Asphalt Pavement Temperature Prediction Models: A Review

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Abstract: The performance of bituminous materials is mainly affected by the prevailing maximum and minimum temperatures, and their mechanical properties can vary significantly with the magnitude of the temperature changes. The given effect can be observed from changes occurring in the bitumen or asphalt mixture stiffness and the materials' serviceable life. Furthermore, when asphalt pavement layer are used, the temperature changes can be credited to climatic factors such as air temperature, solar radiation and wind. Thus in relevance to the discussed issue, the contents of this paper displays a comprehensive review of the collected existing 38 prediction models and broadly classifies them into their corresponding numerical, analytical and statistical models. These models further present different formulas based on the climate, environment, and methods of data collection and analyses. Corresponding to which, most models provide reasonable predictions for both minimum and maximum pavement temperatures. Some models can even predict the temperature of asphalt pavement layers on an hourly or daily basis using the provided statistical method. The analytical models can provide straight-forward solutions, but assumptions on boundary conditions should be simplified. Critical climatic and pavement factors influencing the accuracy of predicting temperature were examined. This paper recommends future studies involving coupled heat transfer model for the pavement and the environment, particularly consider to be made on the impact of surface water and temperature of pavements in urban areas.

Keywords: pavement temperature; temperature distribution; prediction model; layered systems; heat transfer; climate; asphalt

1. Introduction

Temperature distribution is the one of the most contributing environmental factors which affects the mechanical properties of flexible asphalt paving mixtures and the asphalt pavement structure’s bearing capacity [1,2]. To briefly define, pavement temperature is defined as the changes in pavement surface temperature with the variation in weather parameters over time as influenced by the paving materials and direct solar reflectance, thermal conductivity, thermal emittance, specific heat, and surface convection [3,4]. It should be noted that, Bituminous and asphalt mixtures are temperature sensitive materials, and therefore their strengths and modulus vary with the change in temperature. As a result of this, different types of damages could occur in flexible pavements. For example,
the decreasing temperature can risk pavements crack, while high temperatures can result in rutting (permanent deformation) [5]. It is also been observed that the temperature in one section of an asphalt pavement varies due to several reasons. To better understand, pavement responses are affected primarily by ambient temperature, followed by solar radiation (during the hot season); the effect of wind speed and relative humidity, however, is less significant [6,7]. Thus, these parameters are considered as the necessary parameters in a pavement temperature prediction model [8,9]. Furthermore, extensive research on temperature prediction models has been conducted in several regions with different climates to formulate pavement temperature prediction models that provide the highest accuracy [2]. Several researchers have also raised their concern about temperature algorithms’ precision and the consequences of using predicted values by emerging technologies of deep learning-based regression models for calculating asphalt pavement temperature [10,11]. With all the above facts in consideration, this paper aims to provide a comprehensive review of the available pavement temperature prediction models and offer critical evaluation of the models examined. Apart from this, the challenges and limitations of the relevant prediction models will also be discussed in this paper to better visualize the correct outcome.

2. Measurements of Pavement Temperature

The pavement surface temperature measurement which is based on creating a pavement temperature prediction model enables us to gather the relevant pavement temperature data. Figure 1 shows the design of a mobile and dependable system which is used for collecting continuous and consistent measurements of temperature fluctuations occurring in an asphalt pavement section [12].

![Figure 1. Representation of a pavement temperature measurement system.](image)

The provided system has been used extensively in many researches on-site, and the temperature measurement system of those researches should meet the following requirements [12]:

- The thickness of the flexible pavement base course and wearing surface required should be less than 35 cm.
- The measurement site must have proper ventilation and be able to receive sufficient sunlight without being shaded by trees or buildings.
- The measurement point must be easily reachable by the power supply and protection facilities for the temperature recording and measuring system.
- A weather station must be present not more than eight km away from the measurement site to provide real-time climate data.

3. Primary Factors Influencing Pavement Temperature

Environmental factor variations may influence pavement temperature variations and hence ultimately affecting the stiffness and degradation of pavement materials, thereby
influencing their performance in-service. However, these factors are always considered in pavement design and field installation [13,14]. For example, in order to meet the functional and structural requirements, the selection of bituminous binder grade is determined to address the local temperature condition [13,15]. Even though environmental factors are given serious consideration in pavements, distresses resulting from variations in these factors are unavoidable and are often significant [16–18]. The previous researcher investigated the effect of the environment on the pavement performance and reported influences on pavement environmental conditions (e.g., temperature and moisture profiles) in assessing material responses and predicting long-term performance [19].

Furthermore, the increase in the temperature ranges due to weather and climate changes were reported to increase thermal stresses in asphalt layers and that more thermal cracking could be expected as a result [20]. In addition to these, higher temperature can lead to faster (accelerated) ageing of asphalt layers, and pavements could hence become more prone to cracking due to increased brittleness [21–23]. Additionally, low temperatures may lead to the hardening of asphalt concrete and subsequently results in thermal cracks being generated on the road surface. Also, the low temperature was prone to accelerate cracking processes while high temperature distorts processes, leading to plastic deformation such as rutting [24–27].

