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# Development and Application of Climate Zoning for Asphalt Pavements in China: A Review and Perspective

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## Abstract

Asphalt pavements are highly sensitive to climatic conditions, and their performance and longevity are significantly affected by temperature fluctuations, precipitation, and extreme weather events. With increasing climate variability, the development of refined and adaptive climate zoning systems for pavement engineering has become essential. This study reviews the evolution, methodologies, and applications of asphalt pavement climate zoning in China. First, it delineates the historical progression of climate zoning into three stages, from general natural zoning to the specialized three-indicator model and performance grade (PG) system, and finally to refined spatial processing based on meteorological data. Notably, 48% of provinces have conducted localized zoning studies, with South and Northeast China as key focus areas. Second, this study classifies existing zoning models into three major categories: the traditional three-indicator model (based on high temperature, low temperature, and precipitation), the hydrothermal coefficient model tailored to hot, humid climates, and clustering models incorporating spatial interpolation and multivariate analysis. While the three-indicator model remains the most widely applied due to its simplicity, it may result in coarse divisions in climatically diverse regions. The hydrothermal model offers general guidance but limited accuracy, whereas clustering methods provide high-resolution, adaptive zoning results at the cost of increased computational complexity. Third, the application of climate zoning results to the PG system for asphalt binder classification is analyzed. Although SHRP, LTPP, and C-SHRP formulas are commonly used, C-SHRP tends to overestimate pavement temperatures by 6.0–8.6 °C in China. Approximately 68.8% of studies rely on existing formulas, while 31.2% propose localized conversions to improve PG grading accuracy. Overall, this review identifies both the methodological diversity and key challenges in China's climate zoning practices and provides a scientific foundation for more performance-oriented, climate-resilient pavement design strategies.

**Keywords:** asphalt pavement; climate zoning; performance grade (PG); clustering analysis; temperature conversion; China

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## 1. Introduction

Throughout its service life, asphalt pavement is constantly exposed to a complex natural environment, being subjected to various climatic factors, such as temperature fluctuations, precipitation frequency, solar radiation, and freeze–thaw cycles. These external conditions contribute to various forms of performance degradation and structural distresses, severely impacting pavement's durability and operational safety [1,2]. For example, high summer temperatures can cause asphalt mixtures to soften and deform, leading to rutting; conversely, sudden drops in temperature during winter often result in thermal contraction cracks. Additionally, frequent or extreme rainfall events can induce moisture-related damage, which may weaken the substructure, compromise structural integrity, and even cause asphalt layer delamination. Therefore, developing a scientifically sound and rational climate zoning system is essential in pavement engineering design and maintenance. Such a system offers critical guidance for material selection and the structural optimization of asphalt pavements, thereby enhancing performance, extending service life, and reducing maintenance costs over pavement's life cycle.

Climate zoning refers to the classification and regionalization of geographical areas based on the spatiotemporal variations in major climatic variables, such as temperature, humidity, precipitation, and wind speed. It aims to provide a systematic understanding of regional climate patterns and serve the specific needs of various sectors [3]. The concept of climate zoning can be traced back to ancient Greece, where the Earth's surface was divided into five principal climate zones. With the continuous accumulation of global climate observation data and the advancement of spatial information technologies, climate zoning has evolved from broad-scale classifications to refined, application-oriented systems at micro scales. This evolution has given rise to various specialized zoning frameworks, including agro-climatic zones, architectural climate regions, and highway climate divisions.

Global research on climate zoning for asphalt pavements exhibits strong regional adaptability, with climate-diverse countries developing differentiated technical frameworks based on local conditions. In North America, the performance grade (PG) grading system serves as the core framework. The performance-oriented system developed under the U.S. Strategic Highway Research Program (SHRP) program [4] and long-term performance studies under Canada's C-SHRP initiative [5] have confirmed the significant interaction between overlay thickness and climate–subgrade conditions. Localized temperature calibration models developed in Alaska [6] and Washington State [7] further reveal the limitations of applying international standards in non-temperate regions. In Europe and the Middle East, technological innovations emphasize multi-source data integration. For example, Poland reclassified PG temperature zones using clustering analysis [8], Iran incorporated ten meteorological variables with GIS-based spatial analysis to develop road climate zoning schemes [9], and Russia's Arctic regions proposed composite rigid-polymer mobile pavement structures to address permafrost degradation [10]. In extreme climate regions, Yemen adapted China's three-indicator model to delineate four climatic zones [11]; Ghana validated the superior accuracy of the Park model for predicting tropical pavement temperatures [12]; and countries in Africa have leveraged satellite data to compensate for the scarcity of meteorological stations [13]. Meanwhile, Uzbekistan optimized subgrade design by integrating soil moisture considerations [14]. At the technological frontier, machine learning is advancing the granularity of climate zoning. In the United States, Dong et al. [15] applied a PCA–ANN hybrid model to identify four distinct climate clusters, while Mokoena et al. [13] found that urbanization effects could elevate PG low-temperature grades by two levels, highlighting the influence of microclimates. In comparison, China leads in the scale of subnational empirical zoning, with 48% of provinces having completed localized studies. However, international research demonstrates greater foresight in inte-

grating future climate projections (e.g., Gudipudi et al. [2] used CMIP6 to project a 40% increase in vehicle damage due to climate change) and in the coupling of multi-algorithm approaches. The contrasting practices between China and other countries offer complementary paradigms for advancing climate-resilient pavement design worldwide. Furthermore, recent studies have highlighted the combined effects of climate variability, traffic intensity, and pollutant emissions in urban areas. For example, Dragomir et al. [16] used dispersion modeling and mobile DOAS observations to assess $NO_2$ distribution in a Romanian city, revealing the impact of meteorology and road traffic on spatial pollution patterns. In China, Wei et al. [17] developed a high-resolution $NO_2$ dataset using satellite retrievals and AI models, showing distinct urban–rural contrasts and temporal variations closely linked to mobility and climate. These findings underscore the relevance of integrating air quality metrics when evaluating pavement performance under evolving environmental conditions.

Systematic research on road climate adaptability in China began in the mid-20th century. In 1958, the first national highway climate zoning scheme was proposed, which laid the groundwork for the gradual development of a comprehensive zoning framework. This effort culminated in the release of the Natural Zoning Standards for Highways (JTJ 003-86) in 1986 [18]. Based on both engineering characteristics and regional climatic heterogeneity, the standard divided the country into 7 primary zones, 33 secondary zones, and 19 subzones, thereby providing a foundational reference for the subsequent development of technical specifications for road design and construction. With the growing recognition of climatic impacts on infrastructure performance, climate factors have been increasingly incorporated into various design specifications. For instance, the Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) introduced classification levels for high-temperature, low-temperature, and rainfall effects to guide asphalt mixture selection and application [19]. Although the Specifications for Design of Highway Asphalt Pavement (JTG D50-2017) did not explicitly establish a climate zoning system, it provided temperature parameters and structural adjustment coefficients for 93 cities across China, along with asphalt material performance indicators under varying precipitation and temperature conditions [20]. Furthermore, several infrastructure design codes have proposed engineering countermeasures for extreme climate scenarios. For example, the Specifications for Design of Highway Subgrades (JTG D30-2015) and the Technical Standard of Highway Engineering (JTG B01-2014) adopt the compaction requirements set forth in the Test Methods of Soils for Highway Engineering (JTG E40-2007) [21–24]. In special arid zones (with annual precipitation less than 150 mm, deep groundwater tables, and humidity coefficients $\leq$0.25) and in special humid areas (such as low-lying regions in Southeastern and Southwestern China), the standards allow for appropriate adjustments in compaction criteria. Additionally, regional differences in temperature and precipitation are considered in slope design, with differentiated control requirements prescribed accordingly.

