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Determination of Equivalent Temperature for Asphalt Pavement Design in Vietnam

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ABSTRACT

Temperature is a critical factor influencing asphalt pavement performance and its service life. Current pavement design practices in Vietnam, however, rely on fixed temperature values, disregarding regional climatic variations. To address this limitation, this study introduces a revised concept of "equivalent temperature", which is a representative temperature value that accounts for daily temperature fluctuations over a 20-year period. The objective is to enhance the accuracy and durability of pavement design by determining region-specific equivalent temperatures. Utilizing temperature data from 127 weather stations spanning 20 years, a gridded temperature map of Vietnam is constructed. The Shell method is employed to calculate Weighted Mean Annual Pavement Temperatures (WMAPTs) for each station. Results reveal significant spatial variability in WMAPTs across the country, ranging from 30°C to 41°C. These findings underscore the inadequacy of a singular design temperature for Vietnam's diverse climate. The calculated WMAPTs offer a valuable dataset for estimating asphalt moduli and informing future pavement design and research efforts, ultimately contributing to improved pavement performance and extended pavement service life in Vietnam.

1 Introduction

Temperature is a critical factor influencing the performance and lifespan of asphalt pavements [1, 2]. At low temperatures, asphalt becomes brittle and susceptible to fatigue cracking, while high temperatures result in permanent deformation [3, 4]. Current design methods primarily focus on fatigue cracking, neglecting the significant impact of permanent deformation, which is instead addressed in asphalt mix design. The distribution of temperature, both daily and seasonally, critically impacts pavement performance. For instance, night time traffic under cold conditions can accelerate flexural cracking in thin asphalt layers. Conversely, high temperatures can increase strains in underlying pavement layers, affecting their performance. Temperature data is therefore useful for binder selection in asphalt pavement design [5], investigating the influence of climate change on pavement performance [6], and for pavement design purposes [7].

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In the context of asphalt pavement design, pavement performance is not only significantly impacted by traffic distribution [8, 9] but also temperature variations, both daily and seasonally [10, 11]. Due to the complexity of incorporating all temperature data into pavement calculations, the concept of “equivalent temperature” has been introduced based on Miner's hypothesis in several pavement design procedures [12-14]. This approach allows for the estimation of asphalt pavement behavior using a simplified equivalent temperature, which yields results comparable to those obtained from calculations using actual temperature distributions.

In France, the concept “equivalent temperature - θ_{eq} ” is incorporated into pavement design methodology to solely address fatigue-related damage for a given pavement structure [12]. The theoretical fatigue damage calculated using θ_{eq} aligns with the cumulative damage predicted by considering actual temperature variations, traffic distribution, and Miner's law. The temperature θ_{eq} is defined by the following equation

$$\sum_i \frac{n_i(\theta_i)}{N_i(\theta_i)} = \frac{\sum_i n_i(\theta_i)}{N_i(\theta_{eq})} \quad (1)$$

Or temperature θ_{eq} can be expressed in the fatigue law equation

$$\frac{1}{N(\theta_{eq})} = \frac{1}{\sum_i n_i(\theta_i)} \left[\sum_i n_i(\theta_i) \left\{ \frac{\varepsilon_6(\theta_i)}{\varepsilon(\theta_i)} \right\}^{1/b} \times 10^{-6} \right] \quad (2)$$

where: $n_i(\theta_i)$ is the equivalent axle loads that pavement experiences at temperature θ_i ; $N_i(\theta_i)$ is the load applications that induces fatigue damage at the tensile strain level $\varepsilon(\theta_i)$; $\varepsilon_6(\theta_i)$ is the tensile strain at which failure occurs after 1 million load cycles; $\frac{1}{N(\theta_{eq})}$ is the elementary damage (for 1 load application); b is the slope of the asphalt fatigue law, obtained from a 2-point-bending fatigue test performed according to French standard [12].

In Hungary, equivalent temperature calculations are conducted for both full-depth asphalt pavements and 150mm-thick asphalt pavements with hydraulically bonded subbases, considering four traffic loading classes with corresponding Equivalent Single Axle Loads (ESAL) (see Table 1), one-year (365 days) air temperature data, and asphalt mix dynamic modulus obtained from laboratory tests [15]. The equivalent temperature is determined using Miner's hypothesis, where the effective stress induced in the pavement with a single equivalent temperature is equated to the stresses calculated using insitu variations in temperature. The calculation follows the following equation

$$N_{eff} = \frac{1}{\frac{1}{n} \sum_{i=1}^n \left(\frac{1}{N_i} \right)} \quad (3)$$

where: N_{eff} is the effective load applications; N_i is the real allowed load applications calculated based on measured variations in temperature.

