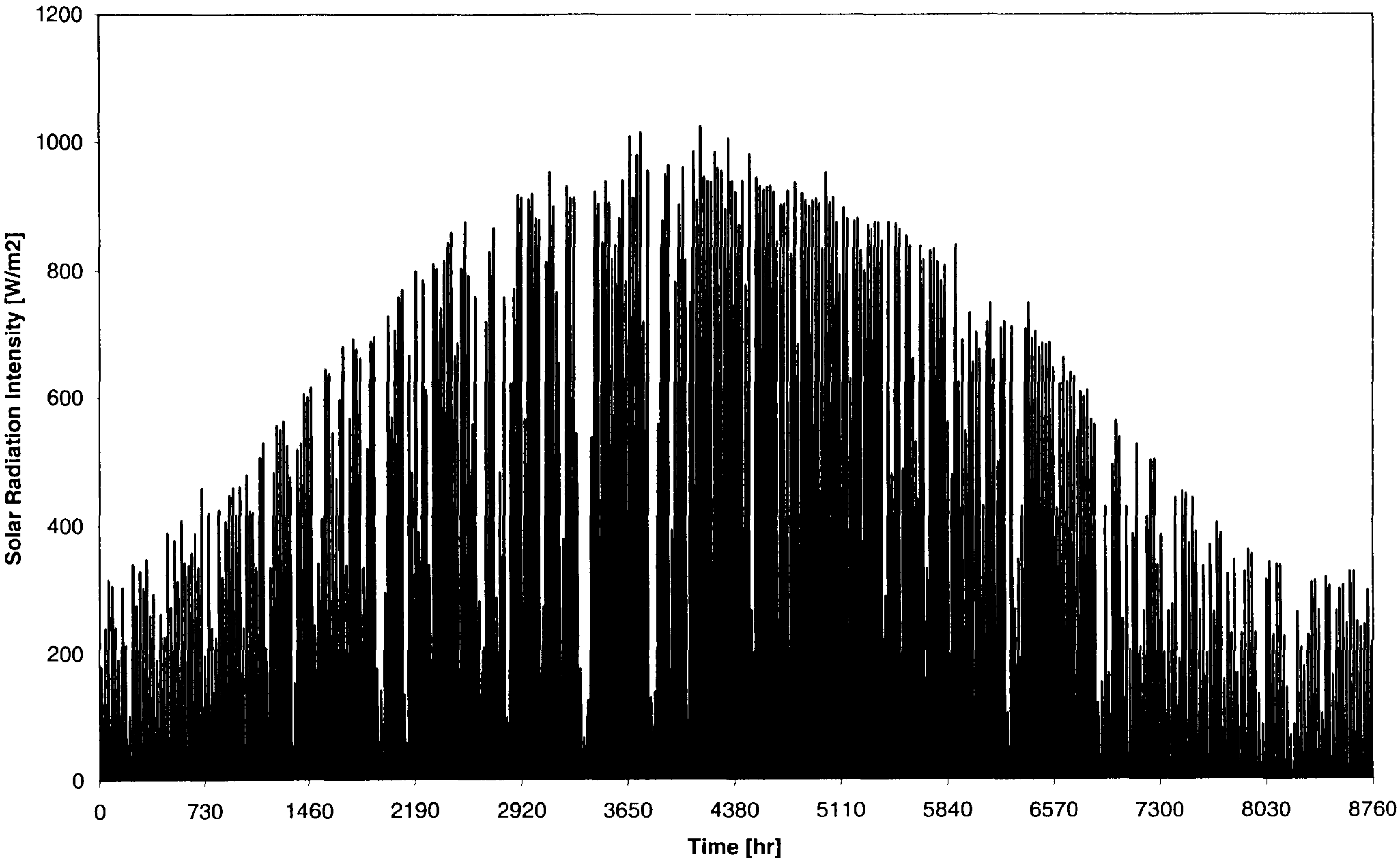


Figure A3. Bismarck, ND Asphalt Temperature Predictions

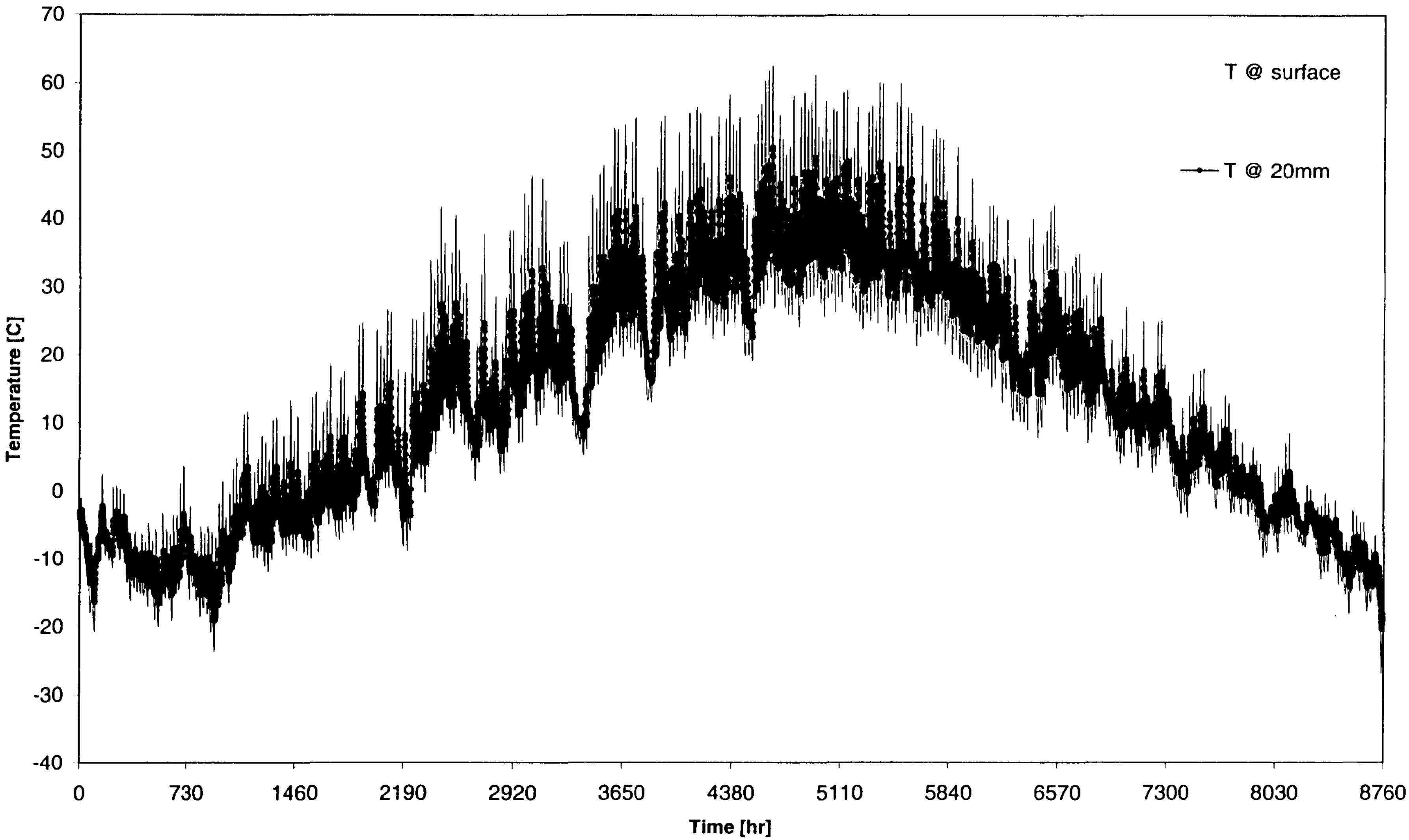


Figure A4. Cheyenne, WY TMY Ambient Dry Bulb Temperatures

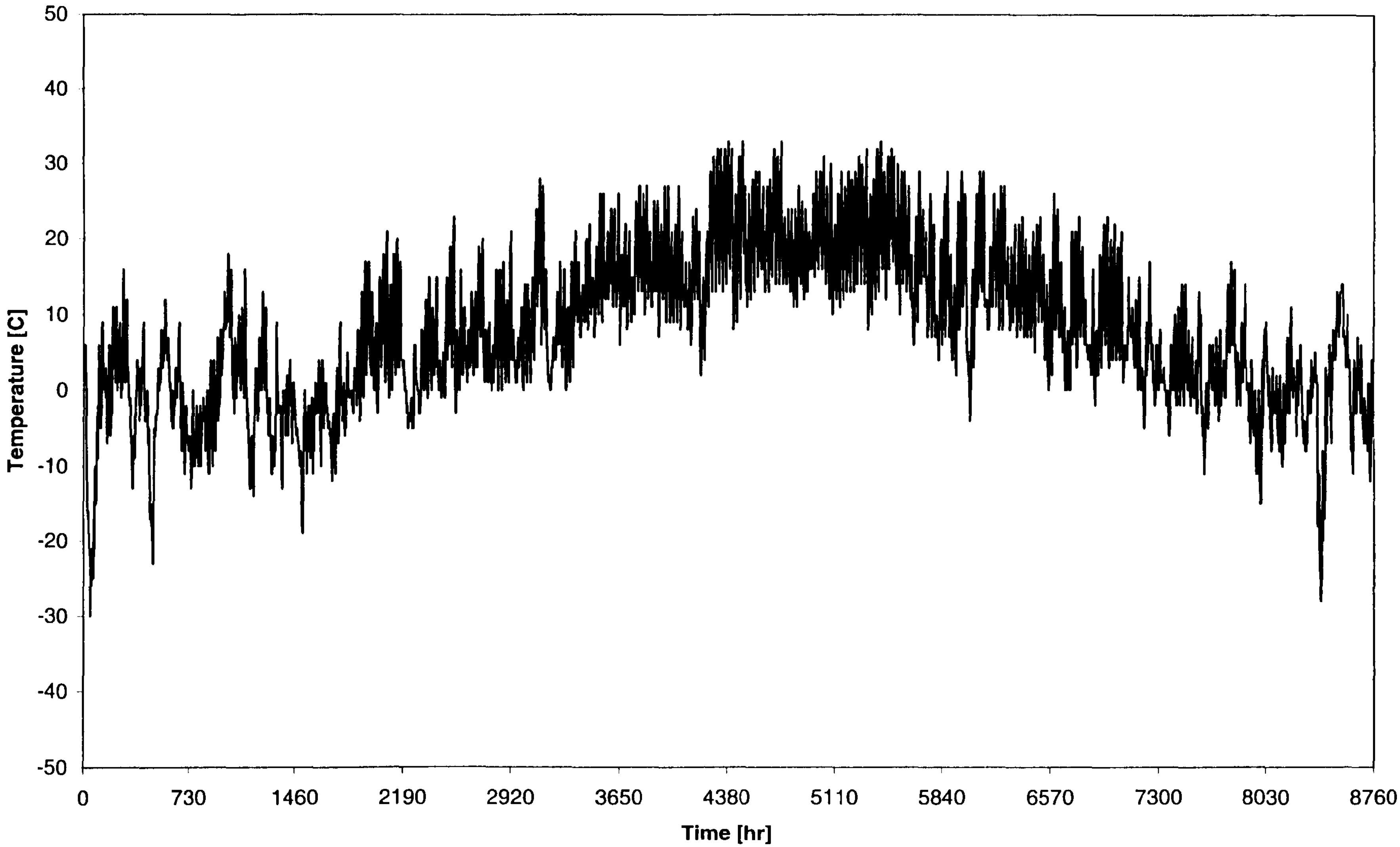