In recent years, the influence of climatic factors on highway design, construction, and operational management has become increasingly significant, particularly concerning the performance and structural adaptability of asphalt pavements. Implementing detailed climate zoning in both planned and existing road projects is essential for optimizing pavement structural design and material selection, as well as for improving the responsiveness of road engineering to regional climatic conditions. However, China's current Natural Zoning Standards for Highways, which have been in effect for nearly three decades, show considerable shortcomings in the face of changing climate patterns. To begin with, the existing zoning system is mainly defined by macro-level classifications and lacks a unified and comprehensive technical framework. The scientific validity and representativeness of the zoning criteria are limited. Initial zoning efforts were hindered by the sparse distribution of meteorological stations and constrained technological capabilities, resulting in

broad classification intervals and indistinct zoning boundaries that fail to accurately reflect local climatic features. Secondly, while generally representative, the traditional zoning indicators—high temperature, low temperature, and precipitation—do not adequately account for the effects of increasingly frequent extreme weather events, such as prolonged heatwaves and sudden torrential rainfall, on pavement structural performance. The simplistic and outdated nature of the current index system significantly limits the applicability and predictive power of zoning outcomes. In summary, the existing zoning framework has clear inadequacies in addressing varied climatic patterns and supporting region-specific pavement design. It does not meet the growing need for differentiated and precise climate-adaptive solutions in road engineering across diverse geographic regions. Consequently, it is crucial to develop a more scientific, detailed, and adaptable climate zoning system for highways, building on the existing standards while incorporating advances in climate science and engineering technologies.

Recent advances in remote sensing have provided valuable tools for improving the spatial resolution and applicability of climate and pavement-related assessments. For instance, Meier et al. [25] employed high-resolution airborne imaging DOAS to generate detailed $NO_2$ distribution maps over Bucharest, demonstrating the potential of airborne spectroscopy in capturing urban-scale atmospheric variability relevant to pavement performance. In another context, Shahi et al. [26] developed a novel Road Extraction Index (REI) based on WorldView-2 satellite imagery, enabling automated and accurate extraction of asphalt road networks. These emerging techniques—particularly those that integrate spectral analysis and high-resolution remote sensing—offer promising avenues for enhancing climate zoning studies through refined spatial representation and improved characterization of urban infrastructure.

Despite notable progress in climate zoning for asphalt pavements in China, two major research gaps remain. First, most existing zoning schemes rely solely on historical meteorological observations and do not incorporate future climate change scenarios, limiting their usefulness for long-term pavement design. Second, current approaches typically adopt empirical air-to-pavement temperature conversion models developed abroad (e.g., SHRP, LTPP), which may not accurately represent Chinese pavement surface temperature regimes. This undermines the precision of PG grading and, in turn, the evidence-based selection of climate-adaptive materials. Therefore, there is a pressing need to develop climate zoning methods that integrate multiple indicators, spatial interpolation, multidimensional spatial representation, and clustering analysis to build robust linkages between climatic factors and pavement performance, thereby enabling intuitive, quantitative, and scientifically grounded zoning outputs. On this basis, region-specific design principles, methodological frameworks, and evaluation indices can be proposed to guide structural design and material selection. Accordingly, this review (1) synthesizes the evolution, research foci, and provincial applications of climate zoning for asphalt pavements in China; (2) compares the characteristics of mainstream models; (3) examines PG-based grading practices; and (4) outlines future research directions, with the aim of strengthening the climate resilience of pavement infrastructure.

*Review Methodology*

This study adopts a structured review methodology to investigate the development and application of climate zoning models for asphalt pavements in China. Relevant academic publications, technical guidelines, and engineering reports were collected from authoritative databases such as CNKI (China National Knowledge Infrastructure) and Web of Science, focusing on the period from 1997 to 2023. The selection criteria emphasized

studies related to zoning principles, model frameworks, climate indicators, and asphalt pavement performance.

To uncover thematic trends and research hotspots, a keyword co-occurrence analysis was conducted using CiteSpace 6.3. The identified zoning models were then systematically categorized into three methodological types: indicator-based models, hydrothermal coefficient models, and clustering-based models. A comparative analysis was carried out to assess the characteristics, regional applicability, and performance relevance of each zoning approach, particularly in relation to the PG binder classification system.

## 2. Asphalt Pavement Climate Zoning Development Characteristics

### *2.1. Development Stages of Asphalt Pavement Climate Zoning*

The development of asphalt pavement climate zoning in China can be broadly divided into three distinct stages [3], as shown in Figure 1. In the first stage, no specific climate zoning system was established for asphalt pavements. Highway design largely relied on the general Natural Zoning Standards for Highways, which did not account for the specific performance requirements of asphalt materials. The second stage marked the emergence of specialized climate zoning tailored to asphalt pavement. Representative efforts during this period include the "three-indicator, three-level" zoning approach proposed under China's Eighth Five-Year National Scientific and Technological Program and the PG classification system developed in the United States as part of the SHRP. These initiatives began to consider the impact of high temperature, low temperature, and precipitation on asphalt pavement performance. In the third stage, advancements in meteorological monitoring enabled the spatialization of climate data collected from observation stations. This allowed for the construction of more accurate, detailed, and comprehensive climate zoning systems specifically designed for asphalt pavements.

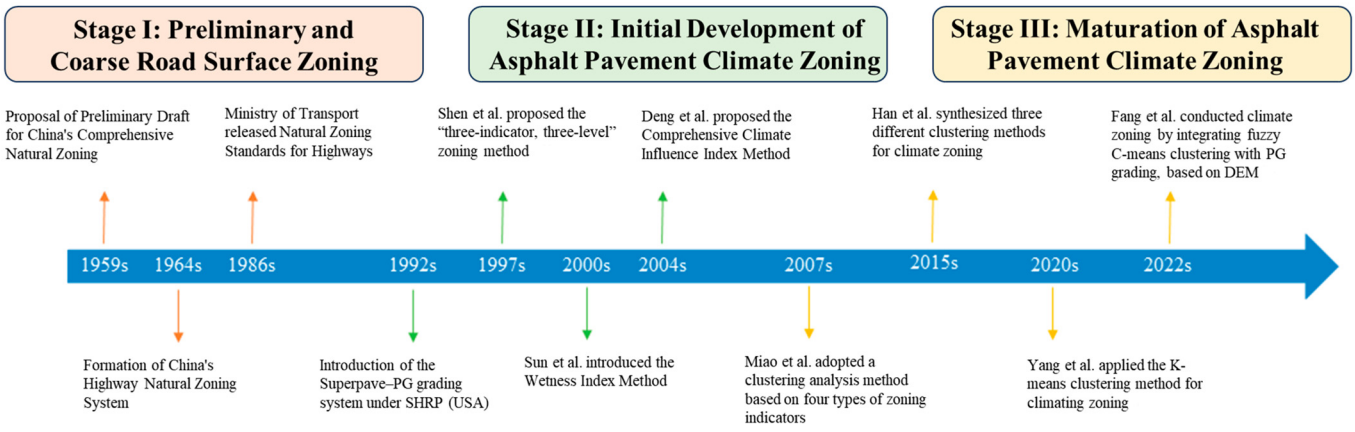



**Figure 1.** Development of climate zoning for asphalt pavement [27–33].

### *2.2. Research Keywords in Pavement Climate Zoning*

To gain a comprehensive understanding of the application of climate zoning in road planning and construction, a keyword co-occurrence analysis was conducted using CiteSpace 6.3 software based on the literature related to China highway climate zoning. Figure 2 illustrates the thematic landscape of climate zoning research in China's road engineering field from 1997 to 2023. In the visualization, the size of each keyword node reflects its frequency of occurrence, while the links between nodes indicate co-occurrence within the same publication. The results reveal that the application of climate zoning in the road sector has primarily focused on topics such as asphalt pavement, typical structural forms, and climatic regionalization.