Figure 2 illustrates the heat conduction within a pavement structure and subgrade and the convection process due to heat transfer between the pavement surface and the surrounding environment, where the latter takes place through a transmission medium, such as air or when water reaches the surface [28,29]. However, in most investigations on the climatic variables, temperature variations were considered the most responsible factor for the varying pavement performance [30,31]. Therefore, it is prudent to understand the mechanisms for seasonal variations and their impact on temperature changes [32–34]. Furthermore, it is widely known that the pavement layers’ response to traffic loads is highly influenced by environmental factors such as temperature and moisture. Therefore, any significant temperature change could severely impact asphalt pavement performance and the rehabilitation requirements [35–38].

![Figure 2. Factors influencing asphalt pavement temperature.](image)

### 3.1. Influence Mechanisms

Most pavements are exposed to their surrounding environments, significantly influencing their internal pavement temperatures [39,40]. Diffused and direct solar radiation, which is considered the essential factors, generally has short wavelengths [41]. As short-wave radiation reaches the asphalt pavement surface, the pavement layers start absorbing a relatively high amount of energy, transmitted as heat flux in the pavement structure whilst the surface reflects the remaining heat towards the sky [1]. It should be considered that asphalt pavements are not only affected by climate variations but also contribute to
them [41]. The reasons for this are two-fold. Firstly, a large amount of Greenhouse Gas (GHG) is emitted in various phases of a pavement’s life cycles. Secondly, asphalt roads cover significant proportions of urban areas. Moreover, road pavements store and release more heat than soils, aggravating urban heat island (UHI) effects. Consequently, any action to reduce such emissions could potentially contribute to mitigating GHG emission on heavily trafficked roads [42].

The amount of reflected and absorbed energy is influenced by cloud cover, precipitation, and pavement surface temperature [43]. The pavement surface concurrently radiates the long-wave radiation as a black body [44]. The net value of that long-wave radiation energy (input long-wave radiation minus pavement emitted long-wave radiation) is known as the effective long-wave radiation [45]. Hence, it may be affected by cloud cover, pavement surface temperature, air temperature, and relative humidity. Direct solar radiation and diffuse scattered solar radiation are also shortwave radiations and can be regarded as incoming shortwave radiation. The combined incoming solar radiation and effective long-wave radiation is called solar radiation [17]. Therefore, it is safe to say that heat can be transferred primarily by air, dynamic terrestrial radiation, and solar radiation [12, 40, 46].

3.2. Moisture Effect

Moisture affects the chemical, biological, and mechanical processes of decay [6]. The moisture formed due to the reaction between asphalt pavement surface and adsorbed water particles is deposited within the asphalt pavement surface [7]. However, it may also be generated by the moisture entrapped within the asphalt layer, leading to the build-up of pore pressure arising on account of repeated traffic loads and freeze-thaw cycles. Furthermore, the moisture layer, when combined with temperature, serves as a conductor in electrochemical reactions and a medium for the chemical reactions of surface contaminants. Two critical variables in the damage caused by humidity are the relative humidity of air and dew point [47].

3.3. Solar Radiation Effect

Solar radiation causes a change in the temperature of bituminous materials, which in turn can cause a change in the volume of pavement structures in the pores due to the expansion of water when exposed to the higher amount of heat from solar radiation [48]. Thus, solar radiation causes indirect and diffuse heat gain on the pavement via solar absorption [49]. Moreover, Solar radiation is also plays a vital role in photochemical reactions since it is the energy source for the excitation and breaking of bonds within the reacting molecules [7, 14, 50]. Therefore, a sufficiently intense solar radiation with appropriate wavelengths could trigger photochemical reactions which can cause damages to pavement materials [14].

3.4. Wind Effect

The wind speed also affects pavement temperature. The difference in pavement surface temperature and air temperature can result into a convection loss from the pavement to the air. The amount of lost energy is determined by wind velocity and the difference between air temperature and pavement surface temperature. Furthermore, the heat exchange that occurs on the pavement surface causes a variation in pavement surface temperature; this results in a difference in the pavement surface temperature and the pavement structure’s temperature as the energy is dispersed to the pavement structure. Another factor influencing pavement temperature is wind speed. However, in reality, wind speed and wind direction are consistently changing. Wind speed for a given stretch of road may differ due to variations in layout and profile of, and any obstacle along, each road section. Therefore, the inclusion of the influence of wind speed in temperature prediction models could be complex.

Therefore, as the wind speed affects pavement temperature [12, 51, 52]. Asphalt pavement materials are affected in different ways by rising wind velocity [13]. Hence accord-
ingly, the wind-water pushes the air’s portable particles to the pavement surface, where they cause local attrition and material deterioration [53,54]. In addition to this, wind velocity also influences the particle kinetic energy and the degree of inertial impaction of droplets on the materials surface [55]. The change in structure volume is influenced by both drying and wetting processes [56,57].