Figure A5. Cheyenne, WY TMY Global Solar Radiation

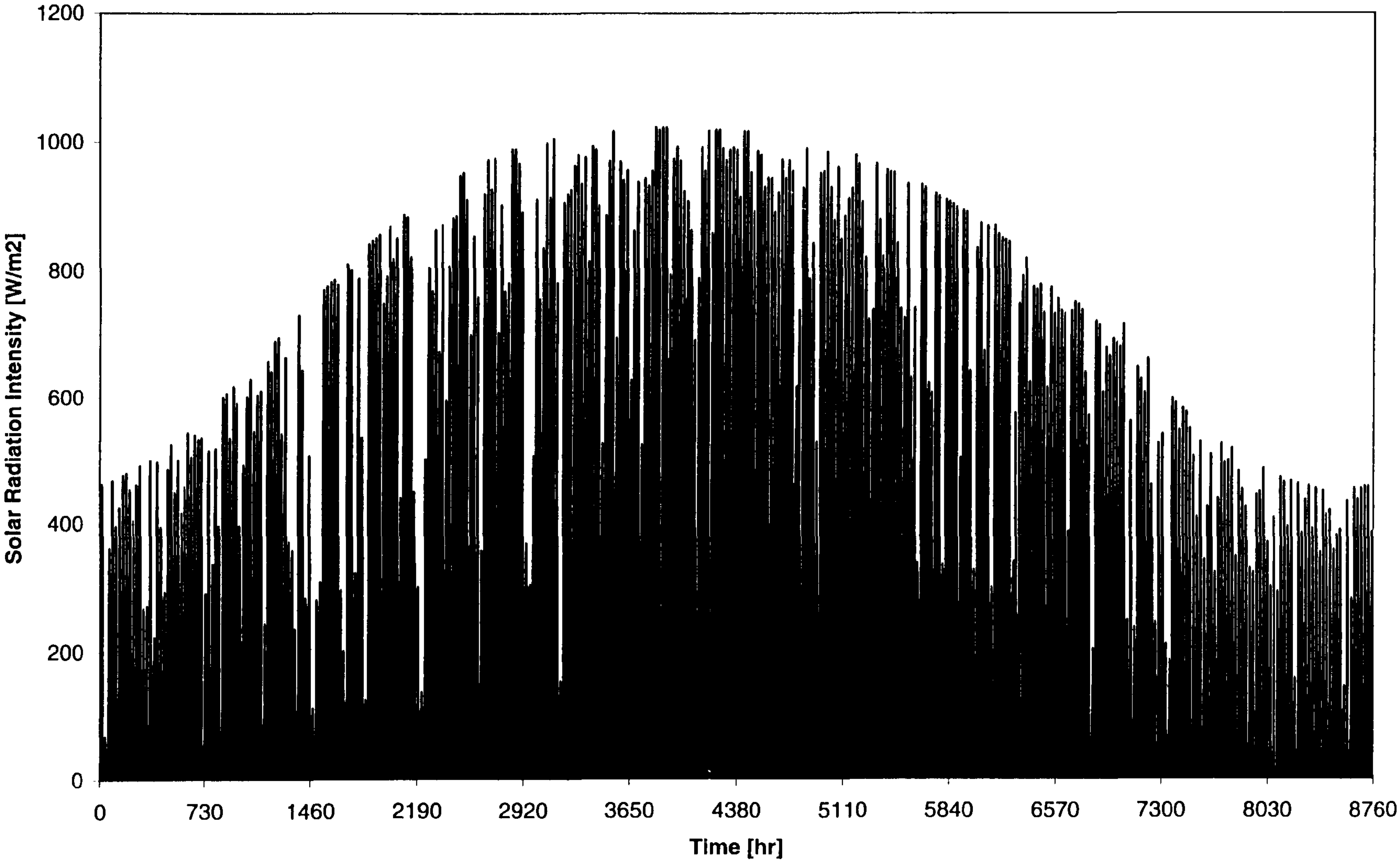


Figure A6. Cheyenne, WY Asphalt Temperature Predictions

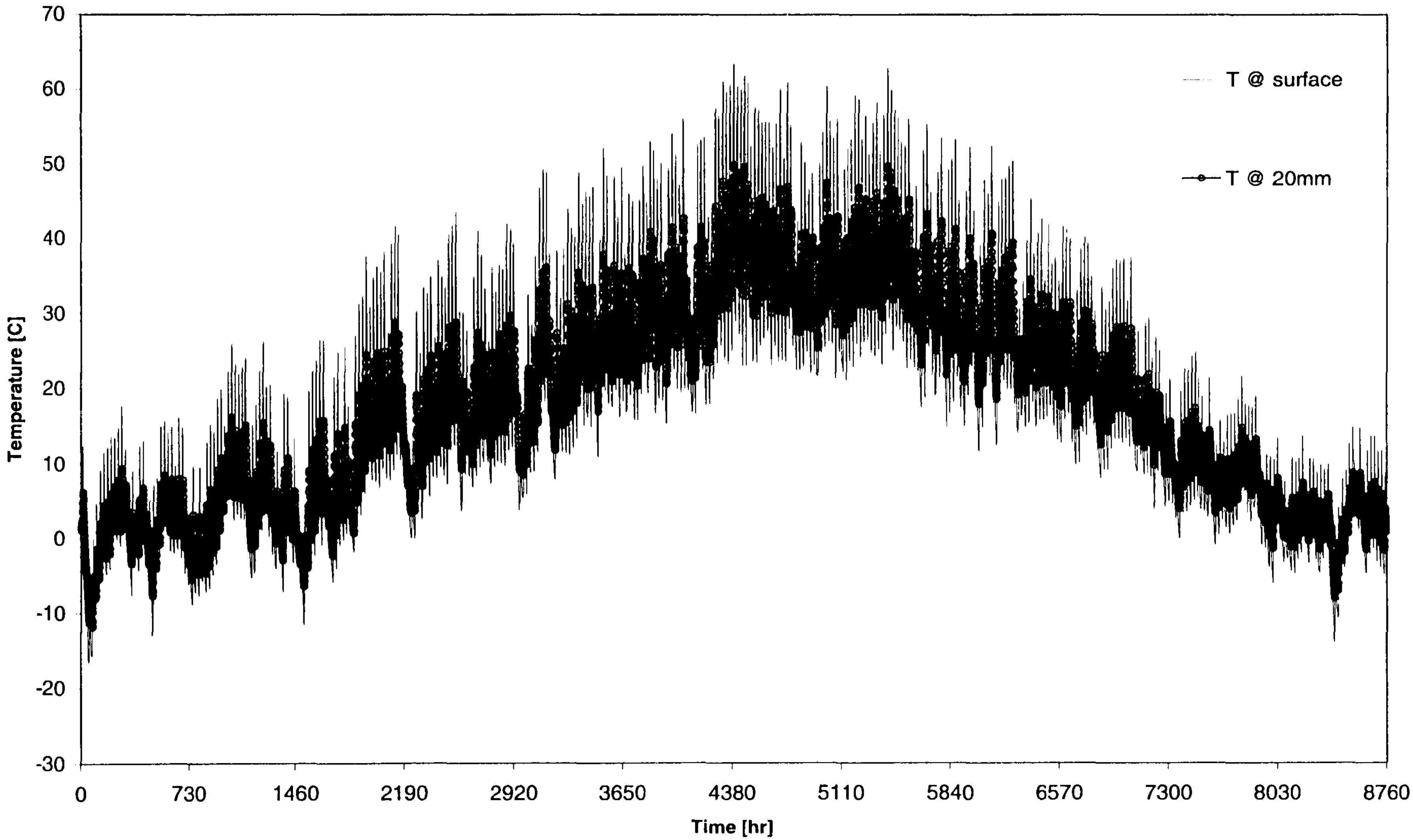


Figure A7. Great Falls, MT TMY Ambient Dry Bulb Temperatures