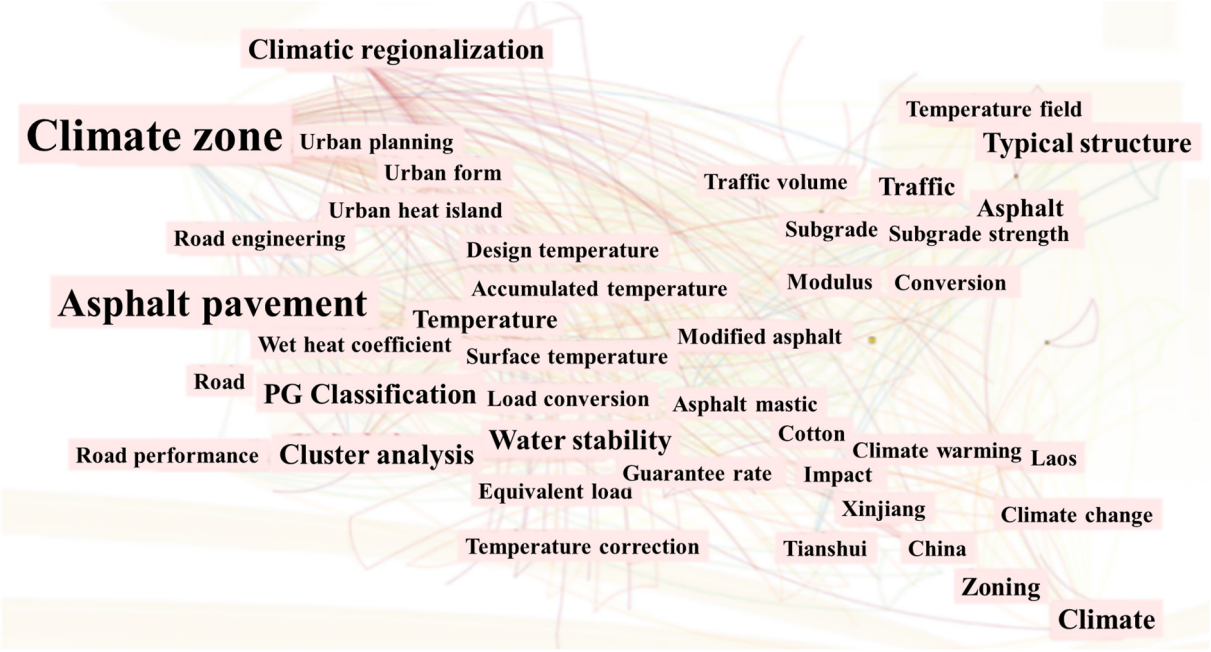



**Figure 2.** Keywords in the research field of road climate zoning (generated using CiteSpace 6.3).

### *2.3. Provincial Applications of Asphalt Pavement Climate Zoning*

Although the current standards divide China's highway natural zoning into three hierarchical levels, the vast territory and highly diverse climatic conditions across the country make it difficult for these classifications to fully meet the practical needs of asphalt pavement material design. In response, Chinese researchers have conducted more detailed studies on asphalt pavement climate zoning at the provincial level, taking into account the specific climatic, topographic, and geomorphological characteristics of each region. The distribution of climate zoning research across various provinces is illustrated in Figure 3, which is based on the statistical count of the published literature related to asphalt pavement climate zoning from 1997 to 2023.

Based on nationwide datasets provided by the National Meteorological Information Center (https://data.cma.cn/, accessed on 1 June 2025), the spatial distributions of the mean maximum temperature of the hottest month, mean minimum temperature of the coldest month, and mean annual total precipitation for the period 1961–2017 were derived, as depicted in Figure 4. A total of 747 representative meteorological stations with relatively complete and reliable long-term records across China were selected to ensure spatial coverage and data consistency. The specific calculation methods for the climatic indicators can be found in Reference [33]. In conjunction with the results presented in Figure 3, it is apparent that approximately 48% of Chinese provinces have undertaken localized climate zoning studies pertinent to asphalt pavement applications. Notably, the South China and Northeast China regions have garnered particular attention due to their climatic extremes. South China is characterized by high temperatures and abundant rainfall, featuring a hot and humid climate with a high proportion of heavy-duty traffic. Under such conditions, asphalt mixtures tend to behave like Newtonian fluids, making them susceptible to rutting. Conversely, Northeast China is prone to extremely cold temperatures and frequent rain or snow during winter. Here, asphalt mixtures exhibit viscoelastic solid properties and are highly vulnerable to low-temperature cracking. These two climatic extremes significantly deteriorate pavement performance and necessitate careful climate considerations in pavement design.

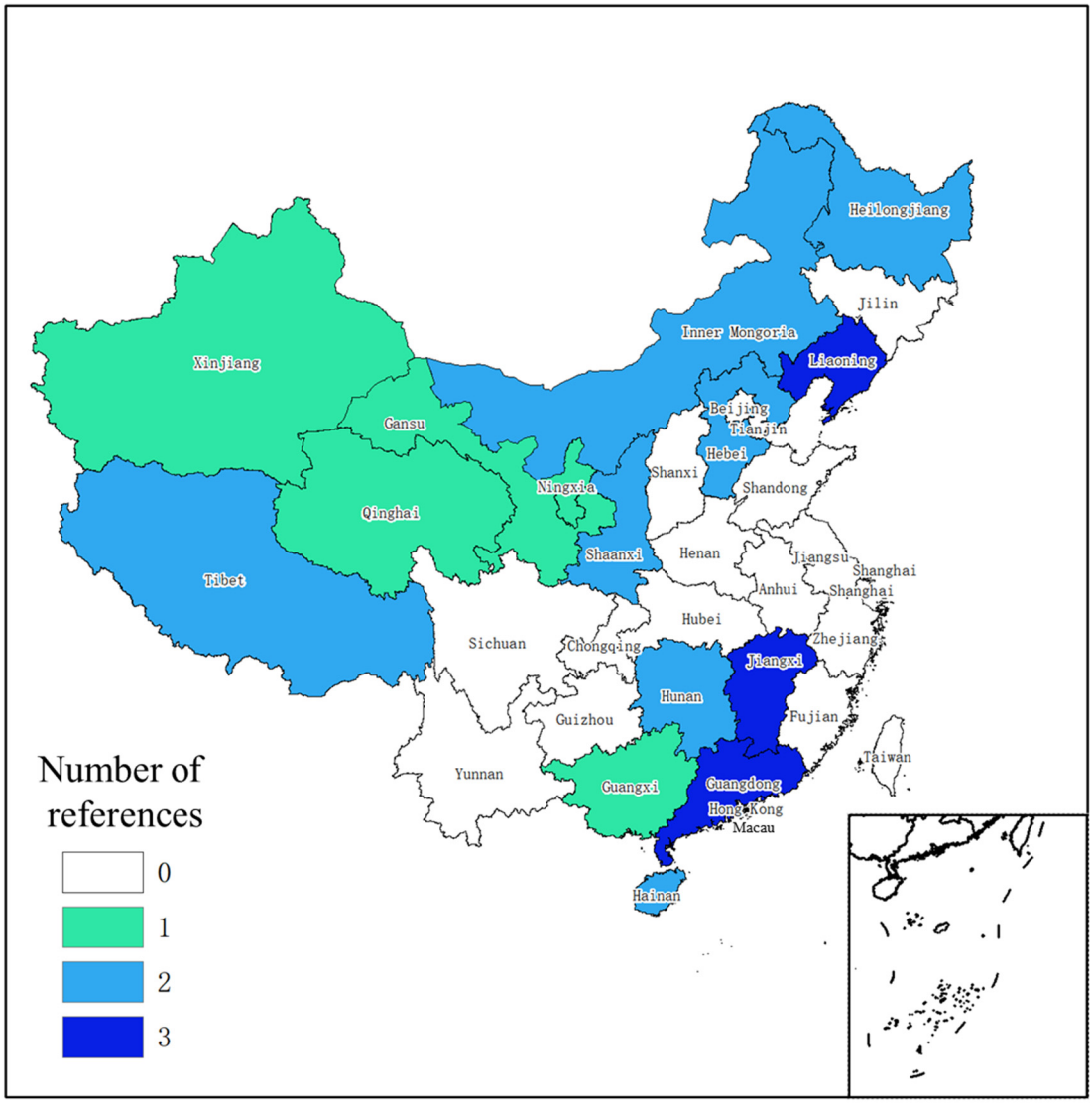



**Figure 3.** Research on climate zoning of asphalt pavement in various provinces of China.

In addition to regional studies, several researchers have undertaken nationwide reclassification efforts of asphalt pavement climate zoning. Shen et al. [34] proposed a method that individually classified climatic indicators and subsequently overlaid the results to identify 26 distinct climatic zones, providing a foundational framework for asphalt pavement climate zoning. Miao et al. [30] applied ordinary kriging and co-kriging methods for the spatial interpolation of meteorological variables. Using clustering analysis, they divided China into 8 primary zones and 39 secondary zones. Han et al. [31] employed fast clustering, hierarchical clustering, and statistical clustering techniques to delineate 10, 9, and 13 temperature zones, respectively. By integrating the results of all three methods and accounting for temperature variability, they ultimately established a unified scheme of nine temperature zones. Liu et al. [35,36] proposed a zoning strategy based on the principles of extreme climate differentiation, dividing Southern China into four zones and Northern China into three zones. Their composite approach considered geographic location, temperature characteristics, and moisture conditions for naming each zone. Fang et al. [33], considering China's unique climatic characteristics, refined the commonly used indicators (high temperature, low temperature, average temperature, precipitation) into eight meteorological variables. To assess spatial interpolation performance, three interpolation methods—inverse distance weighting (IDW), ordinary kriging (OK), and co-kriging

(CK) with digital elevation model (DEM) support—were compared. The CK method yielded the most accurate temperature interpolation results, while IDW performed best for precipitation. Based on these results, climate zoning was conducted using the fuzzy C-means clustering algorithm, dividing the country into ten asphalt pavement climate zones and establishing a preliminary national standard system for asphalt pavement climate classification in China.

