Research Article

A Quantitative Rating System for Pollutant Emission Reduction of Asphalt Mixture

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Received 18 December 2016; Accepted 26 October 2017; Published 21 November 2017

Academic Editor: Sandro Longo

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This study presents a comprehensive pollutant reduction rating system for hot mix asphalt (HMA) with three Level I indices and ten Level II indices, covering various aspects in HMA pollutant emissions, energy consumption, and exhausts from construction equipment. The pollutant emission reduction effects are investigated not only in the laboratory for modified asphalt mixtures with various mixture gradation and binder types but also in the field for several warm mix asphalt (WMA) projects. Furthermore, energy consumption and emission data during pavement construction are obtained from 58 in situ highway projects in 10 provinces of China. Based on the hierarchical clustering method and Bayesian discriminant analysis, individual ranking systems are developed to quantify pollutant emission reduction effects and energy consumption. Subsequently, a comprehensive reduction rating system is established based on the analytic hierarchy process and approximation methods. A case study is demonstrated to implement the proposed system for the assessment of emission reduction effects.

1. Introduction

The development of low-carbon economy and society is currently a strategic focus around the world [1–3]. Significant amounts of pollutant gases are emitted during asphalt concrete production and construction under high temperature conditions (more than 160°C), which not only pollute the environment but also are harmful to the health of highway constructors. Many research efforts based on various methods, such as warm mixing, cold mixing, cold paving technologies, and mixing equipment improvement of asphalt mixture, are conducted to save energy and reduce emissions in road construction. Applying pollutant emission reduction technology has been widely proved to be efficient to reduce energy consumption and decrease pollutant emissions of hot mix asphalt (HMA) mixtures during the process of mixing and construction. For example, the relevant research found that warm mix asphalt technologies can reduce the binder viscosity and enhance the asphalt mixture workability already at lower temperatures (90–140°C), which could save 20–70%

of the energy consumption when compared to hot mix asphalt, mainly due to the temperature reduction in the warm mix processes [4, 5].

Researchers around the world have developed dozens of rating methods to assess pollutant emissions of HMA mixtures, which are primarily based on qualitative principles, while other researchers investigated emission reduction effect and energy consumption quantitatively via quota evaluation. Various green building assessment systems have been established in the past decade, such as BREEAM of UK [6], LEED of USA [7, 8], Ecological Architecture Guidelines LNB of Germany [9], International Organization GBTool in which Canada and other nations participated [10], and NABERS in Australia [11, 12]. These rating systems developed specific standards and scoring systems to establish a healthy and comfortable living environment, save resources, and decrease the effect of pollutants on the environment, which are suitable for site planning, land use, energy conservation, renewable energy utilization, and indoor and outdoor environmental quality. However, these standards are not

particularly customized for road construction. Most current quantitative research on energy conservation and emission reduction of HMA mixtures are mainly based on life cycle analysis (LCA). Horvath and Hendrickson [13] developed the EIO-LCA model and quantized the energy consumption and pollutant emission of HMA mixtures. Stripple [14] analyzed the effect of pavement types on the environment using all life cycle methods. On the basis of the life cycle method and expert decision, Mroueh et al. [15] obtained the rating result of environmental influence through quantitative index weight. Papagiannaki and Diakoulaki [16] determined the influencing factors of road transportation in Greece and Denmark using the logarithmic distribution method. PALATE is a calculation model developed at the University of California, which conducts sensitivity analysis on the collected data on energy consumption and pollutant emission [17]. Chang'an University proposed an analysis model of energy consumption and pollutant emission using the quota method and developed a quantitative rating method for energy conservation and emission reduction effect of asphalt pavements [18]. The majority of researches analyze the effects of energy conservation and emission reduction through the quota method in all life cycles, whereas others examine these effects further by analyzing energy consumption and pollutant emissions reduction. However, no corresponding classification standards regarding the energy consumption and emission reduction effect are established, and evaluations of pollutant emission reduction of asphalt mixture could not be analyzed and assessed comprehensively, which result in the limited application of pollutant emission reduction technology of asphalt mixtures. In addition, current rating methods mainly focus on a single index, and the data volume and the scope of data sources cannot satisfy the rating requirements of pollutant emission reduction of HMA mixtures. Therefore, collecting laboratory and field test data is necessary to achieve an accurate evaluation of the emission reduction and energy conservation effect.