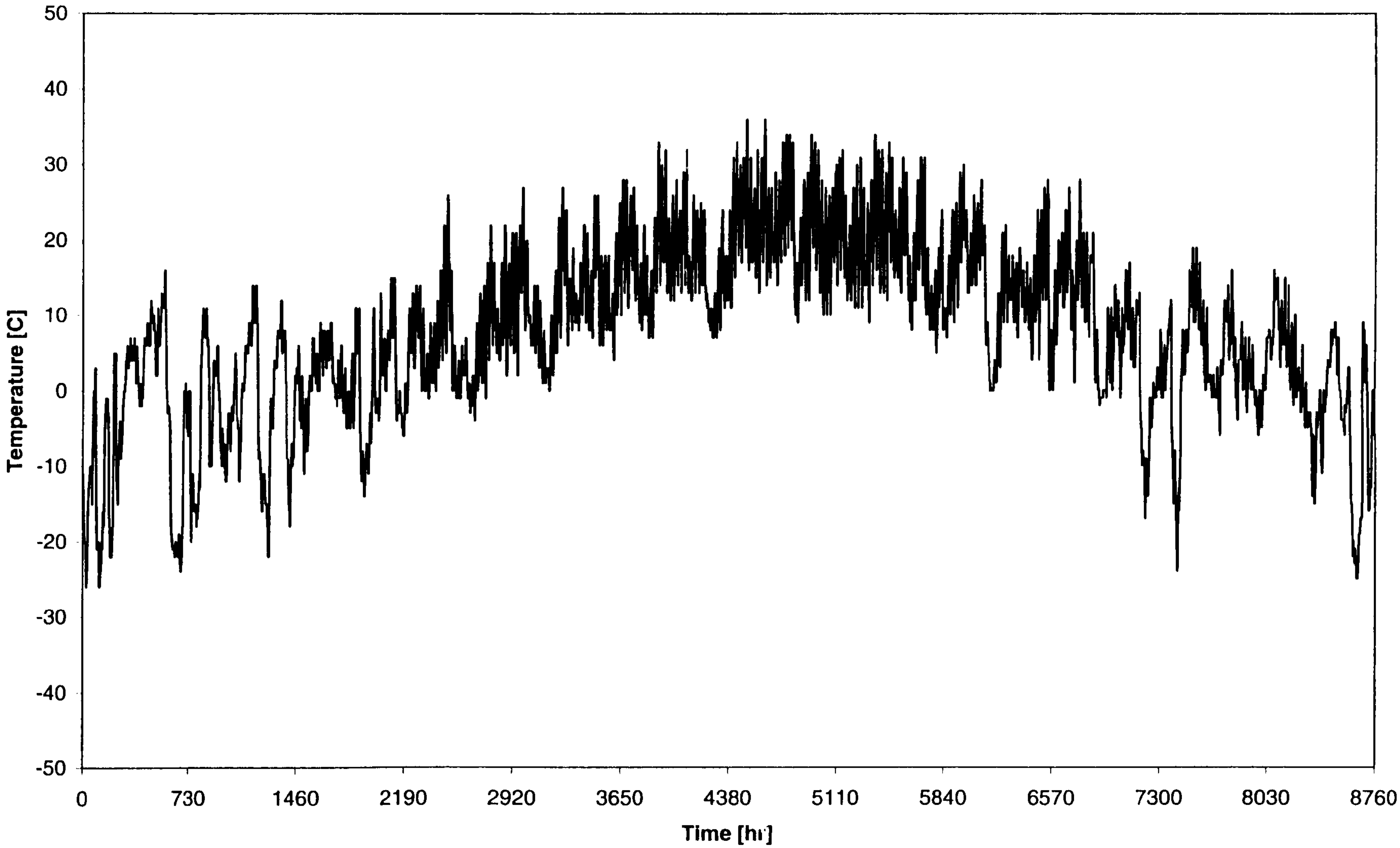


Figure A8. Great Falls, MT TMY Global Solar Radiation

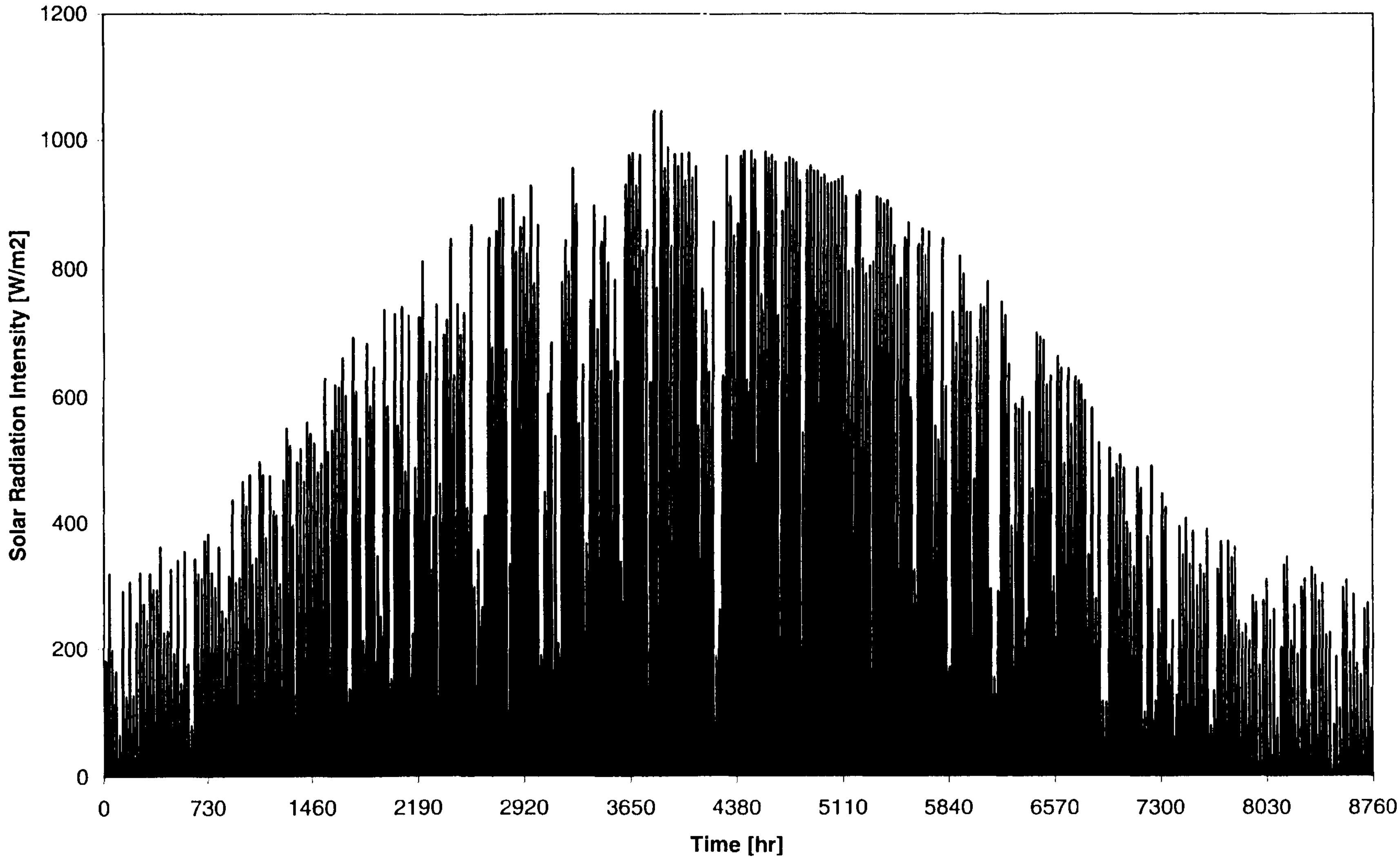


Figure A9. Great Falls, MT Asphalt Temperature Predictions

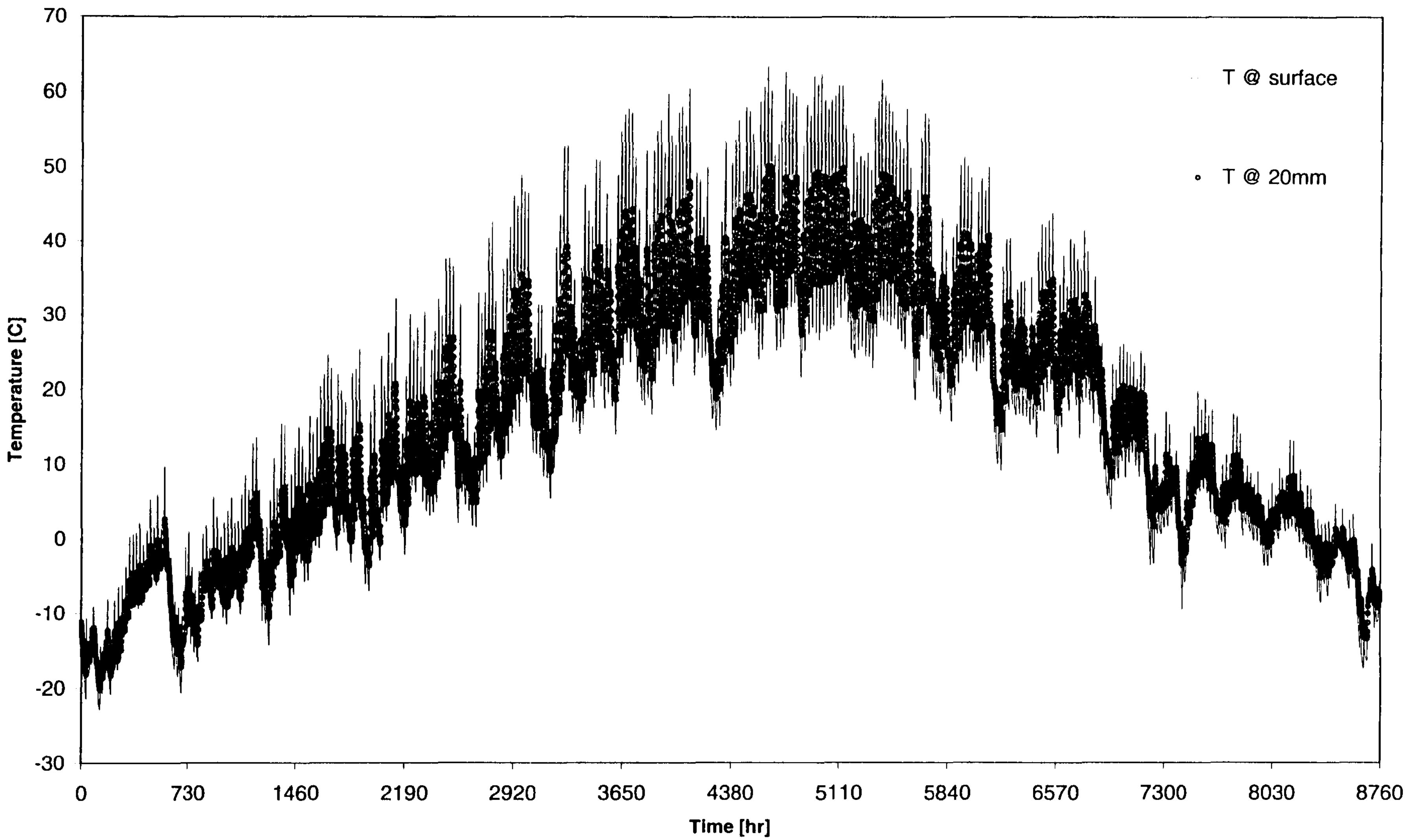