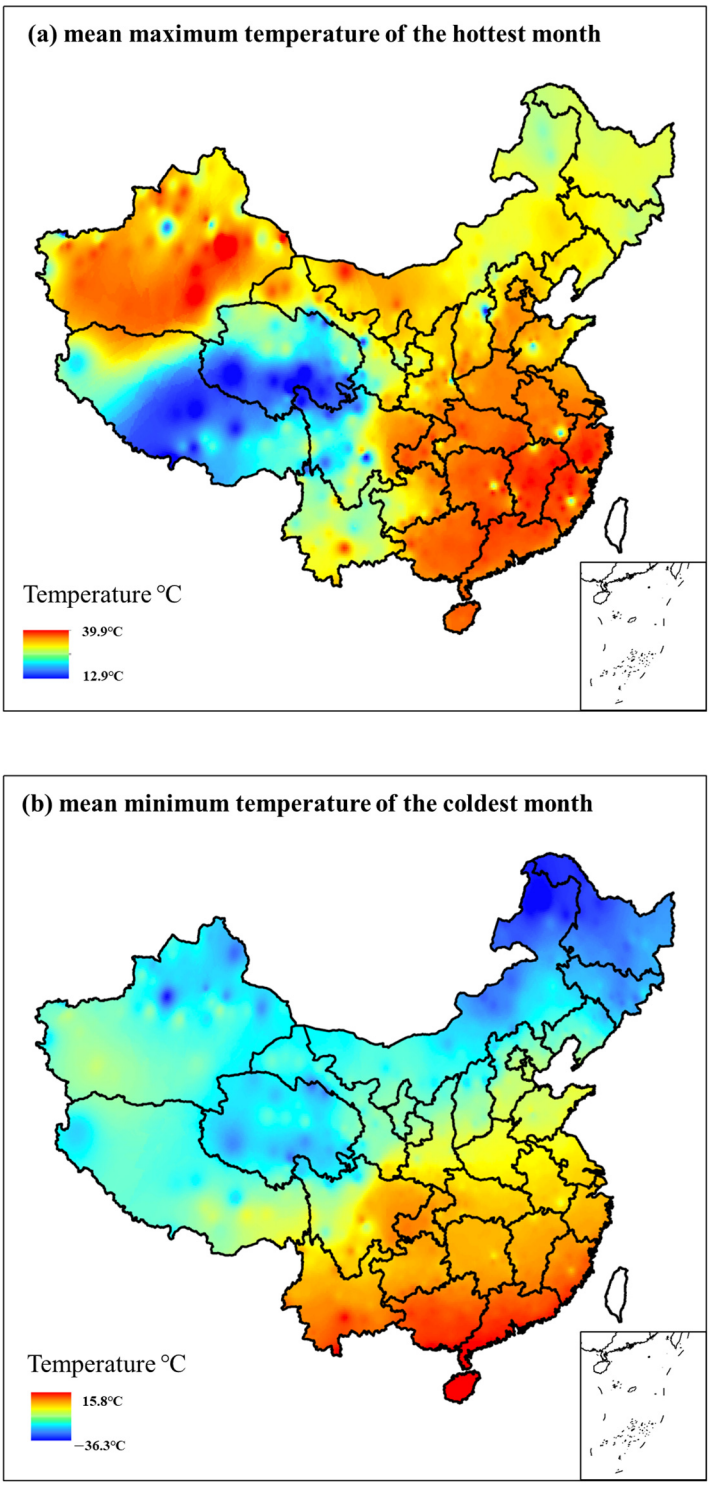



**Figure 4.** *Cont.*

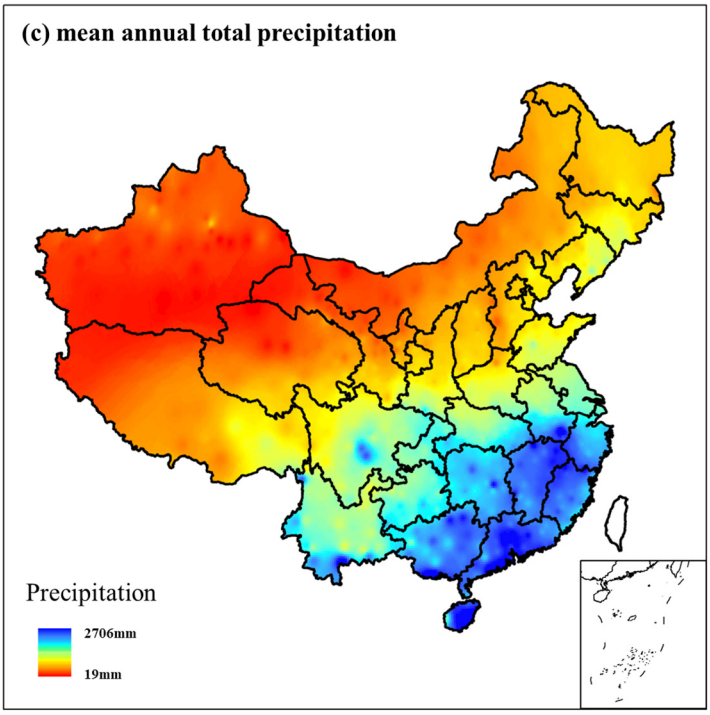



**Figure 4.** Spatial distribution of maximum temperature, minimum temperature, and annual precipitation of China.

Although widely applied in climate zoning and environmental modeling, each spatial interpolation method has its limitations. The inverse distance weighting (IDW) method assigns weights solely based on spatial distance, with closer points exerting greater influence. However, its weighting parameters are determined a priori and do not account for actual spatial autocorrelation, which may lead to oversmoothing or the misrepresentation of localized variability. Ordinary kriging improves upon this by incorporating spatial autocorrelation through a semivariogram model, yet it relies heavily on assumptions of stationarity and isotropy, which may not hold in heterogeneous terrains. Co-kriging further incorporates auxiliary variables (e.g., elevation), but its performance is sensitive to the selection and correlation strength of secondary variables, and the increased model complexity may lead to instability or overfitting when data quality is poor. These limitations should be considered when selecting interpolation approaches for climate zoning applications [33,37].

## 3. Asphalt Pavement Climate Zoning Models

### *3.1. Three-Indicator-Based Climate Zoning Model for Asphalt Pavements*

The "Eighth Five-Year" National Key Scientific and Technological Project, titled "Research on the Performance of Road Asphalt and Asphalt Mixtures," systematically investigated the service performance of seven representative types of road asphalt widely used in China at the time. Based on these findings, the study pioneered the development of a climate zoning framework specifically tailored to asphalt pavement performance in China [27]. The proposed climate zoning model comprises three hierarchical levels, each corresponding to a critical climate-sensitive factor affecting asphalt pavement under different environmental loads.

