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Thermodynamics-Driven Analysis of Temperature Field Distribution and Its Influence on Fatigue Performance in Asphalt Pavements

Chunshui Huang[1*], Jun Wang[1], Yong Pan[2]

[1] College of Civil Engineering, Xuchang University, Xuchang 461000, China
[2] Zhejiang Communications Construction Group Co., Ltd., Hangzhou 310000, China

Corresponding Author Email: 12015042@xcu.edu.cn

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ABSTRACT

Asphalt pavements, serving as the primary structure in modern transportation infrastructure, are significantly influenced by the temperature field distribution. Due to the temperature sensitivity of asphalt materials, complex thermally induced stresses arise under varying environmental conditions such as ambient air temperature and solar radiation, leading to fatigue cracking and other distresses. Existing studies have predominantly adopted steady-state heat conduction models to analyze temperature fields, often neglecting the dynamic influence of environmental fluctuations. Furthermore, fatigue performance is frequently evaluated under single-temperature laboratory conditions, lacking a coupled analysis of temperature field variability and fatigue damage mechanisms. To address these limitations, the intrinsic relationship between temperature field distribution and fatigue performance of asphalt pavements was investigated in this study through two primary approaches. First, based on thermodynamic principles, the variation patterns of thermophysical properties—such as thermal conductivity and specific heat capacity—of asphalt mixtures were examined as functions of temperature, aggregate gradation, and asphalt type. A multi-factor coupled model for pavement temperature field computation was subsequently developed. Second, through laboratory fatigue testing and numerical simulation, the evolution of fatigue damage in asphalt mixtures under different temperature field distributions was analyzed, leading to the development of a predictive model correlating temperature conditions and fatigue performance. The findings are expected to provide an accurate methodology for temperature field analysis and a reliable basis for fatigue performance evaluation, thereby supporting enhanced structural design, construction, and maintenance of asphalt pavements. Moreover, the underlying mechanisms by which temperature fields influence fatigue performance were further elucidated, contributing to the improvement of long-term pavement serviceability.

1. INTRODUCTION

With the continuous advancement of global transportation infrastructure, asphalt pavements have become the predominant structural form for high-grade highways and urban roads, owing to their favorable performance and ease of construction [1, 2]. However, the mechanical behavior of asphalt materials is highly sensitive to temperature fluctuations [3, 4]. During long-term service, the internal temperature field of the pavement structure is subject to complex spatial and temporal variations under the combined influence of environmental temperature, solar radiation, and the thermophysical properties of pavement materials [5]. Cyclic temperature changes have been shown to induce temperature-related stresses and strains within asphalt pavements [6-8], subsequently resulting in fatigue cracking and other distresses [9], which substantially reduce pavement service life and functional performance. Therefore, an in-depth investigation into the relationship between temperature field distribution and fatigue performance in asphalt pavements is of critical practical significance.

Accurately characterizing the distribution patterns of temperature fields and revealing their intrinsic connection to fatigue performance are essential for guiding the design, construction, and maintenance of asphalt pavements. From a design perspective, structural composition and material gradation can be optimized based on temperature field characteristics to enhance fatigue resistance [10, 11]. During construction, precise temperature control can ensure adequate compaction quality of asphalt mixtures [12, 13]. In the maintenance phase, a basis for formulating scientific maintenance strategies can be provided, enabling effective prevention and mitigation of fatigue-related distresses. Such an approach is expected to reduce the life-cycle cost of pavements while improving the safety and reliability of transportation infrastructure [14].

In current research, the temperature field distribution of asphalt pavements has primarily been analyzed using steady-state or quasi-steady-state heat conduction models [11, 15]. However, these models fail to capture the dynamic influence of time-varying environmental factors, leading to insufficient accuracy in predicting temperature field evolution. Regarding fatigue performance, traditional approaches have relied on laboratory fatigue tests to determine the fatigue life of asphalt mixtures. These tests, however, are typically conducted under single-temperature conditions [16, 17], which do not adequately represent the spatiotemporal variability of in-service pavement temperature fields and their cumulative impact on fatigue damage. Moreover, existing studies that explore the relationship between temperature fields and fatigue performance have often employed empirical formulations or simplified mechanical models [18, 19], lacking a coupled analysis framework that integrates thermodynamic principles with the mechanisms of material fatigue damage. As a result, the fundamental processes through which temperature fields influence fatigue behavior remain insufficiently understood.

To address these limitations, the present study is structured around two primary research objectives. First, the thermal properties influencing temperature field distribution in asphalt pavement structures were investigated. Through theoretical analysis and experimental testing, the variations of thermal conductivity, specific heat capacity, and other relevant thermophysical parameters of asphalt mixtures were characterized in relation to temperature, aggregate gradation and asphalt binder type. A multi-factor coupled computational model of pavement temperature field distribution was then established. Second, the relationship between temperature fields and fatigue performance was evaluated. Laboratory fatigue testing and numerical simulations were employed to examine the evolution of fatigue damage under various temperature field distributions, leading to the development of a fatigue performance prediction model grounded in thermodynamic principles.

By integrating thermodynamic theory with fatigue performance analysis, this study addressed existing gaps in dynamic temperature field simulation and fatigue damage mechanism characterization. The findings are expected to offer more rigorous theoretical foundations and technical guidance for the design, construction, and maintenance of asphalt pavements. Furthermore, the results provide important theoretical and engineering value for improving the long-term service performance and durability of asphalt pavement systems.

2. ANALYSIS OF THERMOPHYSICAL PROPERTIES AFFECTING TEMPERATURE FIELD DISTRIBUTION IN ASPHALT PAVEMENTS

This study centers on the investigation of the relationship between temperature field distribution and fatigue performance in asphalt pavements. Fundamentally, the temperature field distribution is governed by the combined effects of external environmental energy input and the thermal conduction characteristics of pavement structural materials. Therefore, emphasis on the analysis of both environmental factors and material thermophysical properties is both necessary and justified. On one hand, environmental factors constitute the direct driving conditions for energy exchange between the pavement structure and its surroundings. The dynamic variability of these factors influences the spatial and temporal evolution of the temperature field through convective, radiative, and conductive heat transfer processes. If the coupled effects of these external variables are disregarded, discrepancies between simulated temperature fields and actual service conditions may arise, thereby hindering the accurate identification of the generation and progression mechanisms of thermal stresses. On the other hand, the thermophysical properties of pavement materials serve as intrinsic determinants of heat transfer efficiency and distribution within the pavement system. Variations in aggregate gradation, asphalt binder type, and air void content can significantly alter the thermal conductivity of the material, which in turn affects the gradient distribution and periodic behavior of the temperature field. A precise characterization of both the dynamic influence of environmental factors and the intrinsic mechanisms governed by material thermophysical properties is essential for establishing a reliable computational model of the pavement temperature field. Such a model forms the foundation for subsequent investigation into the coupling relationship between temperature fields and fatigue performance, ultimately facilitating the identification of fundamental thermodynamic drivers behind fatigue damage in asphalt pavements.