Figure A10. Omaha, NE TMY Ambient Dry Bulb Temperatures

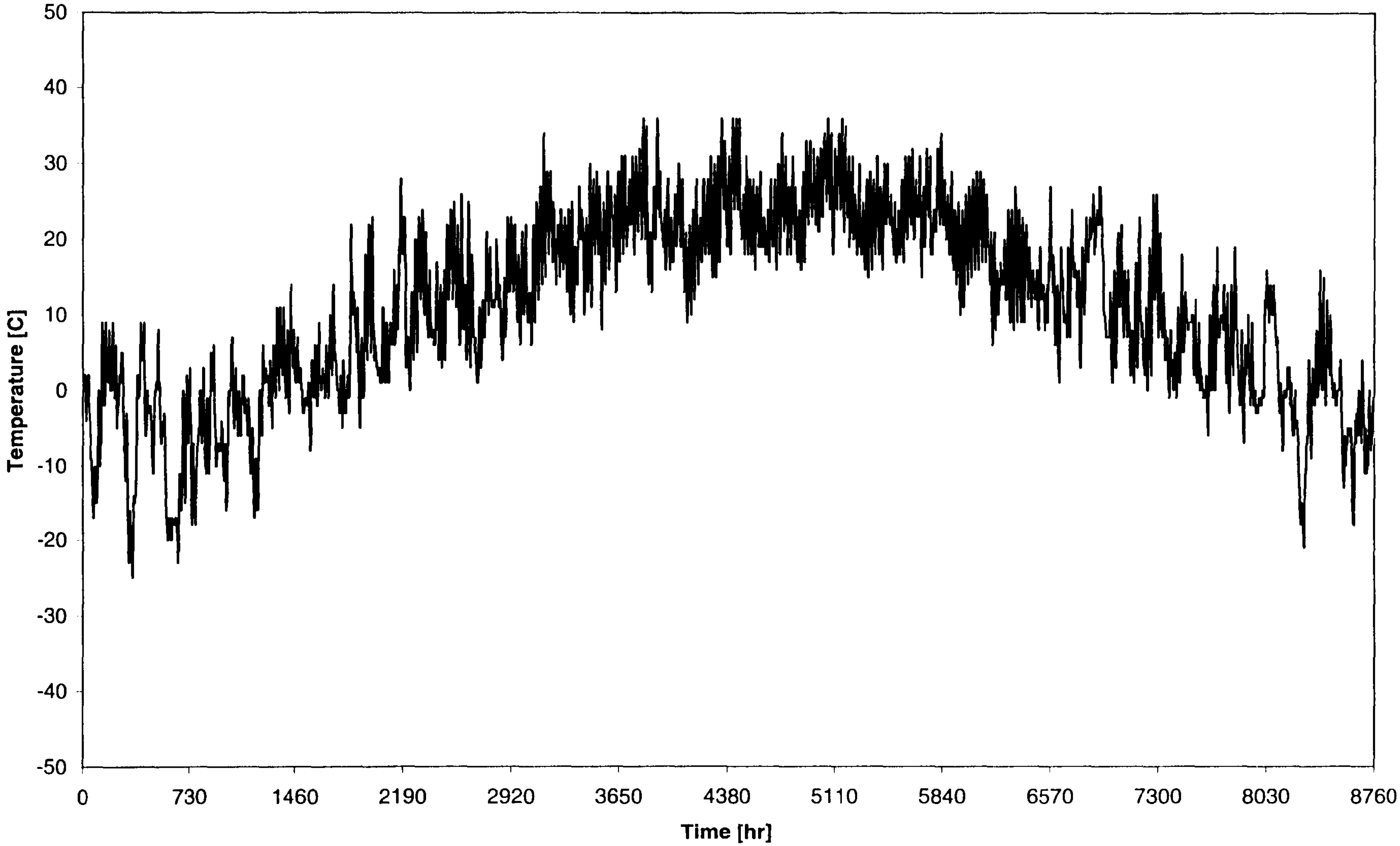


Figure A11. Omaha, NE TMY Global Solar Radiation

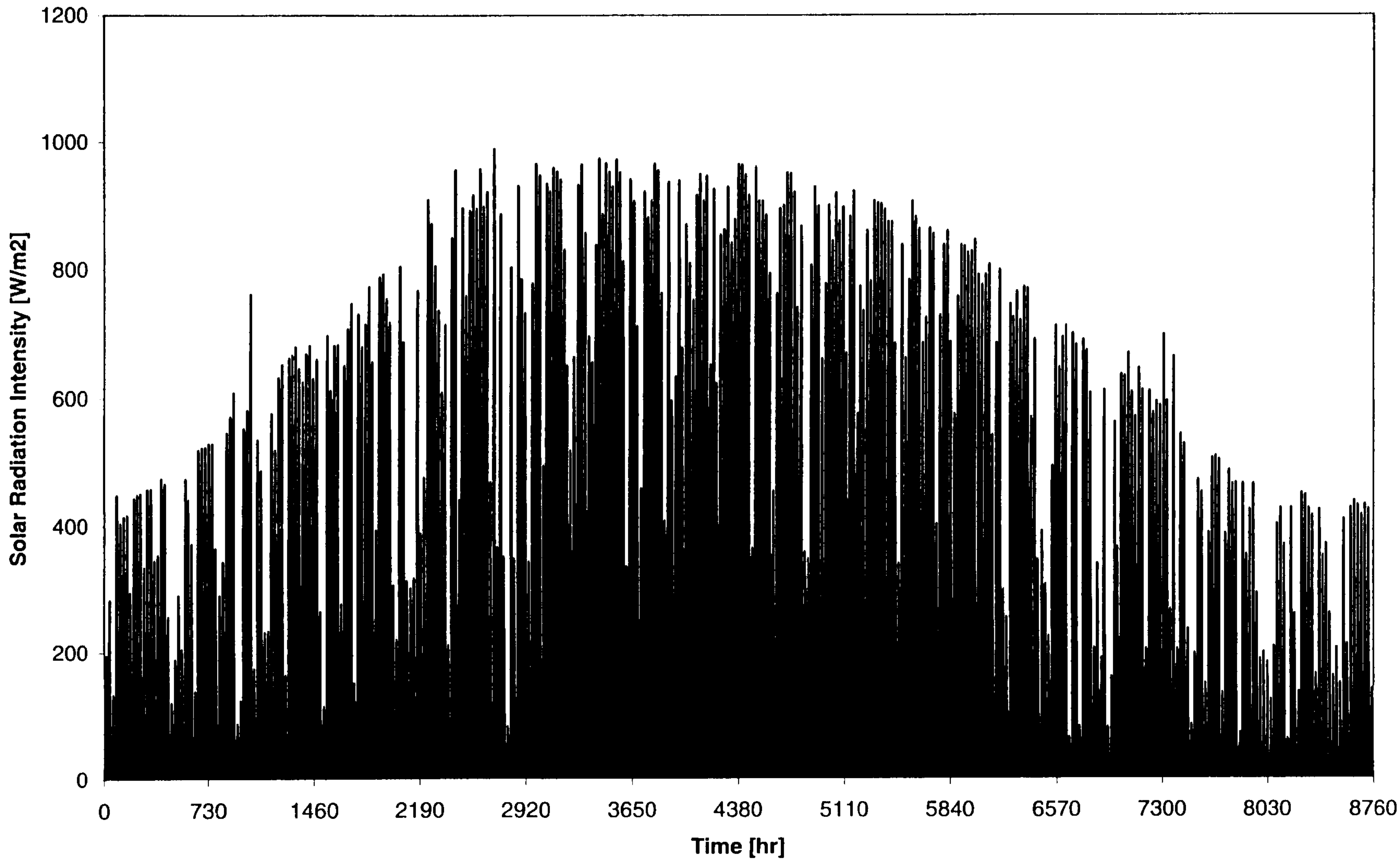


Figure A12. Omaha, NE Asphalt Temperature Predictions

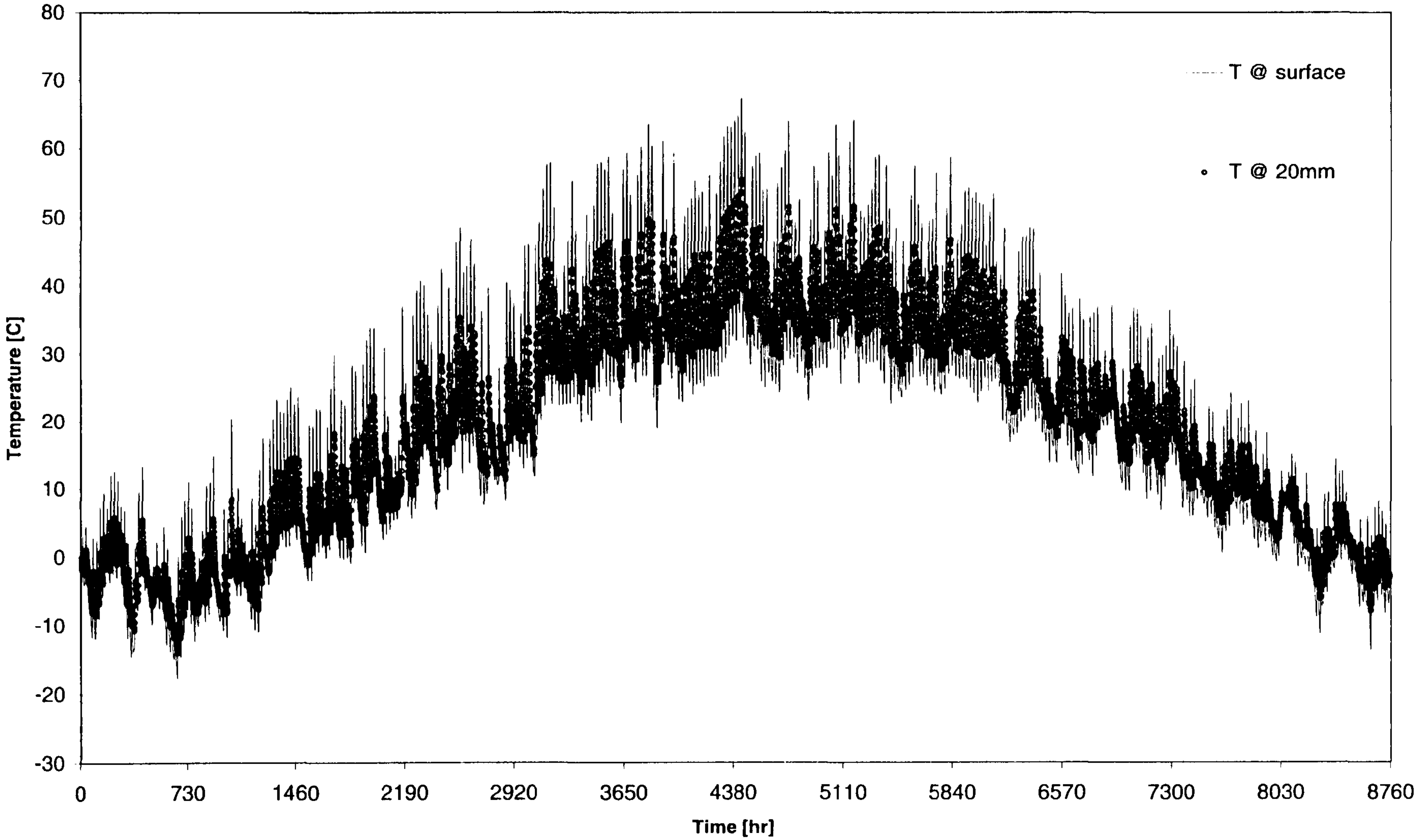