The first-level zoning focuses on the thermoplastic response of asphalt pavements under combined high-temperature and traffic loading. It identifies regional characteristics associated with rutting and other high-temperature deformations, using the maximum regional temperature as the zoning criterion. The second-level zoning addresses thermal stress effects that can cause thermal cracking in cold climates. It classifies regions based

on minimum temperatures, reflecting the risk of asphalt binder brittleness. The third-level zoning emphasizes the influence of precipitation conditions on infiltration, shear strength, and pavement service performance. Here, annual total precipitation serves as the primary indicator.

This framework, commonly referred to as the three-indicator asphalt pavement climate zoning model, was recognized for its scientific rigor, rationality, and broad applicability. It was first formally adopted in the Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) [19] and has since remained a foundational element in guiding asphalt mixture design across various climatic zones in China. In recent years, Chinese researchers have further refined this model, proposing locally adapted zoning frameworks to better suit the climatic characteristics of specific regions. Table 1 presents representative studies and improvements made to the original three-indicator zoning approach.

**Table 1.** Climate zoning model for asphalt pavement based on three indicators.

| Year | Author | Region | Climate Zoning Results |
|---|---|---|---|
| 1994 | Shen et al. [34] | China | Analyzed 30 years of data from 615 meteorological stations nationwide; identified 26 asphalt pavement climate zones. |
| 2004 | Deng et al. [29] | Liaoning | Developed a comprehensive climate impact index using high temp, low temp, and precipitation; divided the province into three zones. |
| 2007 | Sun et al. [38] | Jiangxi | Divided Jiangxi into three regions based on climate influence classification: the 1-3-1, 2-3-1, and 1-4-1 types. |
| 2008 | Zheng et al. [39] | Xi'an | Used three indicators and varying guarantee levels; divided Xi'an into seven zones. |
| 2008 | Zhou et al. [40] | Liaoning | Applied a composite climate impact index with three indicators; identified three zones. |
| 2010 | Feng et al. [41] | Guangxi | Divided Guangxi into a 1-4-1 climate zone classification using the three-indicator model. |
| 2011 | Wang et al. [42] | Guangdong | Based on 30 years of meteorological data from four typical areas; classified Guangdong into the 1-4-1 zone. |
| 2011 | Shi et al. [43] | Jiangxi | Redefined high-temperature thresholds using cumulative temperatures $\geq$30 °C and reclassified rainfall boundaries; identified eight zones. |
| 2011 | Fu et al. [44] | Hunan | Refined zoning thresholds based on Hunan's climatic features; identified six zones. |
| 2012 | Liang et al. [45] | Shaanxi | Analyzed 20 years of climate data from 10 cities; identified three asphalt pavement climate zones. |
| 2012 | Tang et al. [46] | Hainan | Applied spatial interpolation and province-specific thresholds; identified nine zones. |
| 2017 | Lv et al. [47] | Tibet | Statistically analyzed 30-year climate data; classified Tibet into six zones. |
| 2021 | Wu et al. [48] | Qinghai | Integrated sunshine duration into the three-indicator model; divided Qinghai into 10 zones. |

A comprehensive analysis of the representative studies listed in Table 1 reveals both common evolutionary trends and region-specific characteristics in the application of the three-indicator climate zoning model. Initially, earlier studies—such as that by Shen et al. [34]—relied primarily on long-term meteorological station data at the national scale to establish a unified zoning framework. In contrast, more recent provincial-level research has increasingly adopted localized indicator settings. For example, Jiangxi, Hunan, and Shaanxi have introduced cumulative temperature thresholds or regional statistical analyses to refine high-temperature criteria, while provinces such as Hainan and Qinghai have

incorporated spatial interpolation techniques or sunshine duration factors to enhance the model's sensitivity to local climatic conditions. With improved access to high-resolution climate data, the granularity of zoning has also become progressively finer. Earlier studies typically divided entire provinces into two to four broad zones, whereas more recent work—such as that by Shi et al. [43] and Wu et al. [48]—has refined these divisions into 8 to 10 subzones, reflecting improved capabilities in capturing intra-provincial climatic heterogeneity. Finally, regional climatic and geographic conditions have driven different emphases in zoning logic. Southern provinces such as Guangxi, Guangdong, and Hainan prioritize high-temperature stability and moisture-induced damage from heavy rainfall, while cold or high-altitude regions such as Qinghai and Tibet focus more on freeze–thaw cycles and low-temperature cracking risks. This region-specific adaptability demonstrates the practical value of the three-indicator model, while also highlighting its limitations in terms of precision under extreme or transitional climatic conditions.

### *3.2. Climate Zoning Model Based on the Hydrothermal Coefficient*

The traditional three-indicator climate zoning model primarily considers high temperature, low temperature, and precipitation. In response to the hot and humid climate characteristics of Guangdong Province, Sun et al. [28] proposed a model based on the hydrothermal coefficient (Φ)—defined as the ratio of multi-year annual precipitation to the average temperature in July—for climate zoning in high-temperature and high-precipitation regions. The hydrothermal coefficient is expressed as follows:

$$\Phi = \frac{Q}{T_j} \tag{1}$$

where Φ is the hydrothermal coefficient; $Q$ is the annual total precipitation; and $T_j$ is the average temperature in July.

In this model, the value of Φ serves as the primary basis for zoning. A smaller value of Φ indicates that high-temperature stability should be prioritized in asphalt mixture design, while a larger Φ suggests that moisture stability is more critical.

Subsequent studies expanded on this approach. Fu et al. [44] used a threshold of Φ = 36 to divide Hunan Province into two major regions, and further subdivided them based on a low-temperature threshold of −3 °C, resulting in four distinct climate zones. Xie et al. [49] integrated the hydrothermal coefficient with a precipitation–temperature index, dividing Hunan Province into three zones. Tang et al. [46] applied a threshold of Φ = 53 to Hainan Province, classifying the region into two zones: Zone A, where moisture stability is the dominant design concern, and Zone B, where high-temperature stability is prioritized.

The hydrothermal coefficient quantifies the combined thermal–moisture effect by calculating the ratio of annual precipitation to the average temperature in July. However, this index does not consider the actual heat–mass transfer processes at the pavement surface—such as latent heat loss due to evaporation, solar radiation absorption, or the heat capacity of asphalt mixtures. As a result, it lacks the physical fidelity to accurately represent degradation mechanisms in hot–humid climates, such as asphalt softening or moisture-induced damage. Although the hydrothermal coefficient does not directly reflect these physical processes, it has proven regionally applicable in engineering practice as an empirical composite indicator—particularly in tropical areas. For example, Sun et al. [50] analyzed ten years of meteorological data in Laos to determine the probability distribution of the hydrothermal coefficient and, based on the principle of equal probability segmentation, identified a threshold value of 68. Using this, they developed a climate zoning map for asphalt pavements. Their study demonstrates that while Φ cannot mechanistically capture heat–moisture transfer, it can statistically reflect the broader climatic impacts on pavement

performance and offers practical value for rapid assessments in data-scarce environments. In summary, the hydrothermal coefficient model is particularly suited for hot–humid regions and is often used in conjunction with other climatic indicators. However, zoning schemes based solely on Φ tend to be coarse and are thus more appropriate as general guidance than as a precise classification tool for asphalt pavement climate zoning.

### *3.3. Climate Zoning Models Based on Clustering Analysis*

Clustering analysis, as a classical multivariate statistical method, has been increasingly applied in recent years to climate zoning research for asphalt pavements. It is particularly effective when combined with spatial interpolation techniques, enabling enhanced zoning accuracy and higher spatial resolution. By systematically incorporating multiple climatic factors—such as temperature, precipitation, and freeze–thaw cycles—this approach addresses key limitations of traditional models that typically handle single-variable effects and often suffer from fuzzy zoning boundaries due to hierarchical overlaying [51,52]. Clustering analysis helps capture the nonlinear interactions between pavement performance degradation and complex climatic backgrounds, thereby allowing the development of more structured and logically coherent multidimensional zoning models. The integration of spatial interpolation techniques significantly improves the spatial expressiveness of these models, overcoming the traditional reliance on sparse meteorological station observations. Commonly used interpolation algorithms include inverse distance weighting [53] ordinary kriging [54], and co-kriging [55]. Some advanced methods also incorporate DEM and other physical geographic features, enabling smoother and more realistic spatial distributions of climate data, which provide a robust spatial basis for subsequent zoning.