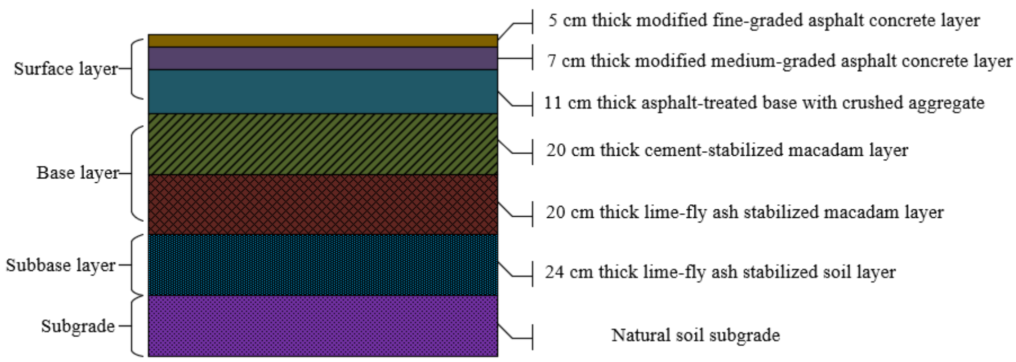


Figure 1. Schematic diagram of asphalt pavement structure

Figure 1 illustrates the schematic structure of the asphalt pavement. From a thermodynamic perspective, the pavement temperature field is determined by the combined effects of external environmental heat input and the internal thermal conduction properties of the constituent materials. The selected parameters correspond respectively to the boundary conditions governing heat transfer and the intrinsic thermal characteristics of the materials. External environmental parameters define the thermal exchange boundaries between the pavement and the atmosphere, solar radiation, and the ground surface. Among these, total solar radiation serves as the primary thermal source for pavement heating, with its diurnal cycle directly influencing the surface heat absorption rate. Ambient air temperature affects convective heat dissipation at the pavement surface, while ground temperature functions as the bottom boundary condition, dictating the direction of heat flux between the pavement structure and the subgrade. These three factors collectively establish the external forcing terms in the pavement heat balance equation. Thermophysical properties of pavement materials reflect the heat conduction capacity of asphalt mixtures. Thermal conductivity governs the rate of heat transfer between layers, specific heat capacity influences the material's ability to store heat, and thermal diffusivity captures the overall rate of thermal propagation. These parameters directly determine the spatial and temporal gradients within the temperature field. Due to the inherent temperature sensitivity of asphalt materials, their thermophysical properties vary dynamically with temperature. Only by incorporating these parameters can the nonlinear evolution of pavement temperature fields across diurnal and seasonal cycles be accurately simulated. This, in turn, is essential for elucidating the coupling mechanisms between temperature-induced stresses and fatigue damage in asphalt pavements.

2.1 Surface heat exchange coefficient *Y*

The exchange of heat between asphalt pavement and the external environment occurs primarily through radiation and convection. Radiative heat transfer involves the exchange of energy between the pavement surface and its surroundings via electromagnetic waves. During daytime conditions, shortwave solar radiation is absorbed by the pavement surface, resulting in surface heating, while longwave radiation is simultaneously emitted toward the atmosphere and sky. At night, with the absence of solar input, the pavement cools mainly through longwave radiative emission to the cooler sky. The efficiency of radiative exchange is strongly influenced by the surface characteristics of the pavement. Dark-colored asphalt surfaces exhibit high absorptivity for solar radiation, thus heating more rapidly, while surface roughness and material emissivity govern the intensity of longwave radiation. Convective heat exchange refers to the transfer of heat between the pavement and ambient air through molecular motion and airflow. When the pavement surface temperature exceeds that of the surrounding air, heat is dissipated via natural or forced convection. The efficiency of convective heat transfer increases with higher wind speeds and larger temperature differentials between the pavement surface and ambient air. Together, radiation and convection determine the rate of energy exchange between the pavement surface and the external environment and constitute major external drivers of pavement temperature variation.

The surface heat exchange coefficient, denoted as Y, represents a comprehensive parameter reflecting the combined efficiency of radiative and convective heat transfer between the pavement and the environment. It quantifies the total heat flux per unit area per unit temperature difference between the pavement and the atmosphere. In temperature field simulations of asphalt pavements, the magnitude of Y directly affects the gain or loss of surface thermal energy. During summer daytime conditions, when solar radiation is intense, the absorbed radiative energy significantly exceeds heat losses via radiation and convection. Under such circumstances, the value of Y tends to be relatively low, resulting in rapid surface heating and the formation of a high-temperature layer. In contrast, during winter nights, the absence of solar radiation leads to substantial longwave radiative losses to the sky, compounded by convective cooling from cold air. This results in an increased Y value, causing a rapid decline in surface temperature and potentially triggering low-temperature shrinkage effects. The dark coloration of asphalt enhances solar absorptivity, while its porous and rough surface texture amplifies convective heat exchange. Consequently, the dynamic variation of Y is closely related to atmospheric conditions and surface characteristics. Specifically, the radiative heat exchange coefficient is denoted as Y_T, and the convective heat exchange coefficient is denoted as Y_j. The total surface heat exchange coefficient Y is expressed by the following equation:

$$Y = Y_t + Y_j \tag{1}$$

Assuming the temperature coefficient is denoted as J_o, it can be expressed by the equation $J_o = S^3{}_1 + S^2{}_1 S_2 + S_1 S^2{}_2 + S^3{}_2 / 10^8$; and the material coefficient is denoted as Z_o, it can be expressed by the equation $Z_o = 1/(1/Z_1 + 1/Z_2 - 1/Z_2)$. The emissivity coefficients of gray bodies are represented by Z_1, Z_2, and Z_3. The surface temperatures of two radiating bodies involved in thermal radiation exchange are represented by S_1 and S_2. The magnitude of J_o is primarily influenced by the values of S_1 and S_2. The radiative heat exchange coefficient Y_t can be calculated using the following formulation:

$$Y_t = Z_o J_o \tag{2}$$

Assuming that the temperature difference between the pavement surface and the adjacent air layer is denoted as ΔS, and the wind speed is denoted as n, then Y_j can be computed under the condition $n \leq 5.0$ m/s using the following empirical expression:

$$Y_j = 2.6\left(\sqrt[4]{\Delta S} + 1.54n\right) \tag{3}$$

The surface heat exchange coefficient Y is given by:

$$Y = Y_t + Y_j = Z_o J_o + 2.6\left(\sqrt[4]{\Delta S} + 1.54n\right) \tag{4}$$

2.2 Diurnal profile of total solar radiation *W*(*s*)

Total solar radiation $W(s)$ represents the primary external heat source for asphalt pavements. Its diurnal profile reflects the dynamic temporal variation of solar energy input and includes both direct and diffuse radiation components. As a dark and porous material, asphalt exhibits high absorptivity for solar radiation. Nearly all incident solar radiation is rapidly absorbed by the surface layer and converted into heat, resulting in a pronounced increase in surface temperature. The diurnal variation of $W(s)$ exhibits strong periodicity. Radiation intensity is low during early morning and late evening and reaches its peak near noon. This periodic thermal input serves as a dominant driver of the diurnal fluctuation observed in pavement temperature fields. In addition, $W(s)$ is affected by meteorological conditions and geographic location. These spatiotemporal attributes directly determine the magnitude and duration of heat input, making $W(s)$ one of the core boundary conditions in the development of dynamic temperature field models for asphalt pavements.