Table 1 - Typical asphalt pavement structures by load class in Hungary (adapted from [15]).

Load class		C	D	E	K
ESAL (million)		0.3-1.0	1.0-3.0	3.0-10	10-30
Full depth asphalt pavement structure	Asphalt thickness (cm)	18	21	24	27
	Subbase (cm)	-	-	-	-
Asphalt pavement structure on hydraulically bonded subbase	Asphalt thickness (cm)	13	17	20	24
	Subbase (cm)	15	15	15	15

In Australia, Austroads has employed the Shell method to calculate the Weighted Mean Annual Pavement Temperature (WMAPT), which considers the relationship between asphalt temperature variations and the fatigue life of thick asphalt pavements [14]. WMAPT is particularly well-suited for pavement design, as fatigue performance is significantly influenced by temperature and the temporal distribution of load applications (heavy vehicles at night with lower temperatures and lighter loads but more frequent applications during the day with higher temperatures). The temperature data used in the calculation comprises a 20-year database of daily minimum and maximum air temperatures.

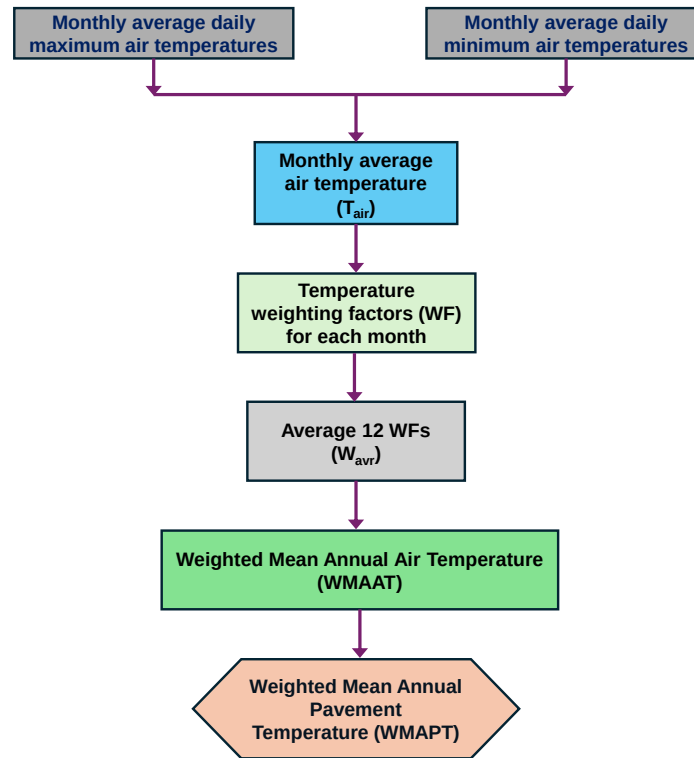


Fig. 1 – Flowchart for calculating Weighted Mean Annual Pavement Temperature (WMAPT).

The method for calculating the WMAPT for a specific region is illustrated in Fig. 1. The method involves the following steps:

- Step 1: Collect the monthly average daily maximum air temperatures and minimum air temperatures.
- Step 2: Calculate the monthly average air temperature (T_{air}) for each month by averaging the maximum and minimum air temperatures. If available, use the existing monthly average air temperature instead. This step will result in 12 average air temperature values, one for each month.
- Step 3: Calculate the temperature weighting factor (WF), obtained from [13] for each month with the Eq. (4)

$$WF = 10^{(-1.224 + 0.06508T_{air} - 0.000145T_{air}^2)} \quad (4)$$

- Step 4: Calculate the mean of the 12 WF s in Step 3 (WF_{avr}).
- Step 5: Calculate the Weighted Mean Annual Air Temperature ($WMAAT$, obtained from [13]) with the Eq. (5)

$$WMAAT = 19.66 + 16.91 * \log WF_{avr} + 0.3117 * (\log WF_{avr})^2 \quad (5)$$

- Step 6: Calculate the Weighted Mean Annual Pavement Temperature ($WMAPT$, obtained from [13]) with the Eq. (6)

$$WMAPT = -12.4 + \frac{6.32(WMAAT)}{\ln(WMAAT)} \quad (6)$$

The $WMAPT$ values are then rounded to the nearest whole number.