For the clustering process itself, commonly used algorithms include hierarchical clustering, fuzzy C-means (FCM), K-means, and Q-type clustering. The choice of algorithm depends on the statistical distribution of selected indicators and the specific zoning objectives. The typical implementation workflow of clustering-based zoning models involves the following steps: (1) collection of meteorological data along road corridors or within the study area, followed by the identification of zoning indicators based on observed pavement distresses; (2) spatial interpolation of selected indicators to generate continuous distribution layers; (3) application of clustering algorithms to the spatialized datasets for initial zone delineation; and (4) validation of clustering outputs, and if boundaries appear inconsistent or overlapping, refinement through parameter adjustment or reevaluation of the number of clusters, ultimately leading to an optimized zoning result. Representative applications of clustering-based climate zoning models are summarized in Table 2.

**Table 2.** Climate zoning model for asphalt pavement based on cluster analysis.

| Year | Author | Region | Clustering Method | Climate Zoning Indicators | Climate Zoning Results |
|---|---|---|---|---|---|
| 2007 | Miao et al. [30] | China | Hierarchical Clustering | Accumulated temperature, precipitation–temperature index, combined precipitation–frost index, solar radiation | Divided China into 8 primary zones using multi-indicator clustering and further refined it into 39 secondary zones using single-indicator zoning. |
| 2012 | Gao et al. [56] | Tibet | Hierarchical Clustering (Ward's Method) | High temp, low temp, daily temperature range, solar radiation | Applied spline interpolation and GIS; selected the seventh merge result to define five climate zones and indicator ranges. |

**Table 2.** *Cont.*

| Year | Author | Region | Clustering Method | Climate Zoning Indicators | Climate Zoning Results |
|---|---|---|---|---|---|
| 2015 | Han et al. [31] | China | Fast, Hierarchical, and Statistical Clustering | Days with stable 5-day sliding average temperature > 10 °C | Classified China into 10, 9, and 13 zones via three methods; finalized 9-zone classification considering temperature variability. |
| 2017 | Liu et al. [35,36] | China | Q-type Clustering | Temperature, precipitation | Developed a zoning framework; divided Southern China into four zones and Northern China into three, using geographic + thermal + moisture traits. |
| 2018 | Yang et al. [57] | Liaoning | Ward's Method | High temp, low temp, precipitation | Used SPSS for clustering; divided Liaoning Province into five climatic zones. |
| 2020 | Sun et al. [51] | Inner Mongolia | Hierarchical Clustering | High temp, low temp, temperature range, rainfall, solar radiation | Applied kriging for interpolation; used 10th merge to classify eight climate zones. |
| 2020 | Yang et al. [32] | Liaoning | K-means Clustering | High temp, low temp, precipitation, solar radiation | Applied PCA to extract cluster factors; identified four zones. Accuracy verified via PNN and SVM (>90%). |
| 2021 | Zhou et al. [58] | Guangdong | Fuzzy C-means Clustering | High temp, low temp, precipitation | Used DEM-based interpolation; identified four climate zones. |
| 2022 | Fang et al. [33] | China | Fuzzy C-means Clustering | High temp, low temp, mean temp, precipitation | Applied IDW, ordinary kriging, and DEM-based co-kriging; classified China into 10 asphalt pavement climate zones. |
| 2022 | Zhao et al. [59] | Inner Mongolia | Hierarchical Clustering + Overlay Method | High temp, low temp, precipitation, accumulated temp, temp range, permafrost depth | Used six kriging methods for interpolation; defined 6 surface climate zones and 10 subgrade performance zones. |

An analysis of the representative case studies listed in Table 2 reveals several notable trends in the development of clustering-based climate zoning models for asphalt pavements in China: First, hierarchical clustering remains the most widely used traditional method due to its intuitive operation and high visual interpretability, particularly in early studies (e.g., Miao et al. [30]; Gao et al. [56]; Sun et al. [51]). However, in recent years, with the increasing complexity and scale of climate data, more adaptive and computationally efficient algorithms—such as fuzzy C-means (FCM) and K-means clustering—have gained attention (e.g., Zhou et al., [58]; Fang et al., [33]; Yang et al., [32]), showing superior performance in handling fuzzy boundaries and large datasets. Second, the dimensionality of selected indicators has gradually expanded. Early models primarily focused on basic meteorological parameters, such as maximum temperature, minimum temperature, and

annual precipitation. In contrast, recent studies have incorporated more complex variables, such as solar radiation, diurnal temperature range, freeze–thaw cycles, and permafrost depth, to better reflect the multidimensional impacts of complex climate conditions on asphalt pavement performance. Some studies (e.g., Fang et al., [33]; Zhao et al., [59]) even used six or more climate variables, combined with various interpolation techniques, to construct high-resolution zoning systems. Third, the implementation of clustering models is increasingly integrated with spatial interpolation techniques. To address the lack of spatial continuity due to sparse meteorological station distribution, most studies have employed kriging, inverse distance weighting (IDW), or co-kriging methods to spatialize climatic indicators. In some cases, digital elevation models (DEMs) were incorporated to improve zoning accuracy in topographically complex regions such as mountainous or plateau areas (e.g., Zhou et al., [58]; Fang et al., [33]), reflecting a growing recognition of terrain's influence on local climate systems. In terms of zoning results, most studies divided target areas into 4 to 10 climate zones, depending on the degree of regional climatic heterogeneity and the clustering method employed. For example, for southern and coastal provinces (e.g., Guangdong, Liaoning), the coupling effect between temperature and precipitation tended to be emphasized, whereas for alpine and arid regions (e.g., the Qinghai–Tibet Plateau, Inner Mongolia), freeze–thaw indices and permafrost depth were incorporated to assess risks to structural performance.

### *3.4. Summary of the Performance of Three Climate Zoning Methods*

The practical performance and application status of current climate zoning methods for asphalt pavements vary significantly:

(1) Three-Indicator Model: This model is the only method currently adopted in national technical standards (e.g., JTG F40-2004) [19] and provides a basic zoning framework due to its simplicity and ease of use. However, the use of broad classification thresholds limits its zoning accuracy—particularly in transitional climate regions (e.g., the Qinba Mountains) and extreme climate zones (e.g., the Qinghai–Tibet Plateau). Field investigations indicate that in hot and rainy regions, the model tends to underestimate rutting risks, while in cold areas, it may overlook cracking caused by rapid temperature fluctuations.

(2) Hydrothermal Coefficient Model: Designed specifically for hot and humid climates (e.g., South China), this model quantifies the synergistic effects of precipitation and high temperature (see Equation (1)), providing directional guidance for designing rutting- and moisture-resistant asphalt materials. However, its zoning results are relatively coarse (e.g., two zones for Hunan, two for Hainan) and do not account for local microclimates or traffic loading variations. To date, this model has not been incorporated into any local or national standards and is used solely as a reference in engineering practice.

(3) Clustering Analysis Models: These models integrate multiple climatic indicators (e.g., extreme temperatures, precipitation, freeze–thaw cycles) with spatial interpolation techniques (e.g., co-kriging), offering high-resolution and highly adaptive zoning results (e.g., 10 zones across China). By employing algorithms such as FCM and K-means, clustering models effectively capture nonlinear relationships between climate and pavement performance. In validation studies conducted in regions like Tibet and Inner Mongolia, they have accurately predicted distress distribution patterns. However, these models rely heavily on large volumes of meteorological data and involve complex computational processes. They remain in the realm of academic research and have not yet been adopted in engineering standards.

In summary, among the three methods, only the three-indicator model has been formally adopted in current technical codes. The other two models—though promising in terms of performance and adaptability—are still in the exploratory stage and have

not been institutionalized in local or national guidelines. Their large-scale application is currently constrained by data and operational limitations. Future research should focus on integrating downscaled climate projections and localized air-to-pavement temperature conversion models to improve their practical utility.

## 4. Application of Climate Zoning in Performance Grade (PG) Asphalt Binder Classification

Upon completing climate zoning for asphalt pavements, research often progresses by aligning asphalt material performance grading with regional climatic characteristics to support climate-adaptive material selection and structural design. Among the various performance classification methods, the performance grade (PG) system has been widely adopted to evaluate the behavior of asphalt binders under specific environmental conditions, and is now considered a mature, performance-oriented international standard.