This study develops a rating system of asphalt mixtures from three aspects, namely, pollutant emissions of asphalt mixture, energy consumption, and exhaust from construction machines, to address the aforementioned problems. The classification of indices is presented to promote energy conservation and emission reduction. The rates of pollutant emission reduction are obtained from laboratory testing, and the energy consumption is examined in the field. Individual classification standards for HMA pollutant emission reduction effects and energy consumption are developed based on hierarchical clustering method and Bayesian discriminant analysis, while the comprehensive rating system is established based on the AHP and approximation methods. A case study is demonstrated in this paper for the Haihe Tunnel project in Tianjin to evaluate the emission reduction effects of the WAM-flame retardant mixture.

2. Selection of Rating Indices

Different pollutant gases, such as asphalt fume, carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulfur dioxide (SO₂), are generated in the mixing

and construction of asphalt mixtures. Construction vehicles and equipment consume energy and produce substantial amounts of exhausts. In this study, a rating system will be developed to evaluate pollutant emissions from asphalt mixtures and construction machines.

Currently, there are few accurate and intensive studies on asphalt fumes and conditions. The ultraviolet spectrophotometry method, whose absorption liquid is benzene, is commonly employed. However, this test method is complicated and expensive. Thus, asphalt fumes are excluded in the pollutant emissions of asphalt mixtures according to reasonable principles of operational evaluation.

The pollutant gas emitted from the surface of HMA mixtures is minimal since asphalt mixtures are covered during transportation. Gas detection equipment cannot easily identify pollutant emissions because it is influenced by many factors in the open environment. No accurate test method has been developed to measure the pollutant emission produced during the transportation, paving, and compaction processes. Therefore, pollutant emissions of HMA mixtures during transportation, paving, and compaction are not considered in the rating system.

Converting the amount of CO and CO₂ into equivalent CO_x is challenging because gas detector sensors available in the market have different calculation method and accuracy, and the components of CO_x are complex. Thus, the rating index is divided into three or four parts (NO_x, CO_x, and SO₂ or NO_x, CO, CO₂, and SO₂) to establish the rating system of pollutant emission reduction of the HMA mixture according to actual conditions of pavement construction.

Energy consumption is mainly produced in four key stages of construction of asphalt mixtures, namely, mixing, transportation, paving, and compaction. Thus, this study develops a rating system of energy consumption based on these four periods. Moreover, the mixing temperature and energy consumption of WMA mixtures are lower comparing to hot mix asphalt (HMA) mixture, whereas not the same trend follows in the mixing process for WMA and HMA mixtures. The differences should be considered in the rating system.

A rating system on reducing pollutant emissions of asphalt mixtures is developed from the three processes in constructing asphalt pavements, namely, transportation, paving, and compaction.

The specific rating system is shown in Table 1.

In addition, rating process used for hot recycling asphalt mixtures should be improved to a higher level.

3. Data Collection

This study presents a laboratory test equipment to test pollutant emissions and proposes a laboratory method to test pollutant emissions of asphalt mixtures.

The procedure of the laboratory test is shown as follows: the stirring system is sealed using high-temperature-resistant materials with a 3 cm to 4 cm wide aperture on the sealing materials. After stirring the asphalt mixture, the stirring system is elevated to an appropriate height to convey the pollutant gas while a paddle keeps stirring the asphalt

TABLE 1: Rating system of pollutant emission reduction of asphalt mixture.

Level I index				Level II index				
Rating system of pollutant emission reduction of asphalt mixture	Pollutant emissions of HMA	0.59	Reduction rate of NO _x	0.40	or	Reduction rate of NO _x	0.29	
			Reduction rate of CO _x	0.40		Reduction rate of CO	0.29	
						Reduction rate of CO ₂	0.29	
			Reduction rate of SO ₂	0.20		Reduction rate of SO ₂	0.13	
	Energy consumption	0.36	Energy-saving effect in mixing process (warm mixing)	0.70	or	Energy consumption per unit mixing production (hot mixing)	0.70	
			Unit energy consumption in transportation process				0.05	
			Unit energy consumption in paving process				0.10	
			Unit energy consumption in compaction process				0.15	
	Mechanical exhaust in construction process	0.05	Quantitative pollutant emissions in mixing period				0.17	
			Quantitative pollutant emissions in paving period				0.28	
			Quantitative pollutant emissions in compaction period				0.55