4. History of Asphalt Pavement Temperature Prediction Models

Based on the research methodology and tools of analysis employed in each investigation, the prediction of asphalt pavement temperature can be divided into: (1) numerical and finite element techniques, (2) theoretical and analytical approaches, and (3) statistical and probabilistic models. Researchers began to study the effect of climate factors on asphalt pavement quite early. In 1957, Barber [58] became one of the first researchers to address the internal temperature of asphalt pavements based on meteorological data measurements. Furthermore, researchers studying asphalt pavement temperature focused on temperature distribution in various depths; they adopted theoretical frameworks based on the one-dimensional thermal conduction model and Finite Difference Method (FDM) to simulate a pavement structure’s temperature distribution [59].

In 1987, the long-term pavement performance (LTPP) project in the United States began measuring asphalt pavement temperature [60]. Their study focused on a new pattern of data analysis for asphalt pavement. A large amount of became data available, including atmospheric temperature and solar radiation and their relationship to pavement temperature, comprise an essential database that facilitates and encourages the research in this field, which used the regression method to formulate models for predicting asphalt temperature [61]. The researchers attempted to develop a regression for the prediction model to correct the deviations and back-calculation of surface asphalt pavement layers [17].

In the first stage (1950–1990), the researchers focused on the variation trend and temperature distribution. However, a small number of researchers used slope methods to predict pavement temperatures. During the 1990s, Canadian and American researchers focused on using a new method to analyse the asphalt pavements data. Consequently, a helpful database is now available to support research at pavement temperature based on a large amount of data and information about pavement temperature and climate parameters such as atmospheric temperature and solar radiation. However, most researchers in this second stage, 1990 to 2000, also made use of the regression method to create models for predicting asphalt temperature by focusing on the minimum and maximum asphalt pavement temperatures during the service period when selecting bituminous for the Superpave method. Hence in accordance, several studies also began discussing the daily prediction of pavement temperature with slight variable modifications, and they had been successfully implemented in road engineering practices. In the third stage, from the year 2000 to present, researchers have been using statistical methods to develop a regression prediction model in two applications, namely to correct the deflection measurements with back-calculation modulus in the asphalt pavement layers and to simulate temperature fluctuation distributions within the structure of the asphalt. The third phase’s research is greatly influenced by those that occurred in the previous phase, despite the research metrics’ scope has been dramatically expanded. To summarize, temperature prediction models had been improved and perfected owing to the rapid database development in the 1990s.

5. Methods for Predicting Pavement Temperature

The methods for predicting asphalt pavement temperature and improving prediction methods have been continuously up for development for the last half of the century. Quite recently, a new research is being carried out which uses more complex numerical methods, and thus the accomplishments of this research have been widely approved and applied in the field of engineering [12]. Moreover, several researchers have attempted to develop mathematical models for predicting the temperature in an asphalt pavement system [51,62].
They adopted three primary methods: numerical and finite elements, theoretical and analytical, and statistical and probabilities techniques \cite{9,17,36,63,64}. The numerical and analytical profiles for heat conduction in specified boundary conditions can be easily obtained by using the partial differential equation (PDE). However, the empirical models were developed using statistical analysis \cite{65}, as discussed in the following subsection.

5.1. Numerical and Finite Elements

The numerical and finite element methods, as presented in Table 1, were carried out in four stages. In the first stage, the governing equation was formulated to determine the heat conduction in a pavement layer system; this equation is usually a one-dimensional (1-D) or two-dimensional (2-D) heat transfer profile simplified by a partial differential equation (PDE). First, the governing equation to account for the heat conduction within a pavement must be set up, which is usually a one-dimensional (1D) or two-dimensional (2D) heat transfer model represented by a time-dependent partial differential equation (PDE) \cite{51}. The finite element method (FEM) is an advanced numerical method used for a variety of engineering problems. In FEM, the PDE is first converted from a robust model to the weak one \cite{65,66}.

In the second stage, the “Dirichlet boundary” or the transit surface temperature, must be established \cite{67}, alternatively, a mixed-type edge that links climate parameters with the temperature gradient within the asphalt pavements depth. However, this link is accomplished by analysing the energy balance at the pavement surface \cite{48,54}. In the third stage, the spatial domain needs to discretised using a numerical method, such as finite-difference method, finite-element method, which results in a large system of ordinary differential equations (ODEs) in time \cite{67,68}, FEM \cite{44,69}, and a finite volume method (FVM) \cite{62,65}.