Currently, China still primarily classifies road asphalt based on the traditional penetration grade system, which categorizes asphalt according to its hardness at standard temperatures. While this system offers some insight into the physical properties of asphalt, it has several significant limitations: (1) It does not sufficiently cover low-temperature performance, making it difficult to assess cracking risks in cold regions; (2) there is a lack of quantitative linkage between asphalt specifications and actual pavement performance, hindering accurate evaluations under complex climate conditions; and (3) the absence of climate-responsive design standards leads to non-targeted material selection. These issues compromise the long-term durability and service performance of asphalt pavements, particularly in regions with challenging climate environments.

In contrast, the PG grading system, developed in the United States, is based on the mechanical response of asphalt binders to extreme temperatures. It uses the maximum and minimum pavement design temperatures as the core indicators and adopts the format "PG X–Y", where X and Y represent the high- and low-temperature grade limits, respectively, in degrees Celsius [60]. This method is more reflective of the actual environmental conditions encountered during the service life and allows for flexible adjustment of grading ranges to accommodate regional climatic differences. As such, it provides a more scientific and climate-adaptive basis for performance evaluation and material compatibility. The detailed temperature grade classification standards are presented in Table 3.

**Table 3.** Performance grade temperature division.

| High-Temperature Grade | Low-Temperature Grade | | | | | | |
|---|---|---|---|---|---|---|---|
| PG46 | −34 | −40 | −46 | — | — | — | — |
| PG52 | −10 | −16 | −22 | −28 | −34 | −40 | −46 |
| PG58 | −16 | −22 | −28 | −34 | −40 | — | — |
| PG64 | −10 | −16 | −22 | −28 | −34 | −40 | — |
| PG70 | −10 | −16 | −22 | −28 | −34 | −40 | — |
| PG76 | −10 | −16 | −22 | −28 | −34 | — | — |
| PG82 | −10 | −16 | −22 | −28 | −34 | — | — |

The PG system is fundamentally built on the in-service performance of asphalt pavements. In other words, the temperature metrics used in PG-based climate zoning represent actual pavement temperatures, rather than ambient air temperatures. Therefore, obtaining reliable conversion relationships between air temperature and pavement temperature is essential to ensure the accuracy of PG grading.

Common international empirical models for converting air temperature to pavement design temperatures are summarized below [61–63]:

(1) High-Temperature Design Models

The SHRP model estimates the pavement temperature at a depth of 20 mm, as shown in Equation (2):

$$T_{20} = 0.9545 \times \left(T_a - 0.00168Lat^2 + 0.2289Lat + 42.2\right) - 17.78 \quad (2)$$

where $T_{20}$ is temperature at 20 mm below the pavement surface (°C); $T_a$ is the average of the 7-day maximum air temperatures (°C); and Lat is latitude of the location (°).

The Long-Term Pavement Performance (LTPP) model provides a more comprehensive equation (Equation (3)), accounting for air temperature variability and pavement depth:

$$T_p = 54.32 \times 0.78T_a - 0.0025Lat^2 - 15.14 \times log_{10}(H + 25) + Z\left(9 + 0.61\sigma_a^2\right)^{0.5} \quad (3)$$

where $T_p$ is the maximum temperature at pavement depth $H$ (°C); $\sigma_a$ is the standard deviation of the 7-day average maximum temperatures (°C); $Z$ is the temperature factor (commonly 2.055 for 98% reliability); and $H$ is the pavement depth (mm).

(2) Low-Temperature Design Models [38]

The SHRP model directly uses the lowest air temperature in winter as the design low temperature:

$$T_{min} = T_a \quad (4)$$

A correction is applied to account for surface–air temperature differences using the C-SHRP model (Canada):

$$T_{min} = 0.859T_a + 1.7 \quad (5)$$

A probabilistic model is employed for pavement surface temperature using LTPP:

$$T_p = -1.56 \times 0.72T_a - 0.004Lat^2 + 6.26 \times log_{10}(H + 25) - Z\left(4.4 + 0.52\sigma_a^2\right)^{0.5} \quad (6)$$

Most researchers adopt these empirical models directly, while some further calibrate them or develop localized regression models based on field-observed temperature data. Specific applications and comparisons of these temperature conversion models are presented in Tables 4 and 5.

**Table 4.** Application of PG model based on improved empirical formula.

| Author (Year) | Indicator | Temperature Conversion Formula | PG Grading Application Summary |
|---|---|---|---|
| Zhang et al. (2003) [64] | High Temperature | Tmax = −12.189 + 1.176Tair1 + 0.966Lat | Extreme maximum surface temperature was selected as the high-temperature indicator based on geographic analysis. A regression formula was developed through comparison with the SHRP model and actual meteorological data, and was ultimately adopted for zoning. The collapsible loess region was classified into six PGs according to the established criteria. |
| | Low Temperature | Tmin = −1.866 + 1.083Tair2 | |

**Table 4.** *Cont.*

| Author (Year) | Indicator | Temperature Conversion Formula | PG Grading Application Summary |
|---|---|---|---|
| Deng et al. (2004) [29] | High Temperature | Tmax = 47.519 + 2.805Tair1 − 1.818Lat | The high-temperature indicator was defined as the average extreme maximum surface temperature through statistical analysis. A regression-based conversion formula was selected over the SHRP model for improved regional accuracy. PG classification was applied to divide Liaoning Province into four performance zones. (In the low-temperature formula, F represents the maximum wind speed in January, in m/s.) |
| | Low Temperature | Tmin = 0.533Tair2 − 1.53Lat − 0.084F + 49.73 | |
| Liang et al. (2012) [45] | High Temperature | Tmax = 11.269 + 1.1Tair1 + 0.996Lat | Three models—linear regression, SHRP, and LTPP—were compared. For high-temperature conversion, SHRP < regression < LTPP; for low-temperature conversion, SHRP < regression < LTPP < C-SHRP. Based on this comparison, the regression model was chosen for temperature index transformation. Shaanxi Province was classified into four PG zones. |
| | Low Temperature | Tmin = −1.7288 + 1.03506Tair2 | |
| Zhang et al. (2012) [65] | High Temperature | Tmax = (Tair1 − 0.00907Lat2 + 0.2773Lat + 2.1273) × 4.3662 − 57.78 | A high-temperature conversion formula was derived for Heilongjiang Province based on the SHRP model, while a low-temperature formula was derived using the C-SHRP approach. The province's asphalt pavement performance was ultimately classified into three PG zones. |
| | Low Temperature | Tmin = 1.91Tair2 + 31.0893 | |
| Liu et al. (2014) [66] | High Temperature | Tmax = Tair1 − 0.0017Lat2 − 0.4936Lat + 48.0 | Similar to the study [49], it is recommended that Heilongjiang Province adopt the SHRP high-temperature design formula and the Canadian C-SHRP low-temperature design formula for temperature conversion and PG determination. The province's asphalt pavement performance was ultimately classified into three PG zones. |
| | Low Temperature | Tmin = 0.967Tair2 + 1.0 | |

**Table 5.** Application of PG model based on empirical formulas.

| Author (Year) | Indicator | Temperature Conversion Formula | PG Grading Application Summary |
|---|---|---|---|
| Wang et al. (2006) [67] | High Temperature | LTPP | A comparison between the SHRP and LTPP temperature conversion formulas showed that the LTPP model consistently yielded higher temperature values. For safety considerations, the LTPP formula was adopted to classify asphalt pavement performance in Inner Mongolia into seven PGs. |
| | Low Temperature | LTPP | |
| Ma et al. (2006) [68] | High Temperature | SHRP | The SHRP temperature conversion formula was directly applied to calculate the zoning indicators; asphalt pavement performance in the Liupan Mountains region was classified into two PGs. |
| | Low Temperature | SHRP | |