FIGURE 1: Design of the testing setup.

mixture. Pollutant gases are produced through a pipe and tested by HA-856 portable gas detector on the nozzle. After repeated experiments, the optimal experimental information is obtained, such as mixing revolution (17 times), mixing temperature (160°C), and mixing quality of asphalt mixture (12,000g). The design and image of the test setup in evaluating the pollutant emissions are shown in Figure 1.

3.1. Reduction Rate of Pollutant Emissions. Different types of basic materials are selected in this work, and WEAM, WEP, and WES asphalt modifiers are developed by compounding the basic materials with dispersants and (or) coupling agents via experimental testing [19]. Thus, this study tests the NO_x and CO_x emissions of asphalt mixtures with different modifiers, asphalt categories, and gradation types based on

the proposed test method and principles. The reduction rate is calculated to investigate the influence of modifiers on the pollutant emissions of the HMA mixture. WEAM, WES, or WEP modifiers are added to the asphalt mixture to replace the same amount of mineral powder, which has a dosage of 20% of the weight of asphalt. The definition of the reduction rate is as follows:

$$R = \frac{E_2 - E_1}{E_2}. \quad (1)$$

Note. E_1 is quantitative pollutant emissions of asphalt mixture with modifiers (ppm), E_2 is quantitative pollutant emissions of asphalt mixture without modifiers (ppm), and R is reduction rate of asphalt mixture (%).

3.1.1. HMA Mixture

(1) *Based on Asphalt Binder Types.* Based on the asphalt types, production areas, asphalt grade, and other factors, this study selects different types of asphalts as experimental asphalt materials. The emissions of NO_x and CO_x of different asphalt mixtures with different modifiers and the reduction rates are calculated. The gradation used in the test is AC-13, and the test results are presented in Table 2.

(2) *Based on Mixture Gradation.* Gradations commonly used in China include AC-13, AC-16, SMA-13, and OGFC-13. Therefore, Shandong base asphalt 70# and the gradations mentioned previously are selected to test the emissions of NO_x and CO_x . The reduction rates are calculated and indicated in Table 3.

3.1.2. WMA Mixture

(1) *Based on WMA Modifier Types.* Considering the WMA modifier types, mixing amounts, mixing temperatures, and gradation types, the reduction rates of WMA mixture (mainly Evotherm, APTL, Aspha-min, and Sasobit, and the mixing temperature is 110°C to 130°C) are obtained from different institutions or research units. The data are shown in Table 4.

(2) *Based on Testing Temperatures and Asphalt Binder Types.* Base asphalt 70# in Shandong and Shaanxi, SBS asphalt in Tianjin, and hard asphalt 20# are selected. The mixing temperatures ranging from 120°C to 140°C are chosen to determine the impact of temperatures and asphalt types on the pollutant reduction rate. The reduction rates of CO_x and NO_x are shown in Table 5.

3.2. Energy Consumption and Energy-Saving Effects of Construction Equipment

3.2.1. *HMA Mixture.* The energy consumption in mixing, transportation, paving, and compaction affects energy conservation and emission reduction effect of the entire process of pavement construction. This study evaluates the energy consumption during the whole construction process. The energy consumption data of highways located in different areas are collected and indicated in Table 6.

3.2.2. *WMA Mixture.* Thorough surveys of the energy consumption of WMA (the most commonly used WMA types are Evotherm, WMA-Foam, Aspha-min, and synthetic zeolite at a temperature ranging from 110°C to 130°C) in the mixing process after employing a pollutant emission reduction technology in different institutions or research units are conducted in this paper. Mixing energy consumption of WMA mixture is shown in Table 7.

4. Methodologies for Individual Ranking and Comprehensive Rating

4.1. *Clustering and Bayes Based Methods for Individual Ranking.* Classification that focuses on the reduction rate of

pollutant emissions of the HMA mixture should be established to classify the effect of pollutant emission reduction on asphalt mixtures using pollutant emission reduction technology and to determine the relative ranking levels. The commonly used methods include natural breaks classification, iteration method, and hierarchical clustering [20–22].

