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Comprehensive Evaluation of Asphalt Pavement Performance in Hot and Humid Areas Based on Self-Organizing Map and Random Forest Algorithms

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Abstract: *With the widespread application of asphalt pavement in highway construction in China, especially in hot and humid areas like Guangdong and Guangxi, this type of pavement faces challenges such as softening, rutting, and accelerated aging under high temperatures and moist conditions. Traditional evaluation models have limitations in these specific environments. This study proposes a new asphalt pavement performance evaluation model using Self-Organizing Map (SOM) and Random Forest (RF) algorithms, re-evaluating and optimizing the weight of pavement performance evaluation indicators based on actual data from 14 highways in hot and humid areas. Through cross-validation and case analysis, the new model not only excels in accurately reflecting the actual performance of asphalt pavement in hot and humid areas but also provides more effective decision support for local asphalt pavement maintenance and management.*

Keywords: *Humid and Hot Areas, Asphalt Pavement, Evaluation Model, SOM, RF*

1. Introduction

Since 2000, China's highway network has undergone significant expansion, particularly asphalt pavement, due to its superior comfort and economic benefits, becoming the preferred material in road construction and dominating road construction in China [1]. However, such pavement faces unique challenges in hot and humid areas like Guangdong and Guangxi. Here, asphalt pavement often suffers from softening, rutting, and accelerated aging due to high temperatures and moist environments, raising widespread concern for road maintenance and safe driving [2]. Current asphalt pavement performance evaluation models do not fully consider the characteristics of hot and humid environments, possibly leading to inaccurate assessments. Although the Chinese Ministry of Transport issued the "JTG 5210 2018 Highway Technical Condition Assessment Standards" in 2019 to guide highway maintenance, the applicability of existing evaluation models in extreme climatic conditions remains questionable, particularly in the weight distribution of key indicators like PBI (Pavement Behavior Index) and SRI (Skid Resistance Index) [3]. This affects the accuracy of the assessment results and may mislead maintenance and management decisions [4]. This paper will detail the application of SOM and RF algorithms in the performance assessment of asphalt pavement in hot and humid areas and demonstrate how this method improves the accuracy and adaptability of assessments.

2. Literature Review

In the field of asphalt pavement performance evaluation, recent studies have shown a diverse trend in development. Early research found that an increase in pavement temperature accelerates the thermo-oxidation of asphalt binders, leading to mixture hardening and fatigue cracking [5]. This finding is particularly significant in hot and humid regions, as environmental factors such as temperature, precipitation, and humidity play a key role in the changes in asphalt pavement performance. For instance, Researchers have noted that these factors could lead to the formation of cracks and fissures, especially under extreme temperature conditions leading to asphalt pavement cracking [6-7].

To address these issues, the introduction of entropy theory has been pivotal in improving the methodology for determining the weight of evaluation indicators, a crucial aspect in accurately assessing pavement performance in these challenging environments [8]. The adaptability of evaluation models under varying climatic conditions and the need to integrate climate change considerations into pavement design have been increasingly recognized [9]. Research has delved into the impacts of climate change on asphalt pavements, exploring potential adaptation strategies [10-11]. These include methods like upgrading asphalt binder grades, increasing the thickness of asphalt concrete and base layers, and using stable base layers to mitigate pavement deterioration and prolong their lifespan [12]. The importance of accurate pavement performance modeling for cost-effective design and management, along with the necessity for climate-specific pavement models, has also been highlighted[13].

Recent research has begun to explore advanced algorithms to improve the accuracy and adaptability of asphalt pavement performance evaluations. The use of an Artificial Neural Network (ANN) model has shown efficiency and accuracy in predicting the Pavement Condition Index (PCI), offering a solution to the complexities of traditional visual inspection methods [14]. The ASENN neural network framework has further enhanced the precision of pavement deterioration predictions, surpassing mainstream models in efficiency [15]. Additionally, the application of the Support Vector Machine (SVM) algorithm and OTSU's method in asphalt pavement crack classification has been noted [16]. The effectiveness of Self-Organizing Maps (SOM) in uncovering deep data structures, thanks to its unique features as an unsupervised learning algorithm, has been demonstrated by studies [17-18]. Additionally, the proven efficacy of the Random Forest (RF) algorithm in handling large datasets, stemming from its characteristics as an ensemble learning algorithm, is evident in studies [19-21].