From a thermodynamic perspective, the analysis of $W(s)$ focuses on revealing its coupling relationship with pavement energy balance as an external heat source. While solar radiation is absorbed at the pavement surface, energy is simultaneously dissipated through surface heat exchange and conduction into the underlying layers, forming a dynamic "absorption–conduction–dissipation" equilibrium. The diurnal curve of $W(s)$ directly governs the net radiative energy acquired by the pavement per unit time. When $W(s)$ is high, the absorbed solar radiation exceeds the combined losses due to convective and radiative heat transfer, resulting in a net thermal gain that causes rapid surface temperature elevation and the formation of steep thermal gradients. Conversely, when $W(s)$ is low or approaches zero, the pavement predominantly loses heat through longwave radiative emission and convective exchange with the atmosphere, leading to a gradual temperature decline. By quantifying the time-dependent behavior of $W(s)$ and integrating it with parameters such as the surface convective heat transfer coefficient, ambient air temperature, and the thermal conductivity of pavement materials, a temperature field control equation based on the principle of energy conservation can be formulated. This enables the prediction of the internal temperature distribution of pavement structures at different times of day. Specifically, assuming the peak solar radiation intensity at noon is denoted by W_0, the diurnal variation of solar radiation can be approximated by the following function:

$$W(s)=\begin{cases}0,\left[0,\dfrac{\tau}{\mu}\left(1-\dfrac{l}{2}\right)\right]\\ W_0 COS l\mu(s-12),\left[\dfrac{\tau}{\mu}\left(1-\dfrac{l}{2}\right),\dfrac{\tau}{\mu}\left(1+\dfrac{l}{2}\right)\right]\\ 0,\left[\dfrac{\tau}{\mu}\left(1+\dfrac{l}{2}\right),\dfrac{2\tau}{\mu}\right]\end{cases} \tag{5}$$

Assuming that the duration of daily sunshine is denoted by z, and the total solar radiation received over the course of a day is represented by W_f, then W_0 can be calculated by the following expression:

$$W_0 = 0.131 l W_f, l = 12/z \tag{6}$$

In order to facilitate the direct incorporation of this function into the heat conduction differential equation, the time variable was defined as s, and $W(s)$ was expanded into a Fourier series:

$$\begin{aligned} W(s) &= \frac{W_0}{\tau}+\frac{W_0}{2} SIN \mu s \\ &+ \frac{2W_0}{\tau}\sum_{1-4j^2}^{\infty} SIN\left(2\mu s+\frac{\tau}{2}\right),(l=1) \end{aligned} \tag{7}$$

$$\begin{aligned} W(s) &= \frac{W_0}{l\tau}+\frac{2lW_0}{\tau} \\ &\sum_{j=1}^{\infty}\frac{COS\dfrac{\tau j}{2l}}{l^2-j^2} SIN\left(j\mu s+\frac{\tau}{2}-\frac{j\tau}{2}\right),(l\neq 1) \end{aligned} \tag{8}$$

2.3 Diurnal profile of ambient air temperature $S(s)$

The diurnal profile of ambient air temperature, denoted as $S(s)$, serves as a direct driving parameter for convective heat exchange between asphalt pavements and the atmospheric environment. Its periodic variation influences the surface temperature of the pavement through surface-air thermal exchange and further propagates inward through thermal conduction, thereby affecting the internal temperature distribution of the pavement structure layer by layer. From a thermodynamic perspective, when the pavement surface temperature exceeds the ambient air temperature, heat is dissipated from the pavement to the atmosphere via natural or forced convection. Conversely, when ambient air is warmer than the pavement surface, thermal energy is transferred from the air to the pavement. Due to the relatively low thermal conductivity of asphalt materials, the rate of heat transfer within the pavement structure is slow. As a result, surface temperature responds more rapidly to changes in air temperature, whereas temperature fluctuations at deeper layers exhibit a significant lag effect. For instance, during the daytime, as air temperature rises, convective heat transfer from the atmosphere to the pavement surface intensifies and combines with solar radiation to form a composite thermal input, accelerating surface temperature increase. At night, as air temperature decreases, the pavement loses heat through both convective and radiative processes, making $S(s)$ a critical boundary condition for the attenuation of the temperature field. The diurnal amplitude and phase of $S(s)$ directly determine the magnitude and timing of pavement temperature fluctuations. As such, it functions as a core environmental parameter in the formulation of dynamic temperature field models for asphalt pavements.

The thermophysical analysis of the diurnal profile of ambient air temperature $S(s)$ essentially aims to elucidate its role as a boundary condition within the pavement energy balance equation. The evolution of the pavement temperature field follows the law of conservation of energy, wherein the heat change within a unit volume equals the combined effect of net external thermal input and internal thermal conduction. The ambient air temperature $S(s)$ directly governs the direction and magnitude of convective heat exchange. In addition, $S(s)$ indirectly influences the radiative balance of the pavement surface by modulating the intensity of atmospheric longwave radiation. Higher atmospheric temperatures result in stronger longwave radiation emitted toward the pavement, while lower atmospheric temperatures lead to greater net radiative heat loss from the pavement to the atmosphere. When constructing temperature field models for asphalt pavements, $S(s)$ is treated as a time-dependent boundary condition. Along with total solar radiation $W(s)$ and the surface heat exchange coefficient Y, it forms part of the external thermal excitation input. This set of parameters drives the internal temperature distribution through the Fourier heat conduction equation. Specifically, let $S_1=(S_{MAX}+S_{MIN})/2$, and $S_2=(S_{MAX}-S_{MIN})/2$. The angular frequency is denoted by μ, and the initial phase by S_0. The diurnal variation of air temperature can then be expressed as:

$$\begin{aligned} S(s) &= S_1 \\ &+S_2\left(0.96SIN\left(\mu\left(s-s_0\right)\right)+0.146SIN\left(2\mu\left(s-s_0\right)\right)\right) \end{aligned} \tag{9}$$

To approximate the influence of effective radiation, the method of amplitude magnification for air temperature can be applied. Let Z_d denote the effective radiation coefficient, and let x_t represent the absorptivity of the pavement surface to solar radiation. The corresponding relationship can be described by:

$$S_x = S_1 + (S_2 + Z_d * x_t) * \begin{pmatrix} 0.96 * SIN(\mu * (s - s_0)) \\ +0.146 * SIN(2 * \mu * (s - s_0)) \end{pmatrix} \tag{10}$$

2.4 Estimation of ground temperature

Ground temperature serves as the lower thermophysical boundary condition for asphalt pavement structures and is a critical factor in understanding heat exchange between the pavement system and subsurface media. The pavement temperature field is not only driven by upper boundary conditions such as solar radiation and ambient air temperature but also influenced by the stability or variability of the subsurface thermal regime. Heat is continuously conducted downward through the base and subbase layers of the pavement, forming a thermal gradient characterized by "hot upper–cold lower" or "cold upper–hot lower" distributions, depending on the relative magnitudes of ground temperature and the temperature at the bottom of the pavement structure. Due to the relatively low thermal conductivity and high heat capacity of soils and other subsurface materials, the diurnal fluctuation of ground temperature is minimal, and a pronounced lag effect is typically observed. The core task in ground temperature estimation is the determination of the thermal flux boundary condition at the bottom of the pavement structure. When ground temperature is assumed to be constant, it may be treated as a steady-state thermal boundary. However, if seasonal or diurnal periodic variations in ground temperature are considered, it must be modeled as a dynamic boundary within an unsteady-state heat conduction framework. The choice of boundary condition directly affects the calculation of internal temperature gradients, particularly in long-term analyses of thermal stress accumulation or deep-layer heat retention. Accurate estimation of ground temperature is thus a prerequisite for constructing a complete pavement temperature field model.