Clustering analytical method is adopted to conduct clustering analysis on pollutant emission reduction and energy consumption of asphalt mixtures. The commonly used clustering methods include hierarchical clustering method, dynamic clustering method, ordinal clustering method, and fuzzy clustering method [23–25]. The hierarchical clustering method is suitable for classifying samples with a large amount of data, and the samples can be classified without referential patterns [26]. Calculation using this method is easy, and the results are definite and accurate. Therefore, this study adopts the hierarchical clustering method to establish the scales of pollutant emission reduction of asphalt mixtures.

The basic principle of hierarchical clustering method is as follows: n samples are assumed, and each sample has m measured indicators. The distance between the samples (or similarity coefficient) and the distance between groups should be defined. n samples can be initially regarded as n groups (a group consists of samples). Thus, the distance between groups is equivalent to the distance between samples. Two groups with closest distances are combined to form a new group, and the distance between the new group and other groups will be calculated. The combination will be repeated according to closest distance until all the samples form one group. This combination process can be comprehensively described using the pedigree clustering diagram.

The mathematical principle is as follows: n samples are assumed to be classified into five groups called G_1, G_2, G_3, G_4 , and G_5 . n_t represents the number of samples in group G_t , $X_{(i)}^{(t)}$ refers to the center of gravity of group G_t , and $X_{(i)}^{(t)}$ is sample number i in group G_t . Thus, the sum of the squares of deviations of the pollutant sample in G_t is expressed as follows:

$$W_t = \sum_{i=1}^{n_t} \left(X_{(i)}^{(t)} - \bar{X}^{(t)} \right)' \left(X_{(i)}^{(t)} - \bar{X}^{(t)} \right). \quad (2)$$

Note. $X_{(i)}^{(t)}$ and $\bar{X}^{(t)}$ are m -dimension vectors and W_t is a value ($t = 1, 2, \dots, k$).

Ward method is used to obtain the sum of the squares of deviations, exhibiting reasonable classification, and is used widely. We employed the Ward method to calculate the ranking level space in this study.

The sum of the squares of deviations is the squared distance between groups when Ward method is adopted because the two groups of the five samples are grouped as one. The distances between the samples utilize Euclidean distance. Thus,

$$D_{pq}^2 = \frac{n_p n_q}{n_r} d_{pq}^2. \quad (3)$$

TABLE 2: Reduction rate of NO_x and CO_x from different modifiers and asphalt types.

Reduction rate (%)	Modifiers types	Base asphalt				SBS asphalt				Hard asphalt 20#
		Shandong 70#	Shaanxi 70#	Tianjin 70#	SK-70#	50#	Shell 90#	Shaanxi	Tianjin	Production area A
NO _x	WEAM	65.93	26.1	44.06	45.41	20.57	42.06	64.42	31.28	39.38
	WES	65.37	73.75	14.57	26.53	20.83	27.90	30.73	16.11	15.03
	WEP	63.71	62.37	12.33	22.96	11.72	45.06	28.03	35.55	14.50
CO _x	WEAM	70.5	42.6	31.94	45.41	14.09	32.51	63.25	29.75	39.38
	WES	64.89	50	18.32	19.39	19.17	22.17	42.17	18.25	17.10
	WEP	61.80	39	12.04	22.96	38.45	33.99	48.43	26.75	21.24

TABLE 3: Reduction rate of NO_x and CO_x influenced by different gradations.

Modifiers types	Reduction rate of NO _x (%)				Reduction rate of CO _x (%)			
	AC-13	AC-16	SMA-13	OGFC-13	AC-13	AC-16	SMA-13	OGFC-13
WEAM	65.93	65.63	2.07	6.45	70.5	78.33	52.94	8.67
WES	65.37	35.66	16.58	3.23	64.89	58.70	8.24	9.45
WEP	63.71	57.88	11.92	0.54	61.80	73.24	31.76	4.72

TABLE 4: Reduction rate of pollutant emissions of WMA.