Figure A13. Phoenix, AZ TMY Ambient Dry Bulb Temperatures

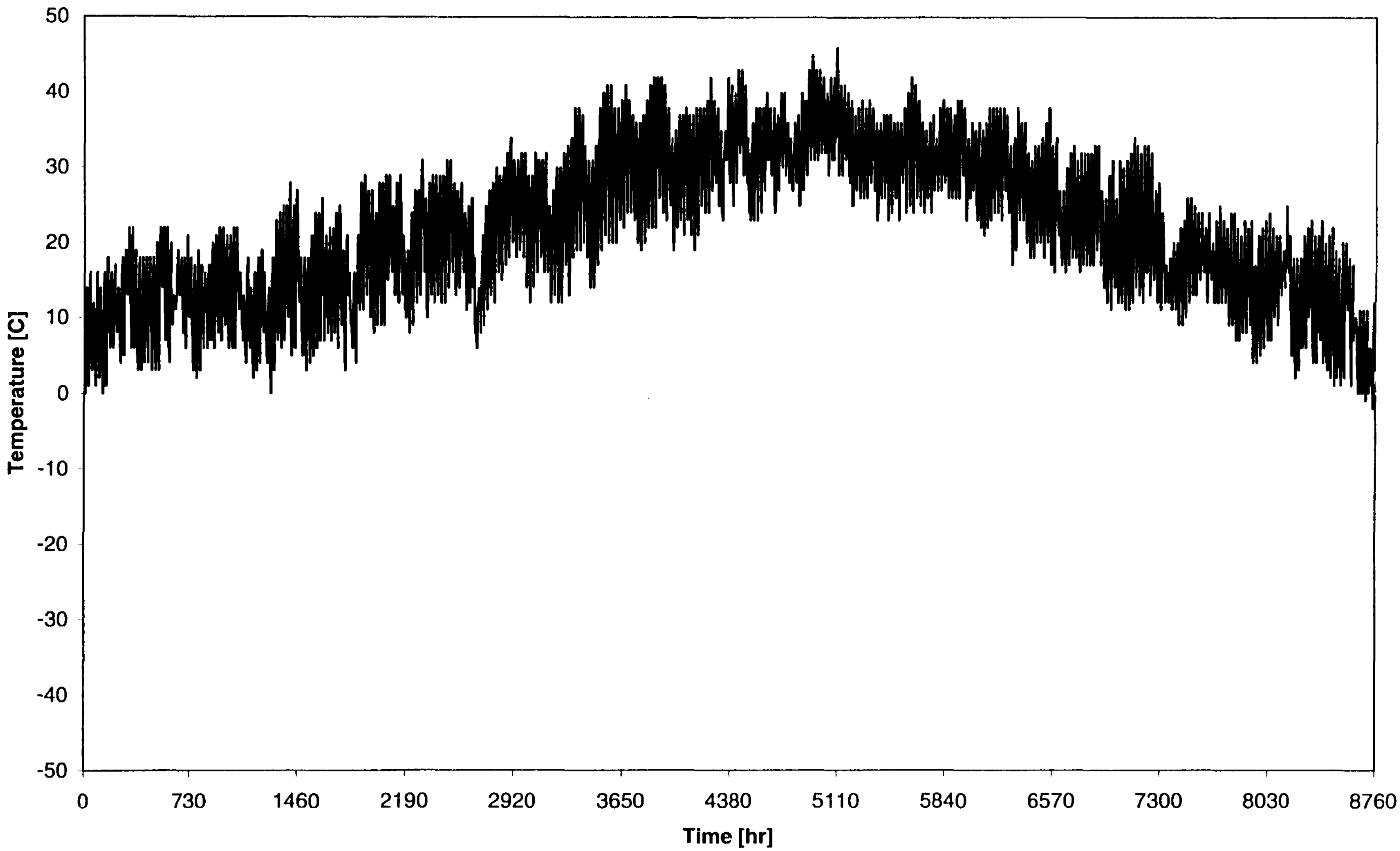


Figure A14. Phoenix, AZ TMY Global Solar Radiation

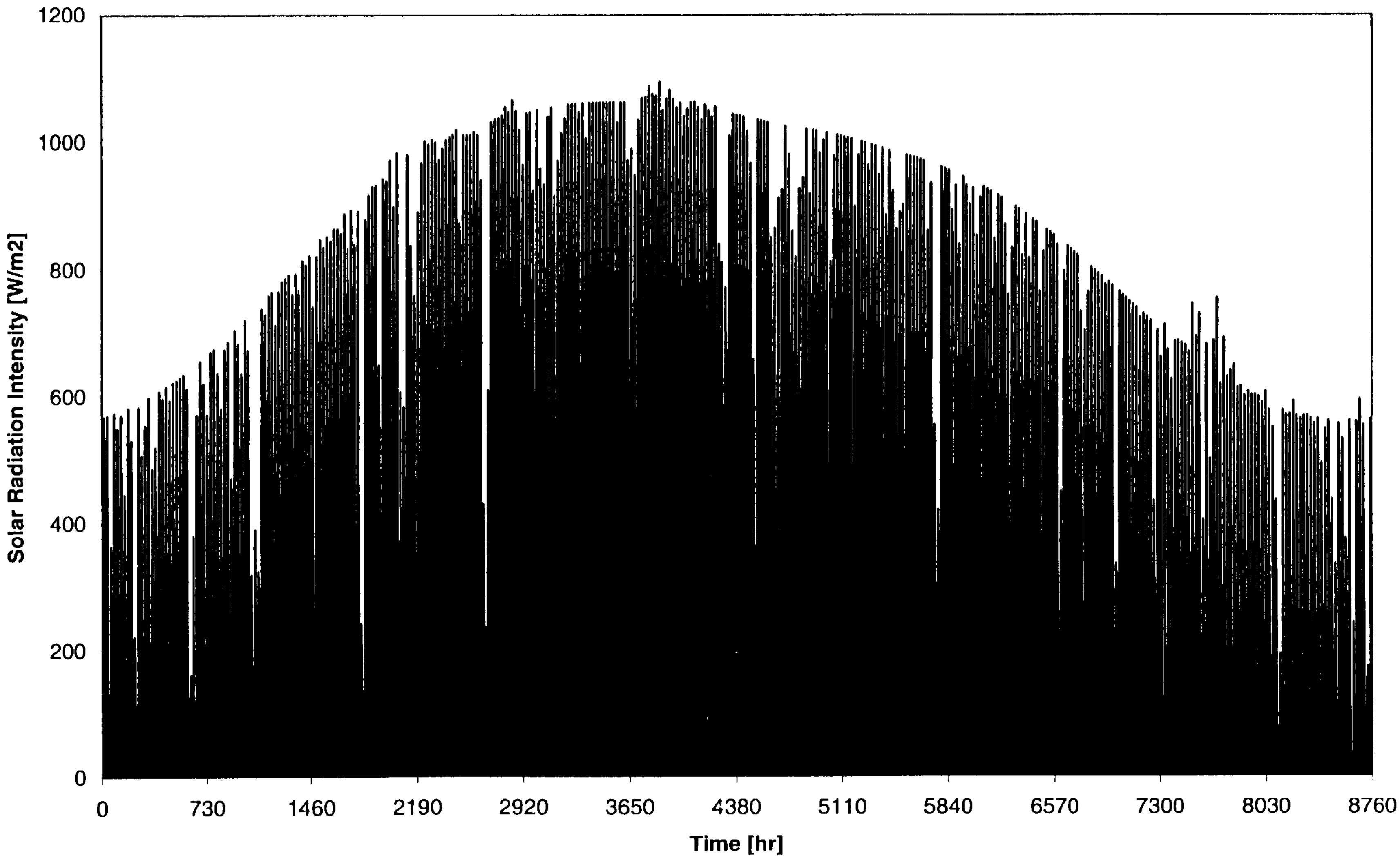
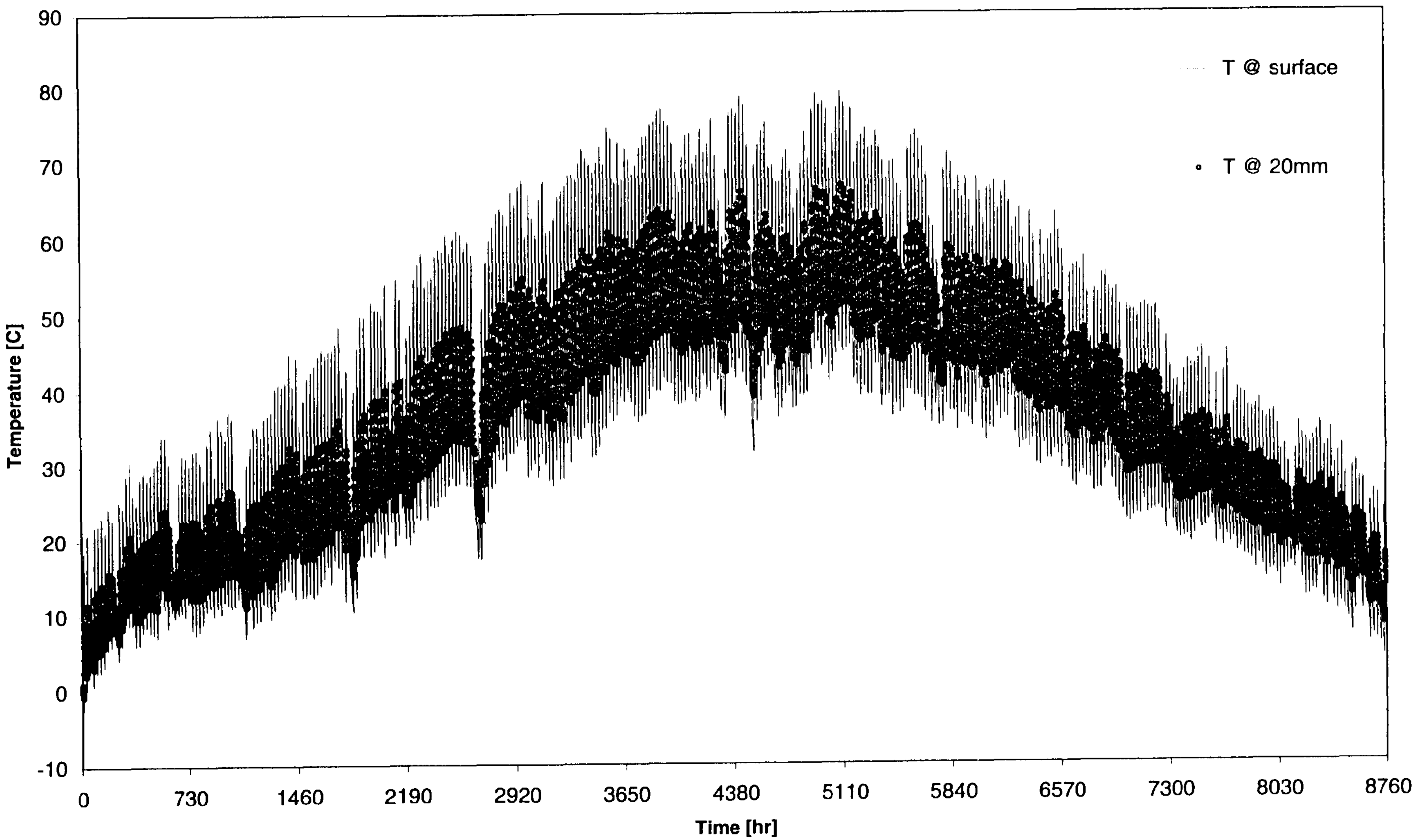