In the fourth stage, a suitable time integrator is desired to solve these ODEs. For instance, this time integrator can either be a linear multistep method or a Runge-Kutta method \cite{62}. In numerical analysis, the complex heat transfer process is considered to ensure that the models can be used universally, and the prediction of pavement temperature can be made under different conditions. One of the advantages of the analytical method is its ability to give a quick solution that can be used in real-time \cite{70}. Furthermore, the calculation of the precision and time of numerical models is strongly influenced by roads density and the number of elements in the model \cite{71}. The disadvantage of numerical methods however, is usually that they are not user-friendly, as they require proficiency in designing the FEM and good judgment to ensure convergence of the solutions \cite{72}. The pavement temperature obtained through analytical solutions is influenced by heat conduction and its initial boundary value problem (IBVP). The analytical models use pavement surface temperature as the initial boundary value \cite{73}. However, by performing this simplification, the influence of climatic parameters on pavement temperatures, such as wind speed, solar radiation, and air temperature, cannot be taken into account \cite{62,74,75}. It should be highlighted that numerical models differ from regression equations in that, by making suitable assumptions, they may be used to obtain strict solutions for pavement temperature \cite{70}. When compared with the analytical models, the boundary conditions in numerical models are observed to be far more complicated. Among the most frequently used numerical methods are FDM, FEM, and FVM.
Table 1. Pavement temperature prediction models using numerical methods.

| Ref, Year                          | Location | Influencing Factors                                      | Summary and Findings                                                                                                                                 |
|------------------------------------|----------|----------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Straub and Przbycien (1968) [76]   | USA      | Pavement temperature, Solar radiation, Air temperature   | • The impact of solar radiation on surface temperature is higher than that of air temperature.                                                        |
|                                    |          |                                                          | • The expected maximum surface temperature is not sensitive to primary input values, although the role of input temperature is more significant, with increasing depth in giving an accurate prediction [7]. |
| Dempsey and Thompson (1970) [77]  | USA      | Shortwave and long-wave light, Thermal properties, Air temperature, Physical weight, Material classification, Moisture content, Thermal capacity, Thermal conduction | • Advanced equations can occasionally be quite complicated, and many variables are needed to make a pavement temperature prediction. These models are not suitable for practical routine use [63]. |
| Rumney and Jimenez (1970) [78]     | USA      | Pavement temperature, Air temperature, Solar radiation   | • The monograph models were not able to give precise results.                                                                                       |
|                                    |          |                                                          | • Chart of the monograph was developed within pavement from 50 to 80 mm depths.                                                                      |
|                                    |          |                                                          | • Correlation monographs for predicted pavement temperature were developed for a specific air temperature and solar radiation intensity.            |
|                                    |          |                                                          | • The research concentrated on the hot desert climate in order to study maximum asphalt pavement temperature.                                        |
| Williamson (1972) [79]             | South Africa | Solar radiation, Air temperature, Thermal properties | • Validation of the model was done using data from 20 cm (8-inches) thick asphalt paving.                                                             |
|                                    |          |                                                          | • The model did not consider the moisture effect and precipitation.                                                                                  |
| Anderson and Christison (1972) [80]| Canada  | Solar radiation, Air temperature, Wind speed, Physical properties | • Investigated pavement performance in low-temperature climate.                                                                                     |
|                                    |          |                                                          | • The model did not consider the effects of moisture and precipitation.                                                                            |
|                                    |          |                                                          | • Demonstrate the differences in natural pavements’ temperature against those painted white and the difference in the cement-treated base’s surface temperatures exposed to natural sunlight against those sheltered [49]. |
| Kondo and Miura (1976) [81]        | Japan    | Air temperature, Pavement temperature                   | • This condition does not exist when measuring asphalt surface temperature.                                                                        |
|                                    |          |                                                          | • The study did not consider low temperatures, which is considered the most crucial cause for asphalt collapse.                                      |
| Ref, Year                      | Location | Influencing Factors                  | Summary and Findings                                                                                                                                                                                                 |
|-------------------------------|----------|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lytton et al. (1990) [82]     | USA      | Pavement structure                   | • The model did not adequately explain the dynamics of heat transfer, and the shortcomings are possible due to numerous factors.                                                                                   |
|                               |          | Materials properties                 | • Solar radiation, as an input parameter, was estimated using a regression equation even though it could have been obtained from more reliable sources.                                                       |
|                               |          |                                      | • The EICM model did not consider the effect of seasonal fluctuation in radiation properties on the pavement surface at a particular location [44,83,84].                                                   |
| Minhoto et al. (2006) [85]    | Portugal | Solar radiation                      | • Accurate temperature prediction compared to the actual pavement temperature measured throughout the year.                                                                                                         |
|                               |          | Air temperature                      | • The models are not suitable for field use. Statistical methods are useful for creating a simple prediction equation [63].                                                                                       |
|                               |          | Daily wind speed                     |                                                                                                                                                                                                                  |
| Lufs de Picado-Santos [86]    | Portugal | Monthly max air temperature          | • Hourly damage was established using hourly meteorological data that made it possible to run a previously validated model to calculate pavement temperature distribution, which is considered accurate pavement temperature distribution [87]. |
|                               |          | Monthly min air temperature          | • Better characterisation of pavement design conditions leads to more reliable results.                                                                                                                             |
|                               |          | Hourly asphalt layer temperatures    | • The structure of the models presented could be quickly adopted elsewhere.                                                                                                                                                                                                   |
|                               |          |                                      | • There is a long and challenging way to go concerning pavement materials’ behaviour modelling for design purposes.                                                                                                 |
| Mammeri et al. (2015) [88]    | France   | Pavement temperature                 | • Comparative experimental and numerical results suggest that night cooling is an essential parameter in a surface temperature model, especially in arid regions.                                           |
|                               |          | Air temperature                      | • Due to the complexity of FEM, engineers usually prefer to perform the analysis using easy and straight-forward methods [89].                                                                                      |
|                               |          | Depth                                |                                                                                                                                                                                                                  |
|                               |          | Humidity                             |                                                                                                                                                                                                                  |
|                               |          | Solar radiation                      |                                                                                                                                                                                                                  |
5.2. Theoretical and Analytical Approaches