Pollutant types	Reduction rate (%)
NO _x	(60.34, 73.5, 75, 58, 60.0, 54.5, 45.5, 72.6, 58.0, 60.5, 41.3, 72.6, 83.6, 59.0, 66.67, 94.3, 68.9, 72.2, 70.2, 73.5, 83.6)
SO ₂	(73.5, 74.6, 70.3, 41.2, 25~30, 75.2, 65, 63.6, 41.28, 69, 62.16, 97.7, 67.7, 74.6, 72.3, 74.6, 75.2)
CO	(63.8, 97.6, 63.5, 80.0, 53.3, 53.61, 63.0, 90.0, 63.1, 62.0, 63.53, 10.5, 12.3, 13.6, 12.2, 28.5)
CO ₂	(32.0, 61.5, 75.0, 45.8, 35.0, 15.6, 18.75, 60.0, 45.9, 56.0, 20.0, 24.0, 78.0, 53.8, 61.5, 57.6, 61.5, 60.0, 31.4, 27.08, 34.58)

Note. The data in this table are collected from the test roads in different engineering project and every piece of data refers to a project.

TABLE 5: Reduction rate of NO_x and CO_x influenced by temperature and asphalt types.

Temperature and asphalt types	Reduction rate of NO _x (%)				Reduction rate of CO _x (%)			
	70# base asphalt in Shandong	70# base asphalt in Shaanxi	Tianjin SBS	20# hard asphalt	70# base asphalt in Shandong	70# base asphalt in Shaanxi	Tianjin SBS	20# hard asphalt
120°C	62.99	61.02	34.60	43.84	74.24	80.36	75.75	49.84
130°C	60.11	60.00	28.91	49.01	69.53	70.54	74.50	45.25
140°C	57.87	56.95	17.06	67.04	65.93	67.63	70.75	41.31

The squared distance between $\bar{X}^{(p)}$ and $\bar{X}^{(q)}$, which are the centers of gravity of G_p and G_q , respectively, is expressed by d_{pq}^2 :

$$d_{pq}^2 = d^2(\bar{X}^{(p)}, \bar{X}^{(q)}). \quad (4)$$

When G_p and G_q are combined into G_r , the recursion formula between G_r and other groups (G_k) is expressed as follows:

$$D_{rk}^2 = \frac{n_k + n_p}{n_r + n_k} D_{pk}^2 + \frac{n_k + n_q}{n_r + n_k} D_{qk}^2 - \frac{n_k}{n_r + n_k} D_{pq}^2. \quad (5)$$

Analyzing the classification results is necessary to obtain a thorough understanding of the rationality of the classification by hierarchical clustering method. Bayesian discriminant analysis and Fisher method are two commonly used methods to distinguish the rationality of sample classification. Fisher method is suitable for two groups, whereas Bayesian discriminant analysis can be used in multicategory discrimination [27–29]. This study aims to present five levels of carbon reduction effect of asphalt mixtures. Bayesian discriminant analysis is more suitable for examining the rating results and determining the consequent ranking levels.

4.2. Interval Approximation Method for Comprehensive Rating of Pollutant Emission Reduction Effects

4.2.1. Determining Scores for Rating Indices. Mechanical exhaust is a qualitative index in the rating system for evaluating the pollutant emission reduction of asphalt mixtures. Thus, relative scores must be assigned to these indices. Single factor fuzzy evaluation is conducted by expert scoring. The ranking levels and relative score limits are excellent (90~100), good (80~90), fair (60~80), poor (50~60), and very poor (0~50).

4.2.2. Interval Estimation and Numbers of Intervals. Interval estimation refers to the score range estimation by experts. The scores of an unknown index with a certain probability are presented based on the relative score range, which better reflects the actual rating situation than that of a constant value. This study selects the following process in conducting interval estimation about the rating index of the pollutant emission reduction effect of asphalt mixtures.

All indices x_{ij} of different plans and random variable index B_j are assumed to obey the normal distribution, whose average parameter and standard division are $\bar{x}_j$ and S . The bilateral confidence interval is expressed as follows:

$$\bar{x}_j - u_{\alpha/2} \times \frac{S}{\sqrt{n}} < x_{ij} < \bar{x}_j + u_{\alpha/2} \times \frac{S}{\sqrt{n}}. \quad (6)$$

TABLE 6: Energy consumption of different process of asphalt paving construction.