**Table 5.** *Cont.*

| Author (Year) | Indicator | Temperature Conversion Formula | PG Grading Application Summary |
|---|---|---|---|
| Luo et al. (2008) [69] | High Temperature | LTPP | Two scholars reached similar conclusions: After comparison, it was found that the LTPP formula produced the highest high-temperature values, while the SHRP formula yielded the lowest low-temperature values. Therefore, the LTPP model was used for high-temperature indicator design, and the SHRP model was used for low-temperature indicator design. Based on these results, asphalt pavements in Guangxi were classified into a single grade: PG70-10. |
| | Low Temperature | SHRP | |
| Feng et al. (2010) [41] | High Temperature | LTPP | |
| | Low Temperature | SHRP | |
| Fu et al. (2011) [44] | High Temperature | SHRP | The SHRP temperature conversion formula was directly adopted for zoning indicators; Hunan Province was classified into two PGs. |
| | Low Temperature | SHRP | |
| Chen et al. (2011) [70] | High Temperature | SHRP | For Hainan Province, the comparison revealed that the SHRP formula produced the highest high-temperature conversion values, while the LTPP formula produced the lowest low-temperature values. As a result, the SHRP formula was used for high-temperature indicators and the LTPP formula for low-temperature indicators; the region was classified into two PGs. |
| | Low Temperature | LTPP | |
| Zhu et al. (2016) [71] | High Temperature | LTPP | A comparative analysis showed that the LTPP model produced the highest high-temperature values, and the SHRP model the lowest low-temperature values. However, the SHRP model was considered overly conservative. Ultimately, the LTPP formula was selected as the temperature conversion model for Jiangxi Province, which was then divided into three PGs. |
| | Low Temperature | LTPP | |
| Jiao et al. (2016) [72] | High Temperature | SHRP | The SHRP temperature conversion model was directly used to calculate zoning indicators; Hebei Province was classified into five PGs. |
| | Low Temperature | SHRP | |
| Lv et al. (2017) [47] | High Temperature | LTPP | For Tibet, it was found that the LTPP formula provided the highest high-temperature values, and the SHRP formula the lowest low-temperature values. Consequently, the LTPP model was used for high-temp indicators and the SHRP model for low-temp indicators; the region was classified into nine PGs. |
| | Low Temperature | SHRP | |
| Tang et al. (2017) [73] | High Temperature | LTPP | For Xinjiang, comparison revealed that the LTPP formula yielded both the highest high-temperature and lowest low-temperature conversion values. Therefore, the LTPP model was used to classify the province into seven PGs. |
| | Low Temperature | LTPP | |
| Wu et al. (2021) [48] | High Temperature | SHRP | The SHRP formula was directly applied for temperature conversion in Qinghai Province, where asphalt pavement performance was classified into seven PGs. |
| | Low Temperature | SHRP | |

Based on Tables 4 and 5, it is observed that the most commonly used high-temperature conversion formulas are derived from the SHRP and LTPP programs, while the most widely used low-temperature formulas include those from SHRP, C-SHRP, and LTPP. Notably, the C-SHRP formula was specifically calibrated for Canadian climatic conditions. When applied to Chinese regions, it may lead to unsafe low-temperature designs, as its predicted values are reported to be 6.0 to 8.6 °C higher than actual pavement temperatures. Therefore,

a consensus among researchers holds that the C-SHRP model is not suitable for direct use in China.

Approximately 68.8% of scholars directly adopt these empirical formulas for converting air temperature to pavement temperature. Among them, 36% focus primarily on climate zoning, and during PG grading, they directly apply the SHRP high- and low-temperature conversion formulas based on empirical recommendations; 45% evaluate multiple models by substituting local observational data into both SHRP and LTPP high- and low-temperature formulas. These studies often find that the LTPP model produces higher high-temperature values than SHRP, leading to its preferred use for high-temperature design. However, opinions on low-temperature conversion formulas vary. Scholars such as Luo et al. [69], Feng et al. [41], and Lv et al. [47] believe that the SHRP low-temperature formula provides safer estimates, better accounting for critical temperature extremes. In contrast, Wang et al. [67] and Zhu et al. [71] argue that the SHRP low-temperature formula is overly conservative, and therefore prefer the LTPP model for low-temperature conversion. In a region-specific analysis, Chen et al. [70] compared local temperature data for Hainan Province using SHRP and LTPP models. It was found that the SHRP formula yielded the highest high-temperature values, while the LTPP formula provided the lowest low-temperature values, and accordingly they adopted the SHRP model for high-temperature conversion and the LTPP model for low-temperature conversion. Similarly, Tang et al. [73] found for Xinjiang Province that the SHRP model was more suitable for high-temperature conversion, whereas the LTPP model was more reliable for low-temperature conversion, ultimately using LTPP for both indicators in PG grading.

The remaining 31.2% of scholars opted to develop new regression-based pavement temperature conversion formulas tailored to local conditions. These were established by analyzing regional meteorological data and leveraging the structural logic of existing SHRP, C-SHRP, and LTPP models to improve PG grading applicability in Chinese contexts.

## 5. Future Perspectives

This study examined the developmental characteristics of asphalt pavement climate zoning and summarized the prevalent zoning models. It also proposed the implementation of the PG classification system within the framework of climate-oriented pavement design. This method aims to aid road engineers in tackling climate zoning issues and in reducing climate-related performance risks. Future research could progress in two main directions:

(1) Integration of Future Climate Projections: Current climate zoning primarily relies on historical meteorological data, implying that the defined zones reflect past climate patterns, despite being used to guide future pavement design. The Coupled Model Intercomparison Project (CMIP) has been established to predict future climate system developments, and its latest iteration, CMIP6, has been extensively utilized to evaluate projected climate characteristics across various regions in China [74]. For example, Wang et al. [75], Yang et al. [76], and Zhao et al. [77] have employed CMIP6 models to assess future changes in temperature and precipitation in Northeast China, Southwest China, and the East Asian monsoon region, respectively. However, no studies have yet integrated CMIP6 projections into asphalt pavement climate zoning, highlighting a substantial research gap.

(2) Refinement of Pavement Temperature Conversion Formulas for PG Grading: Although the PG system is scientifically rigorous and operationally effective, only 31.2% of scholars have endeavored to develop new, localized pavement temperature conversion formulas based on empirical patterns and site-specific meteorological data. Most researchers continue to depend heavily on conventional empirical formulas (e.g., SHRP, LTPP) for converting air temperature to pavement temperature. Future studies should concentrate on thorough exploration of conversion mechanisms, using both simulations and field experi-

ments. By calibrating simulated and observed data, more precise and regionally tailored conversion models can be developed, thereby improving the reliability of PG-based asphalt pavement climate classification.

## 6. Conclusions

(1) The development of asphalt pavement climate zoning in China has undergone three distinct stages. The first stage relied on broad-scale natural highway zoning systems without specific differentiation for asphalt pavements. The second stage saw the emergence of specialized frameworks, such as the three-indicator, three-level model under the national "Eighth Five-Year" research program and the performance grade (PG) classification system introduced by the U.S. SHRP initiative. The third stage incorporated spatial processing of meteorological observation data, enabling the construction of more refined and accurate zoning systems. To date, approximately 48% of Chinese provinces have conducted localized zoning studies for asphalt pavements, with South China and Northeast China being key areas of focus due to their climatic extremes.

(2) This review evaluated three primary zoning models. The three-indicator model, based on high temperature, low temperature, and precipitation, is widely adopted and operationally simple but often lacks resolution in climatically complex regions. The hydrothermal coefficient model, which is applicable in hot and humid regions, offers general guidance but yields relatively coarse zoning results and is not included in technical standards. The clustering analysis model provides higher spatial precision and can capture nonlinear climate–performance relationships, but its reliance on large datasets and complex computation currently restricts its use to academic research settings.

(3) In PG classification practice, the SHRP and LTPP models are most frequently used for high-temperature conversion, while SHRP, LTPP, and C-SHRP are applied for low-temperature conversion. However, the C-SHRP model has been found to overestimate pavement temperatures by 6.0–8.6 °C in China, rendering it unsuitable for local application. Approximately 68.8% of researchers apply standard empirical formulas, whereas 31.2% have developed localized conversion models based on regional meteorological data, improving the precision and applicability of PG grading in Chinese contexts.

(4) Looking forward, future research should prioritize the integration of downscaled climate change projections and the development of region-specific air-to-pavement temperature conversion models. These advancements will be essential for enhancing the precision, adaptability, and engineering applicability of climate zoning frameworks for asphalt pavement design under evolving climate conditions.

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