From a thermodynamic perspective, ground temperature estimation is fundamentally an application of the energy conservation principle to establish thermal exchange equilibrium between the pavement structure and subsurface media. In the vertical direction, the heat conduction process in asphalt pavements can be regarded as a one-dimensional unsteady-state problem, in which the heat flux density at the bottom boundary is determined by the temperature difference between the ground and the bottom of the pavement, as well as the thermal conductivity of the materials involved. When ground temperature is lower than the bottom-layer pavement temperature, heat is transferred downward, forming a heat-dissipating boundary; the opposite condition may lead to heat gain from the subsurface. In practical analysis, ground temperature estimation must take into account local geological and climatic conditions. It may be derived through in situ measurements, empirical formulas, or numerical simulations. Specifically, let the annual average air temperature be represented by S_{1v}, with $S_{1v}=(S^{MAX}_{xv}+S^{MIN}_{xv})/2$, and the annual temperature amplitude by S_{2v}, with $S_{2v}=(S^{MAX}_{xv}+S^{MIN}_{xv})/2$(°C). The highest and lowest monthly average air temperatures are denoted by S^{MAX}_{xv} and S^{MIN}_{xv}, respectively. The angular frequency is represented by μ_v, with $\mu_v=2\tau$ / 365, and the v-th day of the year is denoted by s_v. The phase shift is given by ψ. The annual variation in temperature can then be approximated by the following sinusoidal expression:

$$S_{xv} = S_{1v} + S_{2v} SIN\left(\mu_v\left(s_v + \psi\right)\right) \tag{11}$$

Assuming that the annual temperature increase of the pavement due to absorbed solar radiation is denoted by S_W, and that the average daily heat accumulation at a given pavement depth caused by solar radiation is expressed as $((x_t W_0)/(\tau Y)$, where W_0 represents the annual average maximum solar radiation at noon, x_t denotes the pavement surface absorptivity for solar radiation, and Y is the annual average surface heat exchange coefficient. The annual heat loss coefficient due to effective radiation is denoted by F_D, and the annual heat consumption coefficient due to surface evaporation is denoted by F_M. Under these definitions, the actual annual heat accumulation in the pavement resulting from net solar radiation can be calculated by the following expression:

$$S_W = \frac{x_t W_0}{\tau Y} \cdot F_D F_M \tag{12}$$

If a homogeneous semi-infinite medium is used as the model, and the depth from the pavement surface to the calculation point is represented by b, the theoretical solution for ground temperature can be expressed as:

$$\begin{aligned} S_v &= S_W + S_{1v} + S_{2v}\exp(-bt) \\ &SIN\left[\mu_v\left(s_v + 252\right) - bt\right] \end{aligned} \tag{13}$$

2.5 Thermophysical parameters of pavement materials (*FENIX*)

The thermal conductivity λ, specific heat capacity C, and thermal diffusivity α are the core parameters determining the heat conduction characteristics within asphalt pavement structures. The analysis of these thermophysical properties aims to reveal the intrinsic mechanisms by which material properties influence the distribution of the temperature field. Thermal conductivity λ characterizes a material's ability to conduct heat along the direction of thermal flux and directly governs the rate at which heat is transferred across pavement layers. Higher values of λ indicate stronger heat penetration capacity and a smaller internal temperature gradient. Conversely, materials with low λ values act as thermal resistors, resulting in substantial temperature differences between surface and deeper layers. Specific heat capacity C reflects a material's ability to store thermal energy. A larger C implies that more energy is required to raise the temperature of a unit mass, thereby moderating the rate of temperature change. Thermal diffusivity α, defined as $\alpha=\lambda/(\rho C)$, where ρ denotes material density, encapsulates the relationship between thermal conduction and thermal storage. A higher α indicates faster heat propagation within the material and a tendency toward thermal homogenization, while a lower α implies a delayed temperature response. These parameters directly enter the formulation of the pavement heat conduction model via Fourier's law and the energy conservation equation and serve as fundamental inputs for accurately capturing the spatial and temporal evolution of the temperature field.

The essence of thermophysical parameter analysis lies in uncovering the coupling effects of λ, C, and α under unsteady-state heat conduction. Under daytime conditions, with both solar radiation and ambient air temperature contributing to thermal input, the heat absorbed at the pavement surface propagates downward through conduction. During this process, λ determines the heat flux density, C governs the thermal accumulation capacity of each structural layer, and α controls the attenuation rate and penetration depth of the thermal wave. For example, due to relatively low λ and α, asphalt surface layers can develop steep temperature gradients of 10–15 K/m, resulting in significant thermal stresses between the surface and underlying layers. In contrast, base materials with higher λ are able to rapidly redistribute heat, reducing deep-layer thermal fluctuation. During nocturnal cooling phases, the value of C determines the rate at which stored heat is released. Materials with high C require longer cooling durations, thereby prolonging the cooling process of the pavement structure. Furthermore, differences in thermophysical parameters across pavement layers can lead to abrupt changes in thermal resistance at material interfaces, causing discontinuities in the temperature distribution and intensifying interlayer thermal stress concentrations. By quantitatively analyzing the temperature dependence and frequency dependence of λ, C, and α, dynamic temperature field models can be constructed with higher accuracy, providing a thermodynamic foundation at the material scale for predicting temperature-sensitive distresses such as high-temperature rutting and low-temperature cracking in asphalt pavements.

3. EVALUATION OF THE TEMPERATURE–FATIGUE PERFORMANCE RELATIONSHIP IN ASPHALT PAVEMENTS

Fatigue damage in asphalt mixtures fundamentally involves the initiation, propagation, and eventual coalescence of internal microcracks, culminating in macroscopic failure. This progressive degradation is accompanied by a decline in mechanical performance, and the reduction of the stiffness modulus serves as a direct indicator of such deterioration. As a viscoelastic material, the stiffness modulus of asphalt mixtures reflects their overall resistance to deformation and is highly sensitive to environmental conditions such as temperature and loading frequency. At low temperatures, asphalt mixtures exhibit elastic behavior characterized by a high stiffness modulus and a prompt stress response. At elevated temperatures, viscous components dominate the material response, leading to a significant decrease in stiffness modulus as the duration of loading increases. Under repeated fatigue loading, even with constant strain amplitude, internal damage continues to accumulate, causing a gradual reduction in the stiffness modulus. This degradation trend corresponds closely with the evolution of microstructural defects. In the early stages of loading, the modulus decreases slowly. As damage intensifies, the rate of decline accelerates until the modulus reaches approximately 50% of its initial value. For this reason, the stiffness modulus was adopted as a damage variable, enabling both the capture of viscoelastic property changes under cyclic loading and the precise identification of fatigue failure points by quantifying the degree of modulus decay, providing a readily observable and quantifiable macroscopic physical parameter for evaluating the relationship between temperature conditions and fatigue performance in asphalt pavements.

The combined effect of thermal cycling and vehicular loading creates a complex fatigue environment in asphalt pavements. The temperature dependence of the stiffness modulus renders it a critical link between the pavement temperature field and fatigue performance. Based on the standard four-point bending fatigue test, the degradation curves of the stiffness modulus under varying temperature conditions reveal the mechanisms through which temperature influences fatigue damage evolution. In low-temperature environments, asphalt mixtures exhibit higher stiffness modulus values, with fatigue behavior dominated by elastic deformation. This leads to slower modulus degradation and longer fatigue life. In contrast, under high-temperature conditions, the viscosity of the asphalt binder decreases, promoting viscoelastic behavior. The initial stiffness modulus becomes lower, and its degradation rate increases significantly, resulting in a shorter fatigue life. By incorporating temperature as a variable into the modulus degradation model, a three-dimensional relationship among temperature, load repetitions, and modulus degradation can be established, allowing for quantification of fatigue damage under various temperature field distributions. For example, in pavement structures with pronounced thermal gradients, the modulus disparity between the high-temperature surface layer and the low-temperature base can cause interlayer stress concentrations, accelerating fatigue damage. Modulus-based evaluation methods, when combined with measured temperature field data, enable the prediction of fatigue life across structural layers subjected to thermal cycling. This provides a foundation for selecting materials and optimizing structural combinations in asphalt pavement design, facilitating a transition from purely mechanical fatigue assessment to a coupled thermo-mechanical fatigue performance evaluation. Specifically, let the stiffness modulus of the asphalt mixture be denoted by T, stress by σ, strain by γ, loading time by s, and test temperature by S. The stiffness modulus is expressed as:

$$T_{(S,s)} = \left(\frac{\sigma}{\gamma}\right)_{(S,s)} \tag{14}$$

The viscoelastic properties of asphalt mixtures inherently lead to energy dissipation under temperature cycling or loading conditions. This dissipated energy serves as a thermodynamic metric of internal structural damage evolution. When temperature changes cause expansion or contraction in the pavement structure, thermal stresses induce cyclic elastic–viscous deformation in the material. During the loading phase, part of the energy is stored as elastic strain energy, while the remainder is dissipated as heat due to viscous effects or consumed in the extension of microcracks. During unloading, the elastic energy is released; however, if internal damage has occurred, the loading–unloading curve no longer closes, and the increase in dissipated energy becomes evident. In low-temperature conditions, the elastic behavior of asphalt mixtures dominates. If the thermal stress-induced elastic energy exceeds the material's storage limit, it may suddenly convert into surface energy for crack propagation, leading to brittle fracture. Under high-temperature conditions, viscous flow becomes the primary deformation mechanism. Dissipated energy in this case predominantly manifests as viscous frictional losses, resulting in progressive fatigue degradation. Thus, the accumulation of dissipated energy inherently couples thermal stress variations with microstructural damage in the material. Its magnitude directly reflects the extent and rate of fatigue damage.

From the perspective of energy conservation, temperature-induced fatigue in asphalt pavements can be regarded as a cumulative process of dissipated energy under repeated temperature differential loading cycles ΔS. The Miner linear damage rule provides a quantitative framework to describe this accumulation effect. Assuming that a single temperature differential cycle ΔS generates a unit of dissipated energy Q_0, and that the corresponding fatigue life of the material under this condition is V_d, the total damage F under a complex service temperature history can be expressed as the sum of dissipated energy contributions across all thermal loading cycles. This approach transcends the limitations of traditional mechanical indicators by directly linking the frequency and amplitude of temperature cycles to the viscoelastic dissipative behavior of the material. For example, high-frequency, low-amplitude thermal fluctuations may result in linearly accumulated damage due to dominant viscous dissipation, while low-frequency, high-amplitude temperature variations may lead to sudden crack initiation driven by the concentrated release of elastic strain energy. By experimentally obtaining dissipated energy versus load cycle curves under various temperature conditions and combining them with the actual pavement temperature field distribution, a quantitative relationship model can be established that captures the chain of processes from "thermal loading – energy dissipation – fatigue failure." This framework provides a unified energy-based criterion for evaluating the fatigue life of asphalt pavements in temperature-sensitive regions. Specifically, the cumulative dissipated energy in the fatigue process of asphalt pavements can be calculated by:

$$Q_d = V_d Q_0 \tag{15}$$

The energy dissipated in each temperature cycle S is given by the area of the corresponding hysteresis loop, expressed as:

$$Q_u = \int_0^S \delta(s)\gamma(s)\, fs \tag{16}$$

The total energy consumption at failure is calculated as:

$$Q_d = \sum_{u=1}^{V_d} Q_u \tag{17}$$

The following equations related to dissipated energy were introduced to evaluate three key indicators of temperature-induced fatigue performance in asphalt pavements:

a) Dissipated energy ratio method

The dissipated energy ratio method evaluates the fatigue damage contribution of a single temperature cycle by calculating the ratio of dissipated energy per cycle to the material's critical dissipated energy. This metric captures the instantaneous impact of an individual thermal load on fatigue degradation. Due to the viscoelastic behavior of asphalt mixtures, temperature cycling results in a non-closed stress–strain hysteresis loop. The enclosed area of each loop corresponds to the dissipated energy for that specific cycle, while the critical dissipated energy represents the total energy loss accumulated from the undamaged state to fatigue failure. The ratio of per-cycle dissipated energy to the critical value offers a direct means to quantify the damage weight of a single cycle under a given temperature difference ΔS and thermal condition. For instance, under low-temperature environments, thermal stress-induced elastic strain energy may be rapidly converted into surface energy for crack initiation, causing a higher per-cycle energy ratio. This indicates that low-temperature extremes significantly accelerate fatigue damage. In contrast, under high-temperature conditions, although absolute dissipated energy may increase due to enhanced viscous flow, the extended fatigue life of the material results in a relatively lower per-cycle energy ratio. Assuming the u-th loading cycle is denoted by u, and the dissipated energy for that cycle is represented as Q_u, the equation is as follows:

$$FRE = \frac{u \bullet Q_1}{Q_u} \tag{18}$$

b) Cumulative dissipated energy ratio method

The cumulative dissipated energy ratio method is founded on the principle of linearly additive damage. It evaluates the fatigue damage accumulation in asphalt pavements by comparing the total energy dissipated under various thermal cycles with the total energy capacity that the material can endure under corresponding temperature conditions. This approach allows the cumulative degree of fatigue damage to be quantitatively assessed. In service, pavements are subjected to a wide range of temperature fluctuations. Each thermal cycle leads to a certain degree of energy dissipation. Over time, these energy losses accumulate until the material's energy-bearing capacity is exceeded, resulting in fatigue failure. For example, frequent small-amplitude diurnal temperature cycles may gradually contribute to damage through repeated low-level energy dissipation, while occasional large-amplitude seasonal temperature variations may rapidly accelerate damage due to high-energy loss in single events. By integrating energy dissipation data across different temperature conditions and incorporating actual pavement temperature histories, this method enables dynamic assessment of fatigue damage under multi-source thermal loading, thereby offering a comprehensive energy-based criterion for predicting pavement service life and informing maintenance strategies.

$$ZFRE = \frac{\sum_{v=1}^{u} Q_v}{Q_u} \tag{19}$$

c) Dissipated energy rate of change method

The dissipated energy rate of change method identifies fatigue damage progression in asphalt mixtures by evaluating the increase in energy loss per unit loading cycle, thereby revealing the influence of temperature on the rate of damage evolution. In the early stages of fatigue, the internal structure of the material remains largely intact, and energy dissipation primarily occurs through viscous friction, resulting in a relatively stable dissipation rate. As the number of thermal cycles increases, microcrack initiation and propagation begin to dominate, leading to a gradual acceleration in energy loss. Near the point of failure, the rapid expansion of cracks causes a sharp increase in energy dissipation. Temperature significantly affects this progression. Under low-temperature conditions, the material exhibits greater elasticity, and crack propagation may occur abruptly, leading to sudden jumps in the dissipation rate. In contrast, at higher temperatures, viscous behavior prevails, resulting in gradual crack development and a more moderate increase in dissipation rate. By monitoring the rate of energy loss under different temperature conditions, critical temperature intervals associated with accelerated damage can be identified. This enables targeted optimization of material design and facilitates precise control over temperature-sensitive fatigue damage. Let the average rate of change in dissipated energy between cycle y and cycle x be denoted by $EFRZ_y$, and let Q_x and Q_y represent the dissipated energy at loading cycles x and y, respectively. The equation is as follows:

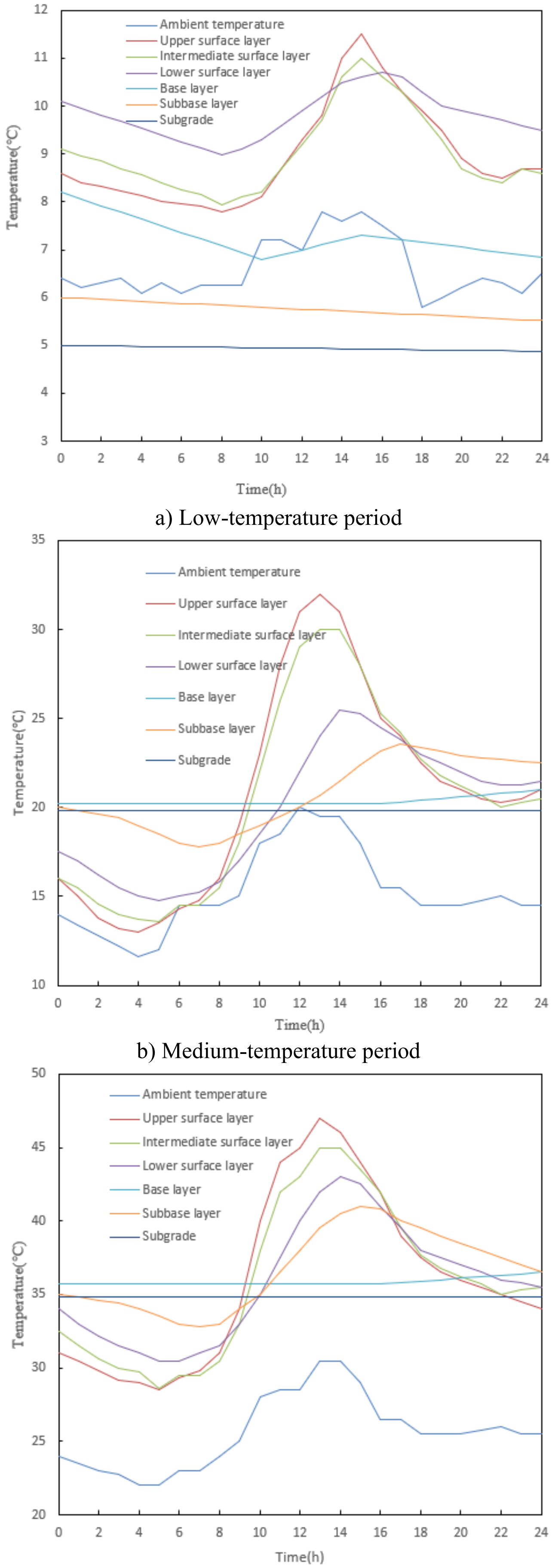
$$EFRZ_y = \frac{Q_y - Q_x}{Q_x \bullet (y - x)} \tag{20}$$

Based on dissipated energy theory, and denoting fatigue life as V_d, the corresponding temperature–fatigue relationship can be described by the following expression:

$$Q = 2.2070 \times 10^{-4} \times V_d^{\,0.4505}, \quad (E = 0.8636, V = 22) \tag{21}$$

4. EXPERIMENTAL RESULTS AND ANALYSIS

As shown in Figure 2, the asphalt pavement temperature field distribution was recorded during low-, medium-, and high-temperature periods. In the low-temperature period (Figure 2(a)), ambient temperature remained low with minimal fluctuation, and the temperature across all structural layers was relatively low overall. Some variation was observed in the upper and intermediate surface layers, while the lower surface layer, base, subbase, and subgrade temperatures remained relatively stable. During the medium-temperature period (Figure 2(b)), ambient temperature increased and exhibited greater volatility. The temperature of the upper surface layer rose rapidly at midday and was significantly higher than that of other structural layers. Noticeable temperature variation occurred in both the intermediate and lower surface layers, whereas the base, subbase, and subgrade temperatures showed limited fluctuation but trended upward overall. In the high-temperature period (Figure 2(c)), ambient temperature was higher. The upper surface layer exhibited the highest midday temperature, far exceeding that of other layers. Both the intermediate and lower surface layers experienced substantial temperature increases, while the base, subbase, and subgrade exhibited relatively minor variations in comparison with the surface layers. The experimental results indicate that the surface layers, particularly the upper surface layer, are highly sensitive to environmental temperature fluctuations. Pronounced temperature variations during medium- and high-temperature periods were attributed to the thermophysical properties of asphalt mixtures, which enable rapid heat absorption and dissipation. In contrast, the base, subbase, and subgrade layers were only minimally affected by environmental fluctuations and remained relatively thermally stable. These spatial differences in temperature field distribution have significant implications for fatigue performance. Surface layers are more susceptible to fatigue damage due to repeated temperature fluctuations. Rapid thermal variation during high-temperature periods accelerates aging and degradation of the asphalt mixture, while thermal stress during low-temperature periods may induce surface cracking. Consequently, when developing computational models for asphalt pavement temperature fields and predicting fatigue performance, particular attention must be given to temperature variations in the surface layers and their role in fatigue damage evolution.



a) Low-temperature period

b) Medium-temperature period

c) High-temperature period

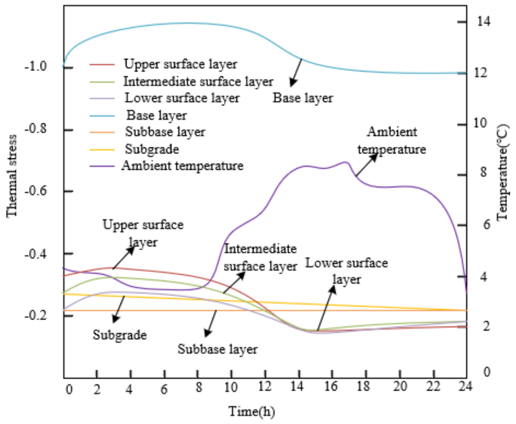
Figure 2. Temperature field distribution of asphalt pavement during low-, medium-, and high-temperature periods

Table 1. Verification of asphalt pavement temperature prediction

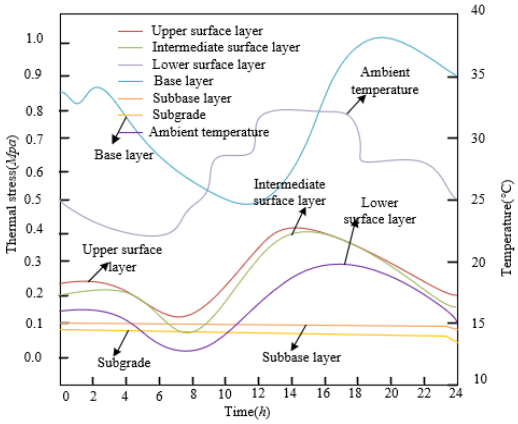
Time	Predicted Temperature (°C) at 2.6 cm	Error (%)	Predicted Temperature (°C) at 7.6 cm	Error (%)	Predicted Temperature (°C) at 11 cm	Error (%)	Predicted Temperature (°C) at 16 cm	Error (%)
1	28.9	22.6	32.4	21.8	34.8	17.5	35.6	15.8
2	26.5	25.4	31.5	21.5	36.2	18.5	34.5	15.6
3	25.4	21.8	32.8	22.6	33.5	22.6	32.8	14.8
4	24.3	17.5	31.5	21.4	32.8	21.4	31.5	17.9
5	25.8	21.6	31.2	21.8	32.5	21.8	32.8	16.5
6	26.9	23.5	31.6	21.5	31.6	23.5	31.5	15.2
7	28.9	22.6	31.8	22.6	31.8	24.8	31.2	13.4
8	32.8	22.5	32.5	22.6	31.5	24.6	31.5	13.8
9	33.5	14.8	32.8	18.9	32.8	21.6	31.6	11.5
10	37.8	8.3	34.6	12.4	33.4	17.8	32.8	12.4
11	42.6	-1.6	36.8	5.2	34.6	8.1	31.6	9.1
12	42.4	-5.2	38.9	1.4	35.8	4.4	33.8	5.5
13	44.1	-8.2	41.5	-3.2	36.2	-1.4	35.4	5.7
14	45.6	-9.2	41.8	-5.8	37.8	-5.4	37.6	3.7
15	45.7	-12.5	41.5	-7.5	39.5	-7.2	41.2	2.8
16	44.2	-12.4	41.5	-8.2	41.2	-8.2	42.6	2.1
17	42.6	-9.2	41.5	-6.4	41.5	-8.5	41.2	2.6
18	41.8	-0.1	42.6	-4.2	41.6	-6.1	41.5	2.5
19	41.5	6.1	41.5	-0.7	38.5	-3.7	42.5	4.1
20	37.8	11.5	38.9	2.8	38.4	-1.7	41.8	4.2
21	35.6	13.4	37.5	6.3	37.6	2.6	41.6	6.1
22	33.5	12.8	36.5	8.4	36.5	5.2	38.5	6.3
23	32.1	14.9	35.4	12.8	36.4	12.5	37.4	6.4
24	32.5	18.9	34.8	17.8	35.5	17.6	36.5	6.5