Survey area	Energy consumption in mixing process (heavy oil: kg/t)	Energy consumption in paving process (diesel: kg/t)	Energy consumption in compaction process (diesel: kg/t)
Shaanxi	(7.1179, 7.0592, 6.8523, 7.0717, 6.8152, 6.5526, 6.9728)	(0.1394, 0.1544, 0.1130, 0.1130, 0.2298, 0.3126, 0.1544)	(0.3126, 0.2222, 0.1959, 0.1959, 0.1582, 0.4030, 0.3955)
Gansu	(6.6546, 6.8739, 7.2879, 7.0655, 7.2694)	(0.1055, 0.1055, 0.2561, 0.2524, 0.2524)	(0.4030, 0.1243, 0.2750, 0.2335, 0.2335)
Tianjin and Hebei	(7.1551, 6.2035, 7.3651, 6.4476, 7.1025)	(0.1883, 0.2222, 0.1657, 0.2222, 0.2298)	(0.0339, 0.3051, 0.0377, 0.3051, 0.2335)
Liaoning	(6.8863, 7.1856, 6.1973, 7.1829, 7.1551, 7.2014)	(0.2222, 0.2524, 0.1394, 0.2524, 0.1130, 0.2825)	(0.1733, 0.1582, 0.2448, 0.2109, 0.2222, 0.1959)
Shandong	(6.6917, 7.1025, 7.1952, 6.7164, 6.8956, 6.1417)	(0.2034, 0.2034, 0.2147, 0.2825, 0.2147, 0.1394)	(0.3842, 0.1582, 0.2750, 0.1959, 0.2750, 0.2448)
Hunan	(6.8461, 7.1674, 6.7998, 6.7504, 6.9759, 6.9141)	(0.1507, 0.1921, 0.1544, 0.2298, 0.2298, 0.2298)	(0.3541, 0.3503, 0.3126, 0.2599, 0.1921, 0.2147)
Guangxi	(6.6917, 6.7411, 6.8183, 7.2941, 7.2323, 7.2508)	(0.2034, 0.1507, 0.1883, 0.2524, 0.2750, 0.252)	(0.3842, 0.2109, 0.2298, 0.2750, 0.2637, 0.2373)
Yunnan	(7.1334, 7.0253, 7.2416, 7.2168, 7.1273, 6.9512)	(0.2260, 0.1657, 0.1657, 0.2298, 0.2298, 0.2260)	(0.0490, 0.1582, 0.1996, 0.2109, 0.2222, 0.2298)
Guizhou	(6.4878, 7.1489, 7.2138, 7.2230, 6.4476)	(0.1431, 0.2524, 0.2524, 0.2524, 0.143)	(0.2335, 0.1582, 0.2750, 0.1959, 0.2335)
Sichuan	(6.5495, 7.2261, 7.1118, 7.0438, 7.0315, 6.9573)	(0.1356, 0.1883, 0.1657, 0.1733, 0.2448, 0.2260)	(0.4256, 0.0753, 0.1996, 0.2298, 0.2034, 0.1733)
Survey area	Energy consumption in transportation process (diesel: L/km×t)		
Shaanxi	(0.030, 0.009, 0.008, 0.011)		
Tianjin	(0.008, 0.017, 0.021)		
Liaoning	(0.039, 0.060, 0.013)		
Gansu	(0.010, 0.010, 0.012, 0.012)		
Hebei	(0.042, 0.046)		
Henan	(0.0136, 0.0193, 0.020, 0.0189)		

Note. Every date in this table refers to the energy consumption in one project in relative province of China.

TABLE 7: Data of energy consumption in mixing process.

Construction process	Energy-saving rate (%)
Energy consumption in mixing process	(40, 31.25, 22.1, 30, 47.71, 40, 69.9, 35, 30, 40~60, 21.57, 20~30, 22.9, 28.4, 20~30, 22.9, 20~30, 30, 38.5, 23.1, 30, 30, 10, 30, 20, 31.25, 20, 15)

Note. The data in this table are collected from the test roads in different engineering project and every piece of data refers to a project.