Early studies that used analytical methods to predict pavement temperatures began in the 1950s when Barber derived pavement temperatures using climate data [58]. Table 2 presents the studies that had attempted to predict pavement temperatures by using analytical methods. The primary characteristics of this pavement temperature modelling are that most climatic parameters, such as the geographical and meteorological data mentioned in the above methods, were used in the numerical or statistical temperature models [9]. Besides, the analytical method does not need any spatial uniqueness of the actual field or time of integration to develop a time-dependent temperature model and eliminate computational problems with numerical methods, such as truncated errors and mathematical stability [25]. Despite the advantages of the method, the analytical solution of temperature profiles through a multi-layer pavement system is concerned [62], because quite a few results were available due to the complexity encountered in deriving the closed-form analytical solution [63,89].

5.3. Statistical and Probabilities Techniques

The current empirical models consist of three categories, non-linear regression, linear regression, and neural network [65]. The simplest method for developing empirical models is linear regression, which predicts the minimum or maximum temperature at a particular depth [63,90–92]. Linear regression models typically comprise several parameters and are used in real-time situations to predict surface temperature [93]. A drawback of using this method is that the daily pavement temperature through depth is non-linear and complex. Therefore, linear regression to predict pavement temperature is not encouraged as it depends on time as an independent variable factor [94]. Since the predicted pavement temperature changes over time, advanced empirical models generally include the sine terms [95,96]. However, the statistical analysis method is commonly developed using a large amount of measured field data on asphalt pavement details and climate database. It considers geographical and meteorological factors such as wind speed, ambient temperature, location and solar radiation [5,97–99].

Table 3 presents a list of researches that used statistical methods to predict the pavement temperature. The regression method establishes a quantitative relationship between the temperature data and the asphalt pavement [100,101]. Furthermore, formulas are also applied to provide a mathematical solution for real-world problems and express relationships between various quantities in order to predict asphalt pavement temperatures for a particular area [102]. The advantage of using mathematical models is that they facilitate the analysis and interpretation of the observed data as they describe the evolution law as a function of only a few statistically compared [103]. Generally, statistical methods can provide reliable predictions of temperature with input data, including the original pattern databases [63]. Hence it is observed that this method can evaluate pavement temperature prediction models without requiring multiple inputs such as numerical computation and analytical deviation. Thus, empirical models are used extensively in practice [65]. The Strategic Highway Research Program (SHRP) was introduced in Canada and the United States in 1987. It is a 20-year study to improve the on-site performance description of pavements [104]. Apart from this, the study introduced a new bitumen classification system called Performance Grading (PG) [105]. Consequently, the PG number helps road engineers to locate the minimum and maximum temperatures of pavement that have been selected. Therefore, the appropriate bituminous binder was chosen at a specified temperature to prevent pavement rutting and cracking in hot and cold temperatures [59,106]. Most recently, AASHTO updated the associated pavement design manual called Mechanistic-Empirical Pavement Design Guide. This new guide helped to exploit the benefits of adopting the PG classification system and utilising the actual weather record.
Table 2. Pavement temperature prediction models using analytical methods.

| Ref, Year | Location | Influencing Factors | Summary and Findings |
|-----------|----------|---------------------|----------------------|
| Barber (1957) [58] USA | Pavement temperature, Wind, Precipitation, Air temperature, Solar radiation, Coefficient of thermal properties | The model was applied to asphalt pavements with a thickness of 6.35 cm. The actual temperature was compared with the obtained results; the expected maximum temperature error is about 3 °C and occasionally exceeds 5 °C [17]. The model calculated the maximum temperature and was able to predict the minimum temperature [1,5]. |
| Solaimanian and Kennedy 1993 [41] USA | Maximum air temperature, Hourly solar radiation | The model did not take into account winter conditions since this study investigated maximum temperature [44]. |
| Highter and Wall (1984) [107] USA | Thermal conduction of asphalt pavement temperature at a different specific density | A typical recycling process where an external heat source applied to asphalt pavements. A significant difference was observed in the surface limestone course’s thermal conduction spread and base limestone course, which is apparently due to the gradient and total size of aggregates. |
| Liang and Niu (1998) [30] USA | Ambient air temperature, Pavement surface temperature | The main findings showed that the temperature distribution within depth could be non-linear, especially when considering the daily temperature change. The analytical solution to the temperature distribution was in a three-layer system using a simplified boundary condition that involved only heat transfer between the pavement surface and ambient air. |
| Liu and Yuan (2000) [108] USA | Ambient air temperature, Pavement surface temperature, Depth, Time | The analytical solution can be expanded to understand or predict temperature distribution within the asphalt pavement over weeks or months. |
Table 3. Pavement temperature prediction models using statistical methods.