These studies emphasize the necessity of using complex methods for asphalt pavement performance evaluation in hot and humid areas, revealing the potential of advanced technologies in enhancing the accuracy and adaptability of evaluations. However, existing research on the comprehensive evaluation of asphalt pavement performance in hot and humid areas, especially concerning weight distribution and prediction model accuracy, remains insufficient.

In summary, to effectively assess asphalt pavement performance in hot and humid areas, it is necessary to consider the impact of environmental factors and adopt more advanced assessment methods. The progress of these methods not only helps improve the accuracy and reliability of assessments but also ensures that pavement performance evaluations can adapt to various environmental changes, providing more effective decision support for asphalt pavement maintenance and management in hot and humid areas.

3. Methodology

In light of these findings, this study employed a combination of SOM and RF to optimize weight distribution and construct an assessment model better suited to the characteristics of hot and humid regions.

3.1 Data Collection

Table 1: Survey section of asphalt pavement in hot and humid regions

No.	Highway Name	Climate Zone	Total mileage (KM)	Operating duration (year)	Number of lanes
1	NY	Hot and humid region	180.063	16	6
2	CJ	Hot and humid region	147.636	5	4
3	CS	Hot and humid region	71.541	2	4
4	CZ	Hot and humid region	16.729	2	4
5	DN	Hot and humid region	136.01	12	4
6	NT	Hot and humid region	72.77	13	4
7	NW	Hot and humid region	81.54	12	4
8	LM	Hot and humid region	197	11	4
9	DA	Hot and humid region	4.54	12	4
10	AJ	Hot and humid region	1.57	6	4
11	TB	Hot and humid region	164.904	14	4
12	YB	Hot and humid region	22.911	14	4
13	GX	Hot and humid region	160.203	8	4
14	JG	Hot and humid region	6.912	24	6

This study selected 14 typical highway sections in the hot and humid regions of Guangdong and

Guangxi provinces in China, ensuring comprehensive coverage of major variables affecting pavement technical conditions, such as climate, traffic volume, operating duration, and current pavement performance. The collected data encompassed related detection data of the Pavement Quality Index (PQI), including Pavement Condition Index (PCI), Pavement Bounce Index (PBI), Skid Resistance Index (SRI), Road Quality Index (RQI), and Rutting Depth Index (RDI). These data were collected using standardized road condition detection equipment and techniques to ensure accuracy and consistency. After careful preprocessing, including data cleaning, missing value handling, and outlier analysis, a database of approximately 2086 samples was established, providing foundational data for the construction of the asphalt pavement evaluation model. The specific highway information is presented in the following table 1.

3.2 Weight Determination Method

In this study, SOM, as an unsupervised learning method, played a key role in determining the weight of asphalt pavement performance evaluation indicators. A SOM network with 46×46 neurons was constructed, as shown in Figure 1, and underwent 200 iterations of training to analyze the 2086 samples of 5-dimensional data, as depicted in Figure 2. The SOM network demonstrated high precision and reliability, with an average quantization error of only 0.088954, effectively revealing the relative importance between different evaluation indicators. This process provided a solid foundation for the optimization of weights in the Random Forest model, enhancing the application effect of the model in asphalt pavement assessment in hot and humid areas.

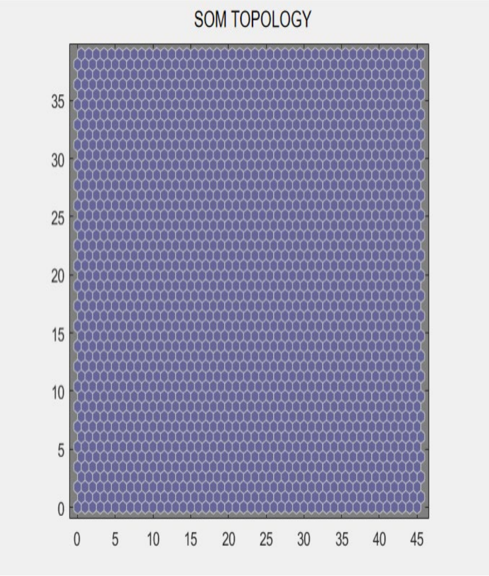

Figure 1: SOM Topology Structure

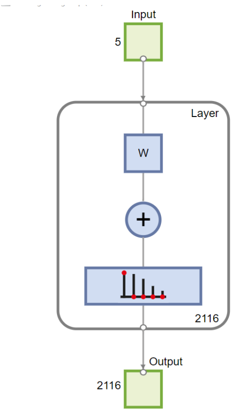

Figure 2: SOM Operating Principle

3.2.1 Pavement Evaluation System and PQI Composition

Prior to this study, the traditional pavement evaluation system used a standardized method of weight distribution to calculate the Pavement Quality Index (PQI). This system included multiple key performance indicators such as PCI, PBI, SRI, RQI, and RDI. Each indicator was weighted differently by experts based on its impact on the overall pavement condition.