Figure A15. Phoenix, AZ Asphalt Temperature Predictions



APPENDIX B

```
PROGRAM pavementtemperatures

!*****************************************************************************
!  PROJECT:     Wyoming DOT
!
!  CREATED:     2000-01
!
!
!  MODIFIED:
!
!  PURPOSE:     Main driver program for the pavement temperature calculations.
!*****************************************************************************

USE PAVEMENTDATA
USE PAVEMENTMODEL

IMPLICIT NONE
INTEGER :: i,j,A,B                                          !COUNTERS
REAL(prec1)  :: DUMMY                                   !DUMMY VARIABLE
INTEGER, DIMENSION(TPROFILES) :: XPRINTNODES           !X NODE TO PRINT
INTEGER, DIMENSION(TDEPTHS)        :: ZPRINTNODES         !Z NODE TO PRINT
INTEGER                            :: T_PRINT             !TOTAL NUMBER OF TEMPERATURES TO PRINT PER
TIME STEP
!ENTER THE X VALUES (in m) AND Z VALUES (in m) TO PRINT
XPRINT(1) = 1.83
XPRINT(2) = 5.49
ZPRINT(1) = 0.00
ZPRINT(2) = 0.02
ZPRINT(3) = 0.1

!GET THE WEATHER DATA
OPEN(10, file='DENWeather.dat',access='sequential',status='old')
DO 5 i = STARTTIME,ENDTIME
      READ (10,*) DUMMY,Tdb(i),DUMMY,WINDSPEED(i),WIND_DIR(i),SOLARRAD(i)
5 CONTINUE
CLOSE(unit=10)

!DETERMINE THE NODES TO PRINT TEMPERATURES
DO 10 i = 1,TPROFILES
      XPRINTNODES(i)=NINT(XPRINT(i)/DELTA)+1
10 CONTINUE

DO 20 j = 1,TDEPTHS
      ZPRINTNODES(j)=NINT(ZPRINT(j)/DELTA)+1
20 CONTINUE

T_PRINT=TPROFILES*TDEPTHS

!OPEN OUTPUT FILE AND WRITE TITLE HEADER
OPEN(unit=9, file='PAVEMENTOUTPUT.dat', access='sequential',status='unknown')

!START TEMPERATURE CALCULATIONS
DO 200, TIME = STARTTIME,ENDTIME

      CALL OLDTYPE98 (TIME)

      !STORE TEMPERATURES FOR PRINTING
      I=1
      DO 50 A = 1,TPROFILES
          DO 40 B = 1,TDEPTHS
              TPRINT(I) = T(XPRINTNODES(A),ZPRINTNODES(B))
              I=I+1
40        CONTINUE
50    CONTINUE

    !WRITE TEMPERATURES
      WRITE(9,80) TIME,(TPRINT(I), I = 1,T_PRINT )
      WRITE(6,90) TIME      !TO SEE STATUS ON SCREEN

200 CONTINUE

CLOSE(unit=9)

80 FORMAT(I6,3X,F8.2,3X,F8.2,3X,F8.2,3X,F8.2,3X,F8.2,3X,F8.2)
90 FORMAT (I8)
```

```
END PROGRAM pavementtemperatures
```

```
MODULE PAVEMENTMODEL

USE PAVEMENTDATA

!***********************************************************************
!  PROJECT:     Wyoming DOT
!
!  CREATED:     2000-01
!
!
!  MODIFIED:
!
!  PURPOSE:     Contains routines to compute the temperature distribution in
!                 pavement slab.

CONTAINS

!***********************************************************************

SUBROUTINE OLDTYPE98 (TIME)


!  PURPOSE:       This subroutine determines the temperature distribution in
!                 a slab in the x-z dimension. The solution scheme consists of
!                 an explicit transient finite-difference approach
!
!
! **************************
! *** SUBROUTINES CALLED ***
! **************************
!
!      (1) h_coeff

!***********************************************************************
IMPLICIT NONE

!DECLARE VARIABLE TYPES
INTEGER       :: A,B,C,I,J,X,Z        !COUNTERS
INTEGER       :: ISTEP                !NUMBER OF TIME ITERATIONS IN THE TIME STEP
REAL(prec1) :: ALPHA              !THERMAL DIFFUSIVITY (m^2/s)                        (m)
REAL(prec1) :: FO                 !FOURIER NUMBER (-)
REAL(prec1) :: Tslab              !TEMPERATURE OF SURFACE CELL (C)
REAL(prec1) :: HC                 !CONVECTION COEFFICIENT (W/(m^2-C))
REAL(prec1) :: HR                 !THERMAL RADIATION COEFFICIENT (W/(m^2-C))
REAL(prec1) :: QCONV              !CONVECTION HEAT FLUX (W/m^2)
REAL(prec1) :: QEMIS              !LONG WAVE RADIATION HEAT FLUX (W/m^2)
REAL(prec1) :: QRAD                   !SOLAR RADIATION HEAT FLUX (W/m^2)
REAL(prec1) :: QTOT                   !TOTAL RADIATION HEAT FLUX (W/m^2)
INTEGER       :: TIME

!INITIALIZE STUFF ON FIRST CALL
!determine number of nodes
IF (TIME.EQ.STARTTIME) THEN
      XNODES=NINT(WIDTH/DELTA)+1
      ZNODES=NINT(THICKNESS/DELTA)+1
      ISTEP=NINT(3600./TIMESTEP)  !assumes global time step is always 1 hour

!Set slab to initial temperature to start
      DO 6 B=1,ZNODES
          DO 5 A=1,XNODES
            P(A,B)=TINITIAL
5         CONTINUE
6     CONTINUE

!Get thermal conductivity and vol. heat capacity data from files
OPEN(11, file='kvalues-25cm.txt',access='sequential',status='old')
OPEN(12, file='rhocpvalues.txt',access='sequential',status='old')
DO 10 A = 1,XNODES
      READ (11,*)  (K(A,B), B=1,ZNODES)
      READ (12,*)  (RHOCP(A,C), C=1,ZNODES)
10 CONTINUE
CLOSE(unit=11)
CLOSE(unit=12)

!Set thermal conductivity and vol. heat capacity values on edges
DO 15 I=1,XNODES
```

```
      K(I,0)=K(I,1)
      RHOCP(I,0)=RHOCP(I,1)
      K(I,ZNODES+1)=K(I,ZNODES)
      RHOCP(I,ZNODES+1)=RHOCP(I,ZNODES)
15 CONTINUE

DO 20 J=1,ZNODES
      K(0,J)=K(1,J)
      RHOCP(0,J)=RHOCP(1,J)
      K(XNODES+1,J)=K(XNODES,J)
      RHOCP(XNODES+1,J)=RHOCP(XNODES,J)
20 CONTINUE

END IF

DO 100 I=1,ISTEP
!---------- START OF EXPLICIT TEMPERATURE LOOP --------
DO 50 Z=1,ZNODES
      DO 40 X=1,XNODES

          ALPHA=(K(X-1,Z)+K(X+1,Z)+K(X,Z-1)+K(X,Z+1))/4.  &
                 /(RHOCP(X-1,Z)+RHOCP(X+1,Z)+RHOCP(X,Z-1)+RHOCP(X,Z+1))/4.
          FO=ALPHA*TIMESTEP/DELTA/DELTA

!++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
!++++ COMPUTE TEMPERATURES AT ADIABATIC & BOTTOM BOUNDARY NODES ++++
!++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

!     (1) LEFT- AND RIGHT-HAND NODES
      IF ((X.EQ.1).AND.(Z.NE.1).AND.(Z.NE.ZNODES)) THEN
          T(X,Z)=FO*(P(X,Z-1)+2.*P(X+1,Z)+P(X,Z+1))+(1-4.*FO)*P(X,Z)
          GO TO 40
      END IF

      IF ((X.EQ.XNODES).AND.(Z.NE.1).AND.(Z.NE.ZNODES)) THEN
          T(X,Z)=FO*(P(X,Z-1)+2.*P(X-1,Z)+P(X,Z+1))+(1-4.*FO)*P(X,Z)
          GO TO 40
      ENDIF

!     (2) BOTTOM BOUNDARY NODES
      IF ((Z.EQ.ZNODES).AND.(X.NE.1).AND.(X.NE.XNODES)) THEN
           T(X,Z)=FO*(2.*P(X,Z-1)+P(X-1,Z)+P(X+1,Z))+(1-4.*FO)*P(X,Z)
          GO TO 40
      END IF

!     (3) BOTTOM CORNER NODES
      IF ((X.EQ.1).AND.(Z.EQ.ZNODES)) THEN
          T(X,Z)=2.*FO*(P(X+1,Z)+P(X,Z-1))+(1-4.*FO)*P(X,Z)
          GO TO 40
      ENDIF

      IF ((X.EQ.XNODES).AND.(Z.EQ.ZNODES)) THEN
          T(X,Z)=2.*FO*(P(X-1,Z)+P(X,Z-1))+(1-4.*FO)*P(X,Z)
          GO TO 40
      ENDIF

!+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
!++++ COMPUTE TOP BOUNDARY NODE TEMPERATURES WITH HEAT FLUXES ++++
!+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

      IF (Z.EQ.1) THEN

!     *** COMPUTE CONVECTION HEAT FLUX AT PAVEMENT SURFACE ***
          Tslab=P(X,Z)
          CALL h_coeff (Tslab,hc)
          QCONV=HC*(Tdb(TIME)-P(X,Z))

!     *** COMPUTE THERMAL RADIATION HEAT FLUX AT PAVEMENT SURFACE ***
           Tsky=0.0552*(Tdb(TIME)+273.15)**1.5 - 273.15  !Swinbank (1963)
           HR=4.*EMISSIVITY*5.67E-8*(((P(X,Z)+273.15)+(TSKY+273.))/2.)**3.
           QEMIS=HR*(TSKY-P(X,Z))

!     *** COMPUTE SOLAR RADIATION HEAT FLUX AT PAVEMENT SURFACE ***
          ! THETA_D=THETA*180./pi      !convert to degrees
          !!Correction for incidence angle from Duffie and Beckman (1991)
          !ABSOR_CORRECTED=ABSOR*(1. + 2.0345E-3*THETA_D &
```

```
          !    - 1.99E-4*THETA_D**2. + 5.324E-6*THETA_D**3. - 4.799E-8*THETA_D**4.)
          !QRAD=ABSOR_CORRECTED*SOLARRAD
          QRAD=SOLARRAD(TIME)

!      *** THE TOTAL SURFACE HEAT FLUX
          QTOT=QRAD+QCONV+QEMIS

!      (1) FOR TOP CORNER NODES
              IF (X.EQ.1) THEN

                  T(X,Z)=2.*FO*(P(X+1,Z)+P(X,Z+1)+QTOT*DELTA/K(X,Z))+(1-4.*FO)*P(X,Z)
                  GO TO 40
              ENDIF
              IF (X.EQ.XNODES) THEN
                  T(X,Z)=2.*FO*(P(X-1,Z)+P(X,Z+1)+QTOT*DELTA/K(X,Z))+(1-4.*FO)*P(X,Z)
                  GO TO 40
              ENDIF

!      (2) FOR NON-CORNER NODES