| Ref, Year          | Location     | Model and Influencing Factors                                                                 | Summary and Findings                                                                                                                                                                                                 |
|--------------------|--------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SHRP (1987) [104]  | USA          | $1331a_1 T_{air} \tan \frac{1}{2} \pi Z + \epsilon \sigma T_{air}^4 - h_c (T_s - T_a) - 164k - \epsilon \sigma T_s^4 = 0$ |
| where $a$ is absorptivity of pavement surface, $\tau$ is heat conduct coefficient for air, $Z$ is 20 degrees latitude, $\epsilon$ is pavement surface emissivity, $\sigma$ is the Stefan-Boltzman constant ($5.7 \times 10^{-8}$ W/m$^2$°C), $h_c$ is surface coefficient of heat transfer (W/m$^2$°C), $k$ is heat conduction coefficient (W/m$^2$°C), $T_s$ is air temperature (K), and $T_a$ is surface temperature (K). |
| Abdul Al-Wahhab et al. (2001) [109] | Saudi Arabia | $T(d) = 3.714 + 1.006 T(a) - 0.146d$ where $T(d)$ is pavement temperature at depth $d$ (°C), $T(a)$ is air temperature (°C), and $d$ is depth below pavement surface (cm). | The model could predict maximum and minimum temperatures that play an essential role in asphalt pavement. Saudi Arabia is located in a desert region where ambient temperature fluctuation is minimal throughout the year. |
| Park et al. (2001) [96] | USA          | $T_d \approx T_s + (-0.3451d - 0.0432d_2 + 0.00196d_3) \times \sin (0.325 \tau + 5.0967)$ where $T_d$ is the temperature of pavement (°C), $T_s$ is the surface temperature (°C), $d$ is depth (mm), $\tau$ is the coefficient associated with time. | This model was verified for a surface temperature range of between −28.4 to 53.7 °C and a depth ranging from 14 to 27.7 cm. |
| Diefenderfer et al. (2003) [59] | USA          | $T_{pmax} = 3.2935 + 0.6356 T_{max} + 0.1061Y - 27.7975P_d$ $T_{pmin} = 1.6472 + 0.6504 T_{min} + 0.0861Y + 7.2385d_b$ where $T_{pmax}$ is predicted maximum temperature (°C), $T_{pmin}$ is the predicted minimum temperature (°C), $T_{min}$ is the minimum daily temperature (°C), $Y$ is one day of the year (1 to 365), and $d_b$ is depth below the surface (m). | This model can be used for the four seasons and across different climate zones after confirming the equation using the data from SMP sites in the United States [62,110,111]. |
| Hassan et al. (2004) [112] | Oman         | $T_{surf} = -1.437 + 1.121 T_{air}$ $T_{20mm} = 3.160 + 1.319 T_{airs}$ where $T_{surf}$ is minimum temperature of pavement (°C), $T_{air}$ is minimum temperature of air (°C), $T_{20mm}$ is pavement temperature at 20 mm in °C, and $T_{airs}$ is maximum air temperature in °C. | The experimental application of these formulae is used to predict the temperature at a particular pavement depth. |
| Jia et al. (2008) [99] | China        | $T_p = P_1 + (P_2 T_{avg} + P_3 Q_s)^2 + H(P_4 T_a + P_5 Q) + (P_6 H + P_7 H^2 + P_8 H^3) + P_9 T_m$ where $T_p$ is pavement temperature at $H$ cm, $T_s$ is air temperature, $Q_s$ is solar radiation, kW/m$^2$, $T_{avg}$ is average air temperature for the previous 5 h, $Q_s$ is average solar radiation for the previous 5 h, kW/m$^2$, $H$ is the depth of prediction point in cm, $P_1$–$P_8$ are the undetermined regression coefficients for the prediction model, $T_m$ is the monthly historical average air temperature for the past 20 years. | The model has many variables, which makes it impractical for fieldwork. This model can be improved to make it more suitable for use in fieldwork. |
| Ref, Year         | Location | Model and Influencing Factors                                                                                                                                                                                                 | Summary and Findings                                                                                     |
|------------------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| Tabatabaie et al. (2008) [113] | Iran     | $T = 0.94Sur + 0.94\sin(2\pi t/24) - 2.99 \log(d) - 0.02\text{comp} + 0.02\text{Air} + 0.32\text{BP} + 0.17\text{BT} - 0.34$ where $T$ is asphalt temperature (°C), $\text{air}$ is air temperature (°C), $S$ is surface temperature (°C), $t$ is time of day in a 24-h system, $d$ is depth (cm), $\text{comp}$ is level of compaction (number of blows), $\text{BP}$ is bitumen content, $\text{BT}$ is bitumen type (1 for 40/50 and 2 for 60/7), and $\text{BP}$ is bitumen content. | - One drawback of this model is that it is not able to give the maximum and minimum asphalt temperature, which is crucial in the design of asphalt pavement.  
  - The relationship between asphalt temperature and climate influences is linear. |
| Zheng et al. (2011) [114]        | China    | $T_{\text{pave-rising}} = 1.170 T_{\text{air-rising}} - 0.50 h + 3.55$  
$T_{\text{pave-falling}} = 1.085 T_{\text{air-falling}} - 0.07 h + 4.3$  
$T_{\text{pave}} = 1.118 T_{\text{air}} - 0.23 h + 4.1$ where $T_{\text{pave-rising}}$ is temperature of asphalt pavement at depth $h$ during the period of rising air temperature (°C). $T_{\text{air-rising}}$ is a period of rising air temperature, and $h$ is a depth of pavement (cm). $T_{\text{pave-falling}}$ asphalt pavement temperature at depth $h$ during period of falling air temperature (°C). $T_{\text{pave-falling}}$ is a falling of air temperature (°C), and $h$ is a depth of pavement (cm). $T_{\text{air}}$ is air temperature, and $h$ is the depth of pavement (cm). | - The resulting models are practical and straight-forward. A comparison of the measured and predicted data shows a very accurate application value.  
  - This model cannot be used in all countries. |
| Al-Hamed and Maryam (2011) [48]  | Iraq     | $T_{\text{pave}} = 3.175 + 0.04866 Z + 0.946 T_{\text{air}}$ where $T_{\text{pave}}$ is pavement temperature (°C), $Z$ is depth below pavement surface (cm), and $T_{\text{air}}$ is air temperature (°C). | - This linear regression is a simple and practical model but was not validated. |
| Matic et al. (2013) [2]          | Serbia   | $y_{\text{max}} = 0.963288 x_{\text{max}} - 0.151137 x d + 4.452996$  
$y_{\text{min}} = 1.004801 x_{\text{min}} - 0.1992731 x d + 0.051532$ where $y_{\text{max}}$ is maximum pavement temperature (°C), $x_{\text{max}}$ is maximum air temperature, $x_{\text{min}}$ is air temperature (°C), $y_{\text{min}}$ is minimum pavement temperatures (°C), and $x d$ is depth (cm). | - The equation is linear in the first order without complications.  
  - The model can be used in fieldwork and is preferred by road design engineers.  
  - Serbia is located in Europe, and the temperature is low throughout the year. The developed model cannot be used in other parts of the world. |
Table 3. Cont.