In the rating system for pollutant emission reduction of asphalt mixtures, $u_{\alpha/2}$ is the assurance rate coefficient (usually expressed by Z). This study sets 95% as its assurance rate coefficient; in other words, $Z = 1.96$. Thus, the interval estimations of the actual test data of all rating indices are shown as follows:

$$\left(\bar{x}_j - 1.96 \frac{S}{\sqrt{n}}, \bar{x}_j + 1.96 \frac{S}{\sqrt{n}} \right). \quad (7)$$

4.2.3. Weights for the Rating Indices Based on the AHP. In the determination process, the analytic hierarchy process (AHP) method is convenient, reasonable, comprehensive, and widely applicable. The AHP is selected to determine the weights of all indices in the rating system. The AHP provides a pairwise comparison of the importance of all factors by the

1–9 scale method to conduct an assessment. The discriminant matrix A of Level I index, discriminant matrix B_1 of Level II index under the energy consumption index, discriminant matrix B_2 of Level II index under the mechanical exhaust index, and discriminant matrix B_3 of Level II index under the pollutant emissions index are presented as follows:

$$A = \begin{bmatrix} 1 & 8 & 1/2 \\ 1/8 & 1 & 1/9 \\ 2 & 9 & 1 \end{bmatrix},$$

$$B_1 = \begin{bmatrix} 1 & 9 & 8 & 7 \\ 1/9 & 1 & 1/3 & 1/4 \\ 1/8 & 3 & 1 & 1/2 \\ 1/7 & 4 & 2 & 1 \end{bmatrix},$$

$$\begin{aligned}
B_2 &= \begin{bmatrix} 1 & 1/3 & 1/2 \\ 3 & 1 & 1/4 \\ 4 & 2 & 1 \end{bmatrix}, \\
B_3 &= \begin{bmatrix} 1 & 1 & 2 \\ 1 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{bmatrix} \\
\text{or } B_3 &= \begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1/2 & 1/2 & 1/2 & 1 \end{bmatrix}.
\end{aligned} \tag{8}$$

Maximum feature $\lambda_{\max}$ of matrices A , B_1 , and B_2 are 3.0369, 4.1739, and 3.2343, respectively, which are calculated by MATLAB. The maximum features of matrix B_3 are three and four.

The average random consistency index $R \cdot I$ is obtained by repeating the feature vector calculation of the random discriminant matrix and averaging the repeated values. The $R \cdot I$ values of different dimensions are shown as follows:

$$\begin{aligned}
&RI_{\text{Dimension(From 1 to 9)}} \\
&= \{0, 0, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41, 1.45\}.
\end{aligned} \tag{9}$$

(1) *Weights for Level I Indices.* The calculation of the consistency index of Level I indices ($C \cdot I$) is as follows:

$$C \cdot I = \frac{\lambda_{\max} - n}{n - 1} = \frac{3.0369 - 3}{3 - 1} = 0.01845. \tag{10}$$

Level I index is a third-order judgment matrix, and the value of $R \cdot I$ is 0.58; thus,

$$C \cdot R = \frac{C \cdot I}{R \cdot I} = \frac{0.01845}{0.58} = 0.0318 < 0.1. \tag{11}$$

Therefore, the consistency is reasonable, as previously verified. The integrated feature vector corresponding to $\lambda_{\max}$ is $W_A = (0.36, 0.05, 0.59)^T$, which represents the weights of all Level I indices in the rating system.

(2) *Weights for Level II Indices*

① The calculation of the consistency index of Level II Indices under energy consumption is as follows:

$$C \cdot I = \frac{\lambda_{\max} - n}{n - 1} = \frac{4.1739 - 4}{4 - 1} = 0.0580. \tag{12}$$

Level II index is the fourth-order judgment matrix, and the value of $R \cdot I$ is 0.90; thus,

$$C \cdot R = \frac{C \cdot I}{R \cdot I} = \frac{0.0580}{0.90} = 0.064 < 0.1. \tag{13}$$

Therefore, the consistency of the judgment matrix of Level II indices under energy consumption is acceptable.

After the integration, the feature vector corresponding to $\lambda_{\max}$ is $W_{B1} = (0.70, 0.05, 0.10, 0.15)^T$, which are the weights of the Level II indices of energy consumption under the rating system for pollutant emission reduction of asphalt mixtures.

② According to the previously presented method, the weight vector of