           T(X,Z)=FO*(2.*P(X,Z+1)+P(X-1,Z)+P(X+1,Z)+2.*QTOT*DELTA/K(X,Z))+(1-4.*FO)*P(X,Z)
           GO TO 40
        ENDIF

!      +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
!          ++++  COMPUTE REMAINING INTERNAL NODE TEMPERATURES ++++
!      +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

          T(X,Z)=FO*(P(X,Z-1)+P(X-1,Z)+P(X+1,Z)+P(X,Z+1))+(1-4.*FO)*P(X,Z)


40        CONTINUE

50     CONTINUE

!STORE TEMPERATURES FOR NEXT TIME
      DO 600 B=1,ZNODES
          DO 500 A=1,XNODES
            P(A,B)=T(A,B)
500       CONTINUE
600    CONTINUE

100 CONTINUE

END SUBROUTINE OLDTYPE98


!*****************************************************************************

SUBROUTINE h_coeff (Tslab,hc)

!*****************************************************************************
!PURPOSE: To compute the convection coefficient

!INPUTS:
!          (1)  Tdb          =   AIR TEMPERATURE                       (C)
!          (2)  Tslab        =   TEMPERATURE AT NODE                   (C)
!          (3)  Length       =   SLAB LENGTH                           (m)
!          (4)  Width        =   SLAB WIDTH                            (m)
!          (5)  orientation    =   AZIMUTH         (degrees from N)
!          (6)  windspeed    =   WIND SPEED                            (m/s)
!          (7)  wind_dir     =   WIND DIRECTION          (degrees from N)


!OUTPUTS:
!          (1)  hc           =   CONVECTION COEFFICIENT          (W/m^2-C)
!*********************************************************************

IMPLICIT NONE
!DECLARE VARIABLES
REAL(prec1) ::AREA                        !PAVEMENT AREA (m^2)
REAL(prec1) ::PERIMETER                   !SLAB PERIMETER (m)
REAL(prec1) ::TFILM                       !FILM TEMPERATURE AT PAVEMENT SURFACE (C)
REAL(prec1) ::TSLAB                       !SURFACE TEMPERATURE (C)
REAL(prec1) ::RHOFILM                 !DENSITY (kg/m^3)
REAL(prec1) ::CPFILM                  !HEAT CAPACITY (J/(kg-C))
REAL(prec1) ::KFILM                       !THERMAL CONDUCTIVITY (W/(m-C))
```

```fortran
REAL(prec1) ::VISCFILM                  !DYNAMIC VISCOSITY (N-s/m^2)
REAL(prec1) ::BETAFILM                  !VOLUMETRIC THERMAL EXPANSION COEFF. (K^-1)
REAL(prec1) ::ALPHAFILM                 !THERMAL DIFFUSIVITY (m^2/s)
REAL(prec1) ::RAair                     !RAYLEIGH NUMBER FOR AIR (-)
REAL(prec1) ::RAfilm                !RAYLEIGH NUMBER FOR AIR FILM (-)
REAL(prec1) ::NUair                     !NUSSELT NUMBER FOR AIR
REAL(prec1) ::Hair                      !FREE AIR CONVECTION COEFF. (W/(m-C))
REAL(prec1) ::WIND_DIR_R            !WIND DIRECTION IN RADIANS
REAL(prec1) ::SLABORIENTATION_R         !IN RADIANS
REAL(prec1) ::LENGTHCHAR            !CHARACTERISTIC LENGTH (m)
REAL(prec1) ::REwindy               !REYNOLDS NUMBER FOR SURFACE WIND (-)
REAL(prec1) ::PRwind                !PRANDTL NUMBER FOR SURFACE WIND (-)
REAL(prec1) ::NUwind                !NUSSELT NUMBER FOR SURFACE WIND (-)
REAL(prec1) ::LENGTHCRIT            !CRITICAL LENGTH (m)
REAL(prec1) ::Hwind                     !FORCED AIR CONVECTION COEFF (W/(m-c))
REAL(prec1) ::HC                    !CONVECTION COEFF (W/(m-c))

AREA=LENGTH*WIDTH
PERIMETER=2.*LENGTH+2.*WIDTH
TFILM=(TSLAB+Tdb(TIME))/2.      !the air film temperature

CALL AIR_PROPS (TFILM,RHOFILM,CPFILM,KFILM,VISCFILM,BETAFILM)

!*FREE CONVECTION CONTRIBUTION
ALPHAFILM=KFILM/(RHOFILM*CPFILM)
RAair=GRAVITY*BETAFILM*(TSLAB-Tdb(TIME))*(AREA/PERIMETER)**3./(VISCFILM/RHOFILM*ALPHAFILM)

RAfilm=MAX(0.0,RAair)
IF (RAfilm.LT.1.0E+7) THEN        !check validity range
      NUair=0.54*RAfilm**(0.25)+0.0001
ELSE
      NUair=0.15*RAfilm**(1./3.)+0.0001
END IF
Hair=NUair*KFILM/(AREA/PERIMETER)

!*FORCED CONVECTION CONTRIBUTION
!first determine characteristic length
IF (WIND_DIR(TIME).GE.180.) THEN      !adjust all wind directions to 0 to 180
      WIND_DIR(TIME)=WIND_DIR(TIME)-180.
      IF (WIND_DIR(TIME).GE.90.) THEN !adjust all wind directions to 0 to 90
          WIND_DIR(TIME)=180.-WIND_DIR(TIME)
      END IF
END IF
WIND_DIR_R=WIND_DIR(TIME)*pi/180.                !convert to radians
SLABORIENTATION_R=ORIENTATION*pi/180.     !convert to radians
LENGTHCHAR=LENGTH*MAX(SIN(SLABORIENTATION_R),COS(WIND_DIR_R))  &
          +WIDTH*MIN( SIN(WIND_DIR_R),COS(SLABORIENTATION_R) )
REwindy=RHOFILM*WINDSPEED(TIME)*LENGTHCHAR/VISCFILM
PRwind=VISCFILM*CPFILM/KFILM
!find the critical length assuming RE=5x10^5 is critical
LENGTHCRIT=VISCFILM*(5.E+5)/(RHOFILM*WINDSPEED(TIME)+0.001)
IF (LENGTHCRIT.GE.LENGTHCHAR) THEN
      !all flow is laminar
      NUwind=0.664*REwindy**0.5*PRwind**(1./3.)
ELSE
      !flow is mixed
      NUwind=0.037*REwindy**0.8*PRwind**(1./3.)
END IF
Hwind=NUwind*KFILM/LENGTHCHAR
HC = MAX(Hwind,Hair)

END SUBROUTINE h_coeff


!***************************************************************
 SUBROUTINE AIR_PROPS (Tair,RHOa,CPa,Ka,VISCa,BETAa)

!***************************************************************
!      PURPOSE: To compute thermal properties of air

!      INPUTS:
!         (1)  Tair   =   AIR TEMPERATURE                      (C)

!      OUTPUTS:
!         (1)  RHOa   =   DENSITY                              (kg/m^3)
!         (2)  CPa    =   HEAT CAPACITY                        (J/(kg-C))
```

```
!         (3)  Ka      =   THERMAL CONDUCTIVITY                  (W/(m-C))
!         (4)  VISCa   =   DYNAMIC VISCOSITY                     (Pa-s)
!         (5)  BETAa   =   VOLUMETRIC THERMAL EXPANSION          (K^-1)
!                              COEFFICIENT

!  Ref:  Irvine, T.F.Jr., and Liley, P.E., "Steam and Gas Tables
!        with Computer Equations," Academic Press, Inc., 1984.

!***********************************************************************

IMPLICIT NONE

REAL(prec1) ::TAIR                          !AIR TEMPERATURE (C)
REAL(prec1) ::RHOa                          !DENSITY OF AIR (kg/m^3)
REAL(prec1) ::CPa                       !HEAT CAPACITY OF AIR (J/(kg-C))
REAL(prec1) ::Ka                        !THERMAL CONDUCTIVITY OF AIR (W/(m-C))
REAL(prec1) ::VISCa                         !DYNAMIC VISCOSITY OF AIR (N-s/m^2)
REAL(prec1) ::BETAa                         !VOLUMETRIC THERMAL EXPANSION COEFF. (K^-1)
REAL(prec1) ::TT
REAL(prec1), PARAMETER :: TCONV=273.15
REAL(prec1), PARAMETER :: A0=-0.98601
REAL(prec1), PARAMETER :: A1=9.080125E-2
REAL(prec1), PARAMETER :: A2=-1.17635575E-4
REAL(prec1), PARAMETER :: A3=1.2349703E-7
REAL(prec1), PARAMETER :: A4=-5.7971299E-11
REAL(prec1), PARAMETER :: B0=4.8856745
REAL(prec1), PARAMETER :: B1=5.43232E-2
REAL(prec1), PARAMETER :: B2=-2.4261775E-5
REAL(prec1), PARAMETER :: B3=7.9306E-9
REAL(prec1), PARAMETER :: B4=-1.10398E-12
REAL(prec1), PARAMETER :: C0=-2.276501E-3
REAL(prec1), PARAMETER :: C1=1.2598485E-4
REAL(prec1), PARAMETER :: C2=-1.4815235E-7
REAL(prec1), PARAMETER :: C3=1.73550646E-10
REAL(prec1), PARAMETER :: C4=-1.066657E-13
REAL(prec1), PARAMETER :: C5=2.47663035E-17
REAL(prec1), PARAMETER :: D0=1.03409
REAL(prec1), PARAMETER :: D1=-0.284887E-3
REAL(prec1), PARAMETER :: D2=0.7816818E-6
REAL(prec1), PARAMETER :: D3=-0.4970786E-9
REAL(prec1), PARAMETER :: D4=0.1077024E-12

!     ** Density **
 !from curve-fit to data in Table B-4b of McQuiston and Parker, 4th ed.
 RHOa=-4.9714E-3*Tair+1.33342

!     ** Dynamic Viscosity **
TT=Tair+TCONV
VISCA=A0+TT*(A1+TT*(A2+TT*(A3+TT*A4)))
IF(TT .GE. 600.) VISCA=B0+TT*(B1+TT*(B2+TT*(B3+TT*B4)))
VISCA=VISCA*1.E-6

!     ** Thermal Conductivity **
TT=Tair+TCONV
Ka=C0+TT*(C1-TT*(C2+TT*(C3+TT*(C4+TT*C5))))

!     ** Specific Heat Capacity **
TT=Tair+TCONV
CPa=D0+TT*(D1+TT*(D2+TT*(D3+TT*D4)))
CPa=CPa*1000.

!     ** Volumetric Thermal Expansion Coeff. **
BETAa=1./(Tair+273.15)

END   SUBROUTINE AIR_PROPS

!***********************************************************************


END MODULE PAVEMENTMODEL
```