The specific calculation formula is as follows:

$$PQI = \omega PCI\times PCI + \omega RQI\times RQI + \omega RDI\times RDI + \omega PBI\times PBI + \omega SRI\times SRI \text{ ...... Eq} \qquad (1)$$

where ω's are weights for specific criteria defined in Table 2.

The traditional method of weight distribution did not fully adapt to the special environmental conditions of hot and humid areas, such as the impact of long-term high temperatures and humidity on pavement materials. This study optimized these weights by combining SOM and RF algorithms to more accurately reflect the performance of asphalt pavements in these areas. This new evaluation model not only improved the accuracy of assessments but also provided a more effective tool for the maintenance and management of roads.

Table 2: PQI Weight of each index

Pavement Type	Weight	Criterion	First Class Highway	Two, Three, Four Class Highway
Asphalt Surface	ω_{PCI}	Evaluates the extent of pavement deterioration and the need for repairs, including aspects such as cracks, potholes, and surface wear.	0.35	0.60
	ω_{RQI}	Measures the levelness and ride comfort of the pavement, including unevenness and undulations.	0.30	0.40
	ω_{RDI}	Assesses the severity and impact of rutting on the pavement, focusing on aspects like the depth and frequency of wheel track depressions on the road surface.	0.15	——
	ω_{PBI}	Evaluates the degree of vehicle bouncing or vibration caused by the pavement, typically associated with the road's unevenness or wear condition.	0.1	——
	$\omega SRI(\omega wI)$	Evaluates the degree of vehicle bouncing or vibration caused by the pavement, typically associated with the road's unevenness or wear condition.	0.10	——
	$\omega PSSI$	Evaluates the load-bearing capacity and durability of the pavement structure, focusing on the strength and thickness of pavement materials, as well as their resistance to heavy vehicle loads and long-term usage.	——	——

3.3 Model Construction

In this study, the SOM and RF algorithms were utilized to optimize and enhance the asphalt pavement performance evaluation model. These algorithms play complementary roles in the assessment process, jointly improving the accuracy and adaptability of the evaluation.

SOM, as an efficient unsupervised learning algorithm, plays a crucial role in data structure analysis and feature extraction. By constructing a network of 46×46 neurons, SOM focuses on uncovering hidden patterns and relationships from complex pavement performance data. Its strength lies in handling large volumes of multidimensional data, revealing interconnections and relative importance among evaluation indicators. This step is foundational for the entire assessment process, providing key inputs for subsequent higher-level analyses.

Subsequently, the RF algorithm was introduced as the main predictive model. RF, known for its ensemble learning characteristics, excels in handling large datasets and complex classification problems. In this study, the RF algorithm used features and patterns extracted by SOM to construct a model comprising 100 decision trees. Each tree independently trained on different subsets randomly selected from the overall dataset, further enhancing the model's generalization ability and robustness. The RF model not only excels in predicting asphalt pavement performance but also provides precise data-driven support for maintenance and management decisions.

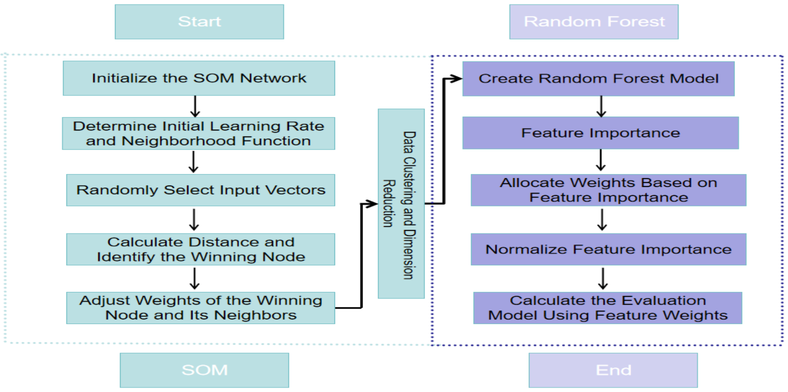

Figure 3: Basic Steps of the SOM-RF Model

By combining the data structure analysis capabilities of SOM with the predictive modeling strengths of RF, this study successfully developed a highly adaptive asphalt pavement performance comprehensive evaluation model for hot and humid environments, as shown in Figure 3. The innovative aspect of this methodology lies in clarifying the distinct roles and interrelationships of the two algorithms throughout the evaluation process, thereby ensuring the overall performance and reliability of the evaluation model.