Table 1 presents the predicted temperatures and corresponding percentage errors at various depths (2.6 cm, 7.6 cm, 11 cm, and 16 cm) within the asphalt pavement at different time intervals. For example, at time 1, the predicted temperature at a depth of 2.6 cm was 28.9°C, with an associated error of 22.6%, while at 7.6 cm the predicted temperature was 32.4°C, with an error of 21.8%. As time progressed, significant variations were observed in both the predicted temperatures and their associated errors across all depths. At time 15, the error at 2.6 cm reached -12.5%, and at 7.6 cm was -7.5%, whereas at time 20, the errors at the same depths shifted to 11.5% and 2.8%, respectively. Overall, the predicted temperatures differed notably across depths and time points, with both positive and negative errors of varying magnitudes. These findings suggest that the predictive accuracy of the pavement temperature field model fluctuates over time and depth, reflecting the inherent complexity introduced by multi-factor coupling. The surface layer, being in direct contact with the external environment, exhibited high sensitivity to temperature variations, leading to more pronounced error fluctuations. This indicates that the model is significantly influenced by the dynamic temperature dependence of the thermophysical properties of asphalt mixtures when capturing rapid surface responses. Fluctuations in error were also observed at deeper layers, suggesting that temperature predictions at these depths are similarly affected by factors such as aggregate gradation and asphalt binder type. These errors provide valuable insights for model refinement. Specifically, they highlight the necessity of incorporating more precise representations of how thermophysical parameters vary with temperature and material composition, improving the accuracy of temperature field predictions under complex multi-factor coupling conditions.

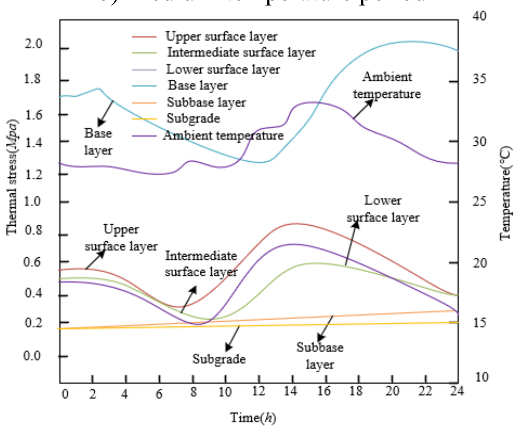
Figure 3 illustrates the temperature-induced stress fields within asphalt pavement during low-, medium-, and high-temperature periods. During the low-temperature period (Figure 3(a)), ambient temperature remained low with minimal fluctuation. The base layer exhibited relatively high and stable thermal stress, while the upper and intermediate surface layers showed minor fluctuations in stress levels. In the medium-temperature period (Figure 3(b)), both ambient temperature and its fluctuation range increased. The base layer continued to exhibit prominent thermal stress values, whereas the upper, intermediate, and lower surface layers displayed distinct temporal variation trends in thermal stress. During the high-temperature period (Figure 3(c)), ambient temperature rose further, and thermal stress levels increased significantly across all structural layers. In particular, the upper, intermediate, and lower surface layers experienced markedly intensified stress fluctuations. The experimental results demonstrate that the spatial distribution of thermal stress fields varied substantially across different temperature periods. The surface layers were shown to be highly sensitive to environmental temperature changes, exhibiting large thermal stress fluctuations, especially during medium- and high-temperature periods. This sensitivity is attributed to the direct exposure of the surface layers to ambient conditions and the strong influence of temperature on asphalt material behavior. The base layer maintained a consistently high level of thermal stress, even under low-temperature conditions, and remained a critical contributor to the structural stress field across all periods. In contrast, the subbase and subgrade layers exhibited relatively stable stress responses with minimal fluctuations. These differences in thermal stress distribution have significant implications for fatigue performance. The surface and base layers are more susceptible to fatigue damage due to the repeated action of thermal stress. Elevated stress fluctuations during medium- and high-temperature periods can accelerate damage evolution. Therefore, when constructing predictive models of pavement temperature fields and fatigue performance, it is essential to account for the dynamic variation in thermal stress across all structural layers. Such consideration is critical for accurately assessing fatigue resistance and for providing a scientific basis for pavement design and maintenance strategies.



a) Low-temperature period



b) Medium-temperature period



c) High-temperature period

Figure 3. Temperature-induced stress fields of asphalt pavement during low-, medium-, and high-temperature periods

As shown in Table 2, the temperature-induced stress level in January in the arid regions of North and Northwest China reached 0.526, with a corresponding fatigue life of 1,895 cycles. By May, the stress level had increased to 0.736, while the fatigue life decreased sharply to 428 cycles. The fatigue life was estimated to be 3.3 years. In Table 3, the coastal regions of South China exhibited a stress level of 0.624 in January, with a fatigue life of 1,124 cycles, while in November, the stress level rose to 0.817 and the fatigue life dropped drastically to 268 cycles, resulting in a fatigue life of 2.8 years. In contrast, Table 4 indicates that the high-altitude cold regions of the Qinghai–Tibet Plateau experienced a stress level of 0.513 in January with a fatigue life of 2,465 cycles; in March, the stress level was 0.562, and the fatigue life was 1,425 cycles. The calculated fatigue life in this region reached 13.5 years. A clear negative correlation can be observed between the temperature-induced stress level and the fatigue life across all regions and months, with significant differences in fatigue life years between regions. Higher thermal stress levels are associated with a marked reduction in fatigue life, confirming that temperature-induced stress is a critical factor influencing asphalt pavement fatigue performance. The longest fatigue life was observed in the Qinghai–Tibet Plateau region, attributed to the relative thermal stability of asphalt materials under low-temperature conditions and minimal fluctuation in thermal stress levels. In contrast, the shortest fatigue life occurred in the coastal regions of South China, where substantial fluctuations in temperature-induced stress were found to accelerate the evolution of material damage. The arid regions of North and Northwest China exhibited intermediate behavior. These results highlight the significant influence of regional climatic conditions on asphalt pavement fatigue performance, primarily through their impact on the thermal stress field.