APPENDIX C

CONTENTS OF THE DATA CD

Raw Weather Data

Contains raw and processed weather data for each of the following test locations:

Alabama

Arizona

Delaware

Nevada

Virginia

The processed files are denoted with a file extension of '.dat' while raw data files are denoted '.xls'.

Raw Pavement Data

Contains raw pavement data for each of the following test locations:

Alabama PVMT

Arizona PVMT

Delaware PVMT

Nevada PVMT

Virginia PVMT

The pavement data files need not to be processed and are denoted with a file extension of '.xls'.

Processed Weather Data

The following weather data files have been processed such that the numerical model code can read them.

ALWeather1.dat

ALWeather2.dat

AZWeather1.dat

AZWeather2.dat

DEWeather1.dat

NVWeather1.dat

VAWeather1.dat

VAWeather2.dat

Source Code and Associated Files

PavementModel.for (FORTRAN Source Code of the Numerical Model)

PavementTemperatures.for (FORTRAN Source Code of the Numerical Model)

RHOCPVALUES.txt (data input matrix that contains the values for the volumetric specific heat of the pavement material)

KVALUES-25cm.txt (data input matrix that contains the values for the thermal conductivity of the pavement material)

Simulations

Data files for the preliminary model validation simulations using field data from AL, DE, NV, VA1 and VA2. The validation simulations are provided in files of '.xls' extensions.

AL_1.xls

DE_1.xls

NV_1.xls

VA_1.xls

VA_2.xls

Data files for model simulations for comparison to Superpave using weather data from Cheyenne, WY; Bismarck, ND; Denver, CO; Great Falls, MT; Omaha, NE; and Phoenix, AZ. The simulations are provided in files of '.xls' extensions.

CheyennePredictions.xls

BismarckPredictions.xls

DenverPredictions.xls

GreatFallsPredictions.xls

OmahaPredictions.xls

PhoenixPredictions.xls

Sensitivity Analyses using Denver, CO pavement temperature responses.

SensAnalysis Using DENPredictions.xls