3.4 Cross-Validation Method

To test the accuracy and stability of the model, this study employed a cross-validation method. Specifically, a five-fold cross-validation was used, dividing the dataset into five equal parts, with each part used for testing and the remaining four for training. By comparing the results of each validation, we assessed the model's performance consistency across different data subsets. In the five validations, the model's accuracy rates were 99.76%, 99.28%, 100%, 98.80%, and 98.56%, as shown in Figure 4, demonstrating high stability and reliability.

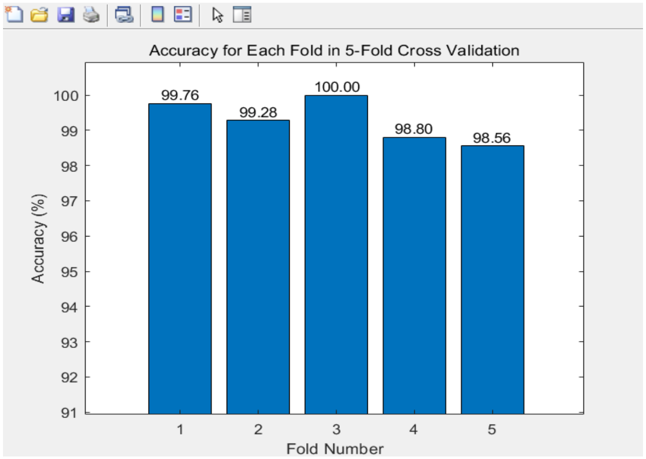

Figure 4: Cross-Validation Accuracy Rates of the SOM-RF Model

4. Results

Using the aforementioned methodology, this study achieved the following key results, demonstrating the effectiveness and adaptability of the newly developed model.

4.1 Weight Analysis and Model Establishment

In this study, weights for the asphalt pavement performance evaluation indicators in hot and humid areas were determined using a combined approach of SOM and RF algorithms. After analysis, weights were assigned for PCI, RQI, RDI, PBI, and SRI as 0.496, 0.131, 0.145, 0.079, and 0.149, respectively, as shown in Figure 5. These weights, based on data analysis under specific conditions of hot and humid areas, reflect the relative importance of each indicator in evaluating pavement performance.

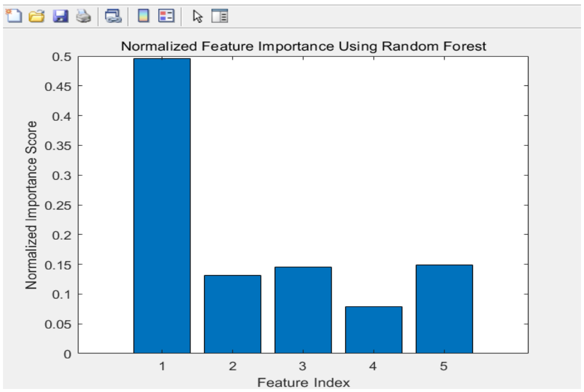

Figure 5: Weight Distribution of Each Evaluation Indicator

Based on these weights, the Pavement Quality Index (PQI) for hot and humid areas (PQIHH) is calculated as follows:

$$PQI_{HH} = 0.496\times PCI + 0.131\times RQI + 0.145\times RDI + 0.079\times PBI + 0.149\times SRI \text{ ....Eq} \quad (2)$$

4.2 Model Cross-Validation Assessment

The model's performance was evaluated through five-fold cross-validation. During the validation process, the model demonstrated high accuracy, with an average accuracy rate of 99.28% and a standard deviation of 0.55%, indicating good consistency and stability across different data subsets. Additionally, the model's average Out-of-Bag (OOB) error rate was 0.77%, further confirming its good generalization ability in assessing asphalt pavement performance in hot and humid areas. These statistical results demonstrate the model's reliability and effectiveness in predicting the performance of asphalt pavements in hot and humid areas (Table 3).