| Ref, Year          | Location  | Model and Influencing Factors                                                                 | Summary and Findings                                                                 |
|--------------------|-----------|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Salem (2015) [7]   | Libya     | $T_{\text{max}_{\text{pay,d}}} = 7.059 + 0.7764246T_{\text{max}_{\text{sur}}} + 0.054628Day - 0.000141\text{Day}^2 + 0.000006\text{Cum}_{\text{SR}} - 0.053402Lat$  |
|                    |           | $T_{\text{max}_{\text{sur}}} = 9.8364 + 0.668591T_{\text{min}_{\text{sur}}} + 0.259098d + 0.099289\text{Day} + 0.000261\text{Day}^2 - 0.000025\text{Cum}_{\text{SR}} - 0.053402Lat$ |
|                    |           | where $T_{\text{max}_{\text{pay,d}}}$ is maximum daily pavement temperature ($^\circ$C), $T_{\text{max}_{\text{sur}}}$ is maximum daily surface temperature ($^\circ$C), $d$ is distance from surface (cm), is day of the year, $\text{Day}^2$ is the square of the day of the year, $\text{Cum}_{\text{SR}}$ is cumulative solar radiation (W/m²), and $\text{Lat}$ is latitude of the section (degrees). $T_{\text{min}_{\text{pay,d}}}$ is minimum daily pavement temperature at distance $d$ from the surface ($^\circ$C) and $T_{\text{min}_{\text{sur}}}$ is minimum daily surface temperature ($^\circ$C). |
|                    |           | • The researcher uses a small amount of data from a short period and therefore is not reliable for developing models. |
|                    |           | • Libya has more than one climate (marine and desert); the difference in air temperatures is enormous, and thus the reactions of asphalt pavement cannot be integrated into standardised models. |
| Ariawan et al. (2015) [115] | Indonesia | $T.00 = 10.813 + 0.919 RH$  |
|                    |           | $T.20 = 6.898 + 0.687T.\text{Air} + 0.640 T.00$  |
|                    |           | $T.70 = 1.965 + 0.755T.\text{Air} + 0.331 T.00$  |
|                    |           | where $RH$ is humidity, $T.\text{Air}$ is air temperature ($^\circ$C), $T.00$ is surface temperature($^\circ$C), $T.20$ is temperature at a depth of 20 mm ($^\circ$C), and $T.70$ is temperature at a depth of 70 mm ($^\circ$C). |
|                    |           | • Indonesia has a tropical climate, plenty of sunshine, rain, and high humidity during the year. |
|                    |           | • The model is accurate, practical and straight-forward but is limited to the depths stated in the equations; the temperature at any other depths cannot be determined. |
6. Regional Variations in Pavement Temperature Model