Table 2. Temperature-induced fatigue analysis of asphalt pavement in arid regions of North and Northwest China

Month	Temperature-Induced Stress Level	Fatigue Life (Cycle)
January	0.526	1895
February	0.554	1678
March	0.623	1235
April	0.678	635
May	0.736	428
October	0.724	465
November	0.628	1326
December	0.615	1125
Fatigue life (year)	3.3	

Table 3. Temperature-induced fatigue analysis of asphalt pavement in the coastal regions of South China

Month	Temperature-Induced Stress Level	Fatigue Life (Cycle)
January	0.624	1124
February	0.758	379
March	0.562	1456
October	0.612	1235
November	0.817	268
December	0.754	362
Fatigue life (year)	2.8	

Table 4. Temperature-induced fatigue analysis of asphalt pavement in high-altitude cold regions of the Qinghai–Tibet Plateau

Month	Temperature-Induced Stress Level	Fatigue Life (Cycle)
January	0.513	2465
February	0.438	5689
March	0.562	1425
October	0.612	1236
November	0.428	8237
December	0.439	5426
Fatigue life (year)	13.5	

5. CONCLUSION

In this study, the relationship between asphalt pavement temperature field distribution and fatigue performance was comprehensively investigated in two aspects. First, based on theoretical analysis and experimental testing, the variations in thermophysical parameters—such as thermal conductivity and specific heat capacity—were examined as functions of temperature, aggregate gradation, and asphalt type. A multi-factor coupled computational model for the asphalt pavement temperature field was thereby established. Second, fatigue damage evolution in asphalt mixtures under different thermal conditions was evaluated by integrating laboratory fatigue testing with numerical simulation, leading to the construction of a fatigue performance prediction model grounded in thermodynamic principles. The results revealed a strong correlation between temperature-induced stress levels and fatigue life, with significant regional variability driven by climatic conditions. For instance, prolonged fatigue life was observed in high-altitude, cold regions of the Qinghai–Tibet Plateau, while considerably shorter fatigue life was noted in the coastal regions of South China.

By integrating thermodynamic theory with fatigue performance analysis of asphalt pavements, this study addressed notable gaps in current research, particularly in the dynamic simulation of temperature fields and the mechanistic interpretation of fatigue damage, providing a more rigorous and accurate theoretical foundation and technical support for the design, construction, and maintenance of asphalt pavements. The findings carry both theoretical significance and engineering value in extending the service life and enhancing the long-term performance of pavements. Nevertheless, certain limitations remain. The parameterization of the model may not fully capture the complexity of real-world environmental interactions, and the depiction of multi-factor coupling effects requires further refinement. Future research is encouraged to enhance the understanding of multi-physical field interactions and to incorporate a broader range of in-situ measurements to improve model calibration. Expanding the model's applicability to a wider range of extreme climatic conditions will further strengthen its generalizability and predictive accuracy, thereby advancing the development of resilient asphalt pavement technologies.

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REFERENCES

[1] Azadgoleh, M.A., Mohammadi, M.M., Ghodrati, A., Sharifi, S.S., et al. (2022). Characterization of contaminant leaching from asphalt pavements: A critical review of measurement methods, reclaimed asphalt pavement, porous asphalt, and waste-modified asphalt mixtures. Water Research, 219: 118584. https://doi.org/10.1016/j.watres.2022.118584

[2] Chantachot, T., Kongkitkul, W., Youwai, S., Jongpradist, P. (2016). Behaviours of geosynthetic-reinforced asphalt pavements investigated by laboratory physical model tests on a pavement structure. Transportation Geotechnics, 8: 103-118. https://doi.org/10.1016/j.trgeo.2016.03.004

[3] Naderi, K., Moghadas Nejad, F., Khodaii, A. (2018). Time-temperature-age superposition validation for linear viscoelastic properties of bituminous materials. Journal of Materials in Civil Engineering, 30(2): 04017292. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002162

[4] Terzi, S., Saltan, M., Karahancer, S., Malkoc, G., Divrik, T., Ergezer, F., Eriskin, E., Erten, K.M. (2024). Long-term aging of recycled asphalt pavements: the influence of meteorological conditions on bitumen properties over 16 years. Journal of Civil and Hydraulic Engineering, 2(4): 250-257. https://doi.org/10.56578/jche020405

[5] Si, W., Ma, B., Ren, J., Hu, Y., Zhou, X., Tian, Y., Li, Y. (2020). Temperature responses of asphalt pavement structure constructed with phase change material by applying finite element method. Construction and Building Materials, 244: 118088. https://doi.org/10.1016/j.conbuildmat.2020.118088

[6] Liu, Y., Qian, Z., Hu, H. (2016). Thermal field characteristic analysis of steel bridge deck during high-temperature asphalt pavement paving. KSCE Journal of Civil Engineering, 20(7): 2811-2821. https://doi.org/10.1007/s12205-016-0027-2

[7] Baykal, T., Ergezer, F., Eriskin, E., Terzi, S. (2024). Impact of meteorological factors on asphalt pavement surface temperatures: A machine learning approach. Journal of Civil and Hydraulic Engineering, 2(2): 100-108. https://doi.org/10.56578/jche020203

[8] Mazurek, G., Buczyński, P., Iwański, M., Podsiadło, M. (2021). Thermal analysis-based field validation of the deformation of a recycled base course made with innovative road binder. Materials, 14(20): 5925. https://doi.org/10.3390/ma14205925

[9] Si, C., Chen, E., You, Z., Zhang, R., Qiao, P., Feng, Y. (2019). Dynamic response of temperature-seepage-stress coupling in asphalt pavement. Construction and Building Materials, 211: 824-836. https://doi.org/10.1016/j.conbuildmat.2019.03.183

[10] McCartney, J.S., Khosravi, A. (2013). Field-monitoring system for suction and temperature profiles under pavements. Journal of performance of constructed facilities, 27(6): 818-825. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000362

[11] Sok, T., Chhay, L., Lee, S.W., Kim, Y.K. (2023). Insulation effects of asphalt concrete overlay on concrete pavement temperature. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 47(4): 2521-2531. https://doi.org/10.1007/s40996-023-01037-6

[12] Izaks, R., Gebauere, L., Kornisovs, R., Haritonovs, V. (2022). Laboratory evaluation of the properties of dense graded asphalt mixtures containing waste glass Fibre and crumb rubber. The Baltic Journal of Road and Bridge Engineering, 17(2): 164-184. https://doi.org/10.7250/bjrbe.2022-17.564

[13] Carreno Gomez, N.H., Oeser, M. (2021). Investigation on the use of a novel chemical bitumen additive with reclaimed asphalt and at lower mix production and construction temperatures: A case study. Road Materials and Pavement Design, 22(sup1): S641-S661. https://doi.org/10.1080/14680629.2021.1900897

[14] Nalbandian, K.M., Carpio, M., Gonzalez, A. (2022).

Assessment of the sustainability of asphalt pavement maintenance using the microwave heating self-healing technique. Journal of Cleaner Production, 365: 132859. https://doi.org/10.1016/j.jclepro.2022.132859
[15] Athukorallage, B., Dissanayaka, T., Senadheera, S., James, D. (2018). Performance analysis of incorporating phase change materials in asphalt concrete pavements. Construction and Building Materials, 164: 419-432. https://doi.org/10.1016/j.conbuildmat.2017.12.226
[16] Bell, H.P., Howard, I.L., Freeman, R.B., Brown, E.R. (2012). Evaluation of remaining fatigue life model for hot-mix asphalt airfield pavements. International Journal of Pavement Engineering, 13(4): 281-296. https://doi.org/10.1080/10298436.2011.566925
[17] Bańkowski, W. (2018). Evaluation of fatigue life of asphalt concrete mixtures with reclaimed asphalt pavement. Applied Sciences, 8(3): 469. https://doi.org/10.3390/app8030469
[18] Maschauer, D., Mirwald, J., Hofko, B. (2022). Viennese Ageing Procedure (VAPro): adaptions and further development to address low-temperature performance of aged asphalt mixtures. Road Materials and Pavement Design, 23(sup1): 147-161. https://doi.org/10.1080/14680629.2022.2029547
[19] Cheng, H., Liu, J., Sun, L., Liu, L. (2021). Critical position of fatigue damage within asphalt pavement considering temperature and strain distribution. International Journal of Pavement Engineering, 22(14): 1773-1784. https://doi.org/10.1080/10298436.2020.1724288