Table 3: Cross-Validation Results of the PQI SOM-RF Model

No.	Indicator	Value	Description
1	Average Accuracy	99.28%	The model's average accuracy rate in five-fold cross-validation.
2	Standard Deviation	0.61%	The standard deviation of the model's accuracy across different data subsets, indicating consistency and stability.
3	Average OOB Error Rate	0.72%	The model's average Out-of-Bag error rate, indicating its generalization capability.

4.3 Practical Application Verification

Table 4: Road Condition Survey Testing Items and Equipment

Test items	Main testing equipment	Type of equipment	Detection purpose
PCI	Multi-functional road condition rapid detection system	Instrument model: CICS	Determining the condition, extent and scope of road damage
RQI	Multi-functional road condition rapid detection system	Instrument model: CICS	Evaluate road surface smoothness
RDI	Multi-functional road condition rapid detection system	Instrument model: CICS	Analysis of road rutting condition, extent and extent
PBI	Multi-functional road condition rapid detection system	Instrument model: CICS	Evaluate the road jumping index
SRI	Pavement lateral force coefficient test system	Instrument model: SFC-2007	Evaluation of pavement skid resistance

Road condition surveys were conducted on two representative asphalt highway sections in Guangxi Province: from K1069 to K1100 and from K23 to K40. The main testing items and equipment are listed in Table 4.

4.3.1 Evaluation Result Comparison

Based on SOM and RF algorithms, a new asphalt pavement technical condition assessment model for hot and humid areas was established, modifying the weights for the standard evaluation method indicators PCI, RQI, RDI, PBI, and SRI from 0.35, 0.3, 0.15, 0.1, 0.1 to 0.496, 0.131, 0.145, 0.079, and 0.149 respectively. A comparison of the weight values for each indicator is shown in Table 5.

Table 5: Comparison of Evaluation Indicator Weights

Evaluation Methods	PCI	RQI	RDI	PBI	SRI
Standard Evaluation Method	0.35	0.3	0.15	0.1	0.1
Evaluation Method of This Study	0.496	0.131	0.145	0.079	0.149

To verify the accuracy of the pavement technical condition assessment model, road condition survey data from the K1069 to K1100 section of a highway in Guangxi were used. This approach incorporated a method for evaluating road marking performance, as described in [22]. The verification results are shown in Figures 6 and 7.

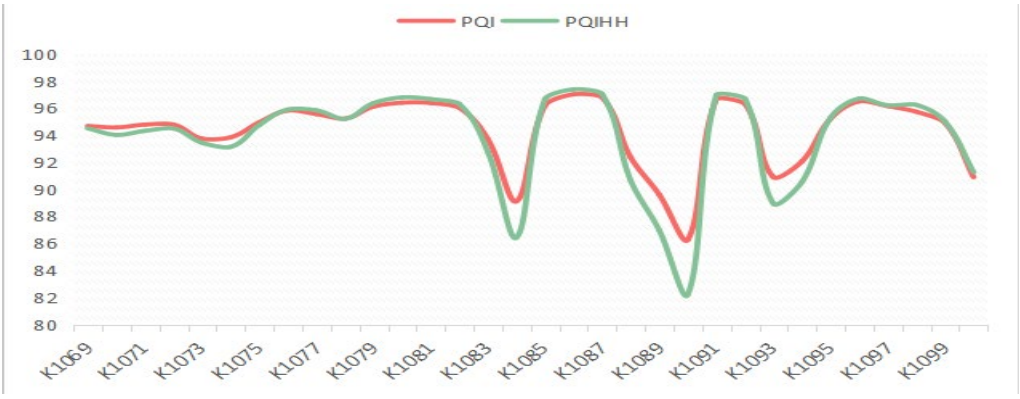

Figure 6: PQIHH vs. PQI Evaluation Indicators Comparison for Highway 1 (K1069-K1100 Section)