Due to regional variations, the temperature prediction model that works for a specific region may not necessarily apply to regions beyond it. Consequently, the geographical area significantly influences the temperature prediction model [63,116]. Therefore, it is essential to deal with the variance between regions in the pavement temperature prediction model and to understand the sources of these discrepancies [117]. The characteristics of pavement structure temperature are affected by environmental factors, the heat flow on the pavement surface (which has a day-to-day variation), and the thermal transfer within the ground’s lower layer [49]. The temperature difference results in thermal conduction between the pavement structure and the Earth; thus, earth temperature influences pavement structures’ temperature [118]. During a particular stage, earth temperature at a particular location may be assumed to be constant, and its impact on pavement temperature can be assumed to be of a relatively consistent value. The difference in earth temperature in different regions means that its influence on pavement temperature differs from one area to another [17]. In other words, pavement temperature can be viewed as a two-part interlocking system. Wherein, the first system is the stable impact of the earth temperature determined by long-term climatic variables while, and the second system is the impact of cyclic fluctuations caused by short-term environmental variables.

7. Challenges and Limitations of Pavement Prediction Model

Pavement prediction model studies for road construction design have been an ongoing challenge in the past decade. Some studies have resulted in predictions of the extreme asphalt temperatures, which triggered the requirements to enhancing pavement stability, strength, and durability. Based on this literature review, the essential factors and challenges in developing temperature prediction models are as follows.

• Current models for predicting the asphalt pavement’s temperature consider environmental factors’ impact on the asphalt pavement. However, these models do not consider the reverse impact that occurs from the heated pavement and thus contributing to heat accumulation in the surrounding environment, such as that found in urban heat island (UHI) effects. To summarise, these models cannot fully reflect the two-way interactions that become apparent between the pavement and the environment, thus making them incapable of evaluating the effect of pavement on UHI effects. Future studies are recommended and advised to be taken with this factor into account.

• The quantitative evaluation for prediction development of pavement temperature model allows for mechanistic-empirical modelling of pavement deterioration caused by climate change. However, qualitative or quantitative techniques to assess indirect impacts from climate variations, specifically to demography and traffic demand changes, should be considered in future studies [105].

• As mentioned in the current literature, asphalt pavement materials’ thermal properties can be specified [119]. However, this range is unnecessarily too broad to ensure that the model would make an accurate prediction. There is a lack of practical guidance for selecting material thermal properties based on material category, gradation, age, water content, and other information [120]. Moreover, current studies also do not take into account critical thermal properties and the resistance to thermal contact between pavement layers. Most studies even assumed a perfect thermal contact between pavement layers that still remain questionable.

8. Conclusions

To conclude, we wish to summarize the main sectors displayed and explored in the above review. The given research aimed to identify the various methods by which asphalt temperature could be predicted in order to aid road design engineers in overcoming the issues and limits the risks associated with the change in temperature. Three basic models were evaluated: numerical and finite element, analytical and theoretical, and statistical
and probabilistic techniques. It was concluded that analytical methods provided simple solutions and required straightforward boundary conditions. Furthermore, it was deduced at many states in the above review that the temperature has a relatively significant impact on the mechanical and physical material properties of the asphalt pavement layer. Moreover, this research has also successfully reviewed the methods available for measuring temperature profiles and the temperature prediction models for pavement structures. Thus, it can be concluded that researchers have been attempting to predict asphalt pavement temperatures since the mid of the previous century. However, these models have their own distinct weaknesses and strengths, and some of the prediction models are unnecessarily complex and require the use of several variables. On this note, the models also provide pavement temperature prediction equations which are duly unsuitable for routine use. Hence, further studies of heat transfer between the environmental and pavement temperatures are highly recommended, while also taking into account the impact of the pavement temperature on UHI effects.

Author Contributions: Conceptualization, I.A. and A.M.; formal analysis, I.A. and A.M.; investigation, A.M. and N.I.M.Y.; resources, I.A. and A.M.; writing—original draft preparation, A.M., N.A.Z. and I.A.; writing—review and editing, N.A.M., Z.A.M., I.W. and N.I.M.Y.; supervision, N.I.M.Y.; funding acquisition, Z.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: Prince Sultan University support for paying the Article Processing Charges (APC) of this publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data used in this research can be provided upon request.

Acknowledgments: The authors would like to thank Prince Sultan University for their financial support.

Conflicts of Interest: The authors declare no conflict of interest.

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