2 Asphalt pavement design procedure in Vietnam

In Vietnam, the selection of asphalt pavement structure is influenced by both traffic volume and climatic conditions. Regarding traffic volume, the minimum thickness of asphalt layers is determined based on the Equivalent Single Axle Load (ESAL) at the 15th year of the design period and the standard axle load. For common cases, a double-wheel single-axle load of 100 kN is considered, while for roads with heavy axle loads exceeding 120 kN, a load of 120 kN is used (see Table 2) [16].

Table 2 - Characteristics of standard axle loads (adapted from[16]).

Standard axle load (kN)	Pressure on the road surface (Mpa)	Equivalent diameter of wheel track (cm)
100	0.6	30
120	0.6	36

In terms of climatic conditions, the selection of bitumen type is primarily influenced by the air temperature of the construction area. For conventional asphalt mixtures such as dense-graded asphalt concrete, semi-porous asphalt concrete, and polymer-modified asphalt concrete, the bitumen grade is typically chosen according to the standards outlined in TCVN 13567:2022 [17]. For asphalt concrete mixtures designed based on Superpave volumetric properties, the bitumen grade is selected based on the Performance Grade (PG) as specified in TCVN 12818:2019 [18] and TCVN 13049:2020 [19]. For specialized asphalt mixtures, including rough asphalt concrete and porous drainage asphalt concrete, the appropriate bitumen grade is determined based on specific standards tailored to their unique properties and applications.

The assessment of the proposed asphalt pavement structure is conducted based on three primary criteria to verify its load-bearing capacity [16]:

- Elastic deflection: Equivalent pavement structure modulus, E_{eq} , must not exceed the required pavement modulus, E_{rq} , which is determined based on the Equivalent Single Axle Load (ESAL) and standard axle load

$$E_{eq} = K_{ED} \times E_{rq} \quad (7)$$

where K_{ED} is the specific coefficient related to the elastic deflection criterion.

- Shear resistance: The shear stresses induced in the unbound material/subgrade layers (both by wheel load, T_{ax} , and by the weight of overlying layers, T_{av}) must not exceed the allowable shear strength, C_{tt} , of the material at its calculated moisture content

$$T_{ax} + T_{av} \leq \frac{C_{tt}}{K_{SR}} \quad (8)$$

where K_{SR} is the specific coefficient related to the shear resistance criterion.

- Tensile strength: the tensile stress, σ_{ts} , at the bottom of asphalt/bound material must be limited to the tensile strength, R_{tt}^{ts} , of these layers:

$$\sigma_{ts} \leq \frac{R_{tt}^{ts}}{K_{ts}} \quad (9)$$

where K_{ts} is the specific coefficient related to the tensile strength criterion.

For calculations involving the three aforementioned criteria, the asphalt layer modulus values are determined at specific temperatures:

- Elastic deflection and Shear resistance: 30°C is used, representing a hot summer condition, as this temperature is considered unfavorable for asphalt layers to resist deformation.
- Tensile strength: 15°C is used, representing a cold winter condition, as lower temperatures can lead to increased brittleness and cracking.

However, given Vietnam's diverse climate and geographical expanse, using fixed temperatures for the entire country may not be entirely accurate. A more comprehensive approach, considering regional climatic variations, could provide a more precise assessment of pavement performance

3 Selection of equivalent temperature method for implementation in Vietnam

While all of the aforementioned methods for determining equivalent temperature are theoretically applicable in Vietnam, practical implementation faces significant challenges based on previous studies:

- The French method requires extensive data that is often unavailable for specific regions in Vietnam, including traffic patterns, temperature variations, and the relationship between asphalt material fatigue performance and temperature. Gathering all necessary input parameters for this method is time-consuming, costly, and resource-intensive [20].
- The Hungarian method is limited by its reliance on a single year (365 days) of temperature data, which may not adequately represent long-term temperature variations and frequencies. Additionally, the equivalent temperature calculations are primarily performed for catalogued pavement structures that may not accurately reflect the characteristics of Vietnamese pavements [15].
- The Australian method appears more suitable for Vietnam due to its consideration of 20 years of temperature variation, encompassing both the coldest and hottest daily temperatures. However, the data used in the calculations is restricted to specific gridded climate data from weather stations in Australia and New Zealand [14]. This challenge can be addressed by utilizing temperature data from the MERRA-2 database, which provides long-term climatic data for numerous regions worldwide.

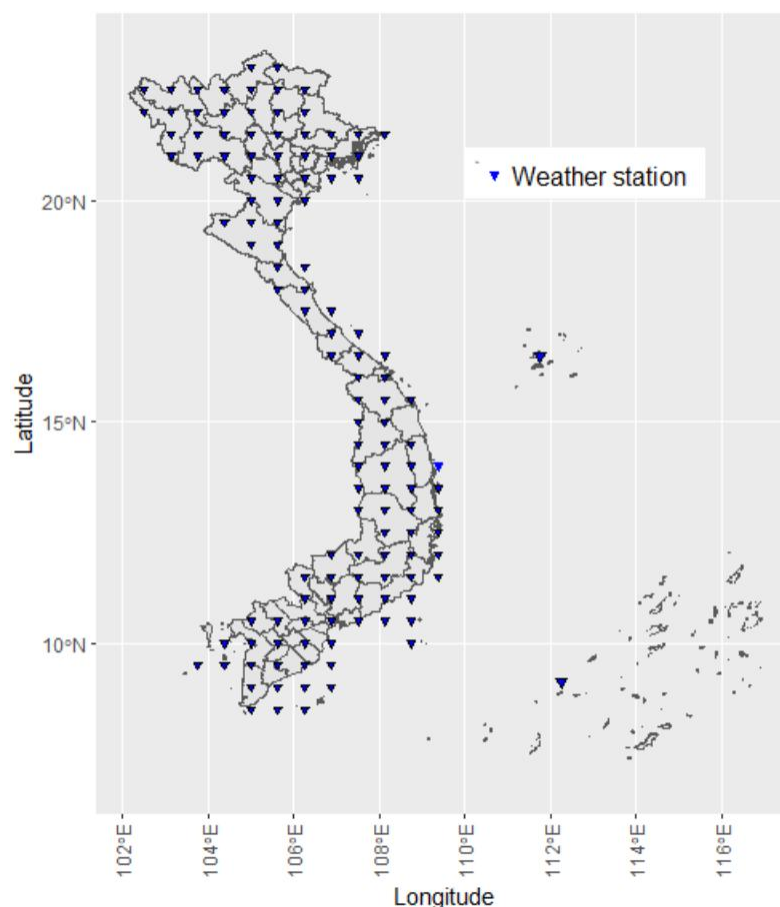


Fig. 2 – Grided map of 127 weather stations in Vietnam used for the study.

Temperature data from the MERRA-2 database [21] will be utilized to create a gridded temperature map encompassing Vietnam's diverse climatic regions. Monthly temperature records from 2003 to 2023, collected from 127 weather stations (see Fig. 2) were collected, providing monthly temperature records from 2003 to 2023. The database therefore includes $127 \times 20 \times 12 = 30\,000$ values for the calculation.

Fig. 3 illustrates the average monthly temperature variations in Hanoi ((Latitude: 21° , Longitude: 105.625°) from 2003 to 2023. As shown, significant fluctuations are observed both within a year and across the 20-year period. These variations underscore the need for a robust methodology to determine an equivalent temperature for asphalt pavement design. A reliable equivalent temperature can serve as a critical input for accurate pavement calculations, ultimately leading to the design of more durable pavement structures.

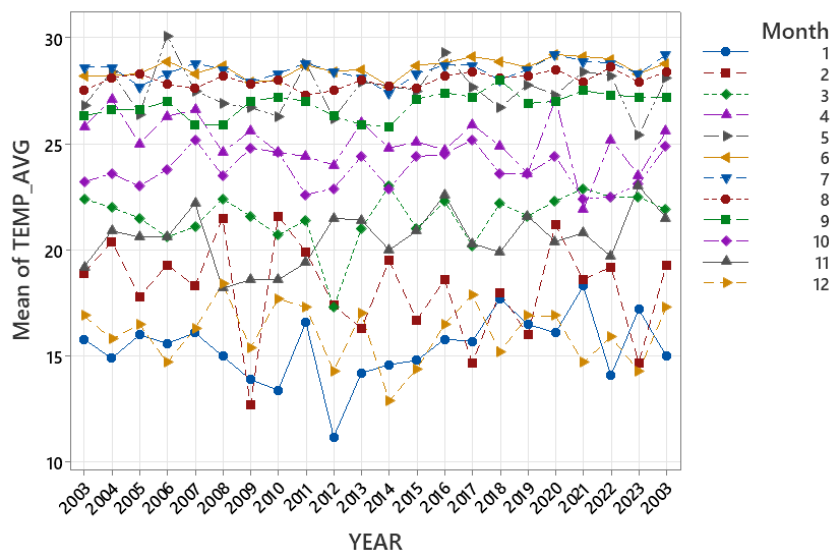


Fig. 3 – Average monthly temperatures in Hanoi (Latitude: 21° , Longitude: 105.625°) from 2003 to 2023.

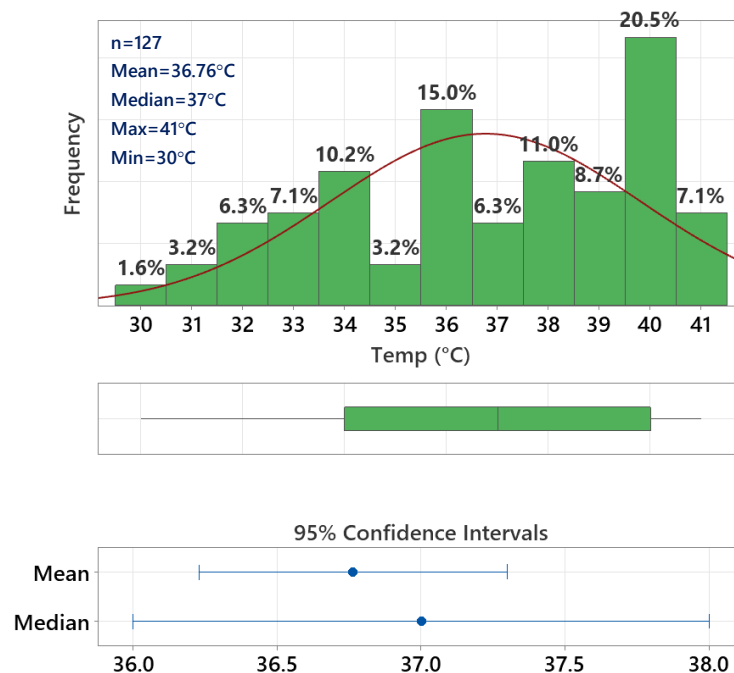


Fig. 4 – Histogram and probability distribution of calculated Weighted Mean Annual Pavement Temperature (WMAPT) for 127 weather stations in Vietnam.

Table 3 – Weighted Mean Annual Pavement Temperatures for 127 weather stations in Vietnam.

Latitude (°)	Longitude (°)	WMAPT (°C)	Latitude (°)	Longitude (°)	WMAPT (°C)	Latitude (°)	Longitude (°)	WMAPT (°C)
10.5	105	41	9	106.875	40	12	108.75	34
10.5	107.5	40	9.5	106.875	40	21.5	105	36
22.5	105.625	33	17.5	106.875	38	13	109.375	39
9	105.625	40	20.5	106.875	38	13.5	109.375	39
21	106.25	36	8.5	106.25	40	13	108.75	36
10	106.875	40	9	106.25	40	13.5	108.75	37
14	109.375	39	18.5	106.25	38	17.5	106.25	36
14.5	108.75	36	8.5	105.625	40	15.5	108.75	39
11.5	106.875	40	9.5	104.375	41	15	108.125	33
12	106.875	40	10	104.375	41	15.5	108.125	36
11	108.125	38	9.5	103.75	41	15.5	107.5	32
8.5	105	40	22.5	105	34	16	107.5	34
9	105	40	23	105	31	15	108.75	37
9.5	105	40	21	105.625	36	21.5	108.125	36
10	105.625	40	18	106.25	38	21	107.5	37
22.5	106.25	32	18	105.625	33	21.5	107.5	34
23	105.625	31	18.5	105.625	38	21	106.875	36
16	108.125	38	10.5	106.875	40	16.5	106.875	35
12.5	108.75	35	20.5	105.625	36	17	106.875	37
12.5	108.125	36	21	105	34	9.5	106.25	40
13	108.125	38	12	109.375	39	9.5	105.625	40
13	107.5	40	12.5	109.375	39	21	104.375	33
12	107.5	36	14.5	108.125	34	21	103.75	32
21	103.125	33	14.5	107.5	36	21.5	103.75	33
21.5	103.125	32	15	107.5	34	11	106.25	41
22	103.125	32	22	103.75	31	11.5	106.25	41
22	102.5	32	22.5	103.125	30	20.5	106.25	37
11	107.5	39	22.5	102.5	31	22	105.625	34
11	106.875	40	11.5	108.125	35	19.5	105.625	37
10.5	105.625	41	12	108.125	34	20	105.625	36
11.5	109.375	40	11.5	107.5	38	20	105	33
10	108.75	40	21.5	106.875	34	20.5	105	34
10.5	108.75	40	21.5	106.25	35	16.5	107.5	38
11	108.75	39	22	106.25	34	10.5	106.25	40
14	108.75	36	22	104.375	33	10	105	41
10.5	108.125	40	22.5	104.375	33	10	106.25	40
13.5	108.125	38	22.5	103.75	32	22	105	36
14	108.125	36	20	106.25	37	21.5	105.625	36
16.5	108.125	39	19	105.625	38	21.5	104.375	30
13.5	107.5	40	19	105	36	16.5	111.75	38
14	107.5	39	19.5	105	34	9.125	112.25	41
17	107.5	39	19.5	104.375	32	-	-	-
20.5	107.5	38	11.5	108.75	37	-	-	-

4 Results and discussions

Table 3 presents the calculated Weighted Mean Annual Pavement Temperatures (WMAPT) for 127 weather stations across Vietnam, which are also visualized in the histogram of Fig. 4. Based on this data, several key observations can be made:

- **Comprehensive database:** The results provide a comprehensive database of equivalent pavement temperatures, each associated with a specific geographic location (longitude and latitude).
- **Wide temperature range:** The calculated WMAPT values range from 30°C to 41°C, with a significant proportion (20.5%) falling within the 40°C range.
- **Current practice vs. Reality:** While the current practice in Vietnam involves using a temperature of 30°C for asphalt pavement calculations, this temperature is applicable to only 1.6% of the 127 regions studied.
- **Impact of climate on pavement performance:** The significant variation in calculated temperatures highlights the substantial impact of climatic conditions on pavement performance. Therefore, it is crucial to apply the findings of this study to ensure accurate pavement structure calculations for specific locations across Vietnam.

5 Conclusions

Equivalent temperature has proven to be a valuable tool in addressing the complexities of pavement design, especially in regions with significant temperature variations and traffic distribution. However, current asphalt pavement design methodologies in Vietnam primarily rely on specific, fixed temperatures for structural design, which may not accurately capture the full range of temperature fluctuations.

This study introduces an application of the Shell method to determine equivalent temperatures for specific regions in Vietnam. By utilizing the Weighted Mean Annual Pavement Temperature (WMAPT), we can incorporate both summer and winter temperature extremes, ensuring that the full spectrum of temperature variations is considered in the design process.

The calculations are performed using 20 years of maximum and minimum monthly temperature data sourced from the MERRA-2 database from 127 weather stations across Vietnam, providing a comprehensive assessment of temperature conditions nationwide. Based on the results, the following conclusions can be drawn:

Gridded Temperature Map: A gridded map of equivalent pavement temperatures has been established for Vietnam, providing valuable data for pavement calculations across various climatic regions.

Significant Regional Variation: The calculated WMAPT values range from 30°C to 41°C, highlighting the significant regional variations in environmental temperatures and their impact on pavement behavior and performance.

Limitations of Single Temperature Value: The results demonstrate that a single, nationwide temperature value is insufficient for accurate and durable asphalt pavement design in Vietnam.

Practical Applications: The WMAPT values provide valuable input for estimating asphalt moduli at in-service temperatures, supporting further pavement research, and serving as a comprehensive database for region-specific pavement design.

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