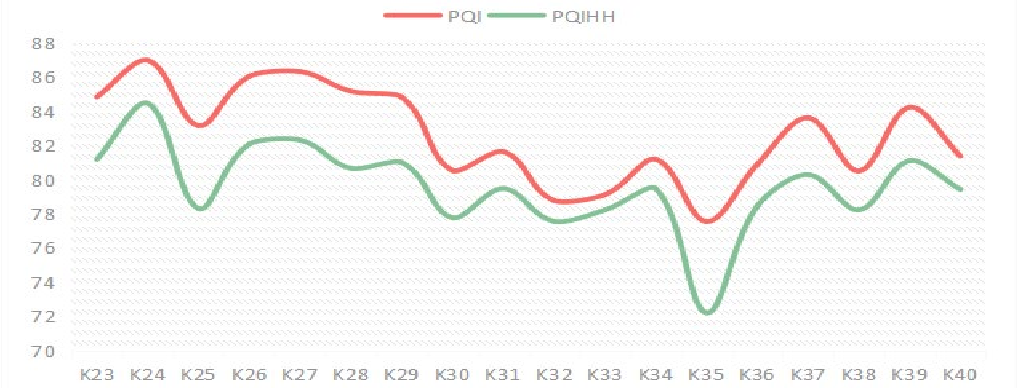

Figure 7: PQIHH vs. PQI Evaluation Indicators Comparison for Highway 2 (K23-K40 Section)

The comparison of evaluation results shows differences between the two evaluation methods. When the score is above 90, the standard model evaluation results reflect the actual road condition well, and the maintenance plan proposed based on the evaluation results is targeted, with the results of the two methods being essentially consistent. However, when the score is below 90, taking the K23-K40 section of Highway 2 as an example, the excellent rate according to the standard evaluation method PQI is 83%, while using the evaluation method of this study, the excellent rate is 44%. On-site surveys found severe damage to the asphalt pavement on this section, and the evaluation results of this study are consistent with the on-site survey results.

5. Discussion

5.1 Interpretation of Results

In this study, the use of the SOM-RF model led to significant changes in the weights of the evaluation indicators, particularly for PCI, whose weight increased from 0.35 to 0.496. This reflects the advantage of SOM and RF algorithms in capturing the unique environmental factors impacting asphalt pavements in hot and humid regions. The high temperatures and humidity conditions prevalent in these regions accelerate the aging and damage of pavement materials, making PCI a key indicator for assessing the overall condition of asphalt pavements. Additionally, the weight of SRI increased from 0.10 to 0.149, indicating the increased importance of skid resistance under humid conditions, especially in frequently rainy and humid conditions where pavement friction characteristics are crucial for traffic safety. Conversely, the weight of PBI decreased from 0.1 to 0.079. This reduction reflects the lower sensitivity of PBI in reflecting pavement conditions in hot and humid environments, where conditions like high-temperature softening of asphalt reduce the overall reliability of the PBI index compared to PCI and SRI.

Further analysis revealed significant differences between the study model and traditional evaluation methods in scenarios where scores were below 90. For example, in the evaluation of Highway 2 (K23-K40 segment), the study's model showed an excellent rate of 44%, while the traditional method showed 83%. This discrepancy indicates that the study's model gives more consideration to the actual damage conditions of pavements under high temperature and humidity, providing a more realistic and detailed assessment, and offering more accurate guidance for road maintenance and repair.

5.2 Advantages and Limitations of the Method

The combination of SOM and RF in asphalt pavement performance evaluation offers significant advantages. This method not only improves prediction accuracy but also enhances the model's adaptability to the unique environmental conditions of hot and humid regions. However, the effectiveness of the method highly depends on the quality and quantity of data. In scenarios with insufficient or poor-quality data, the accuracy of the model may be affected. Additionally, the complexity of the model may pose challenges in some practical application scenarios, especially in resource-limited contexts.

5.3 Comparison with Other Studies

Compared to existing literature, a unique contribution of this study is the combination of SOM and RF algorithms for performance evaluation of asphalt pavements in hot and humid regions. This approach has been rarely attempted in existing research, and the results demonstrate its effectiveness in improving assessment accuracy and adaptability. Future research could explore how to further simplify this method for easy application in resource-limited contexts or how to apply this method to other types of roads and different climatic conditions.

The results support the hypothesis of this study that combining SOM and RF algorithms can more accurately assess the performance of asphalt pavements in hot and humid regions.

In summary, this study not only proposes an effective evaluation model but also offers new perspectives for the management of asphalt pavements in hot and humid areas.

6. Conclusion and Future Research Directions

In conclusion, this study successfully developed an asphalt pavement performance evaluation model suitable for hot and humid areas, combining the advantages of SOM and RF algorithms. This model effectively improves the accuracy of assessments and provides strong support for road maintenance and management decisions. Future research could explore applying this model to other pavement types under different climatic conditions or integrating more emerging technologies, such as big data analysis and the Internet of Things, to further enhance the model's predictive capabilities and real-time applications. Additionally, considering the rapid changes in environmental conditions, especially in the context of global climate change, long-term studies on the performance and sustainability of this model in practical applications will be an important direction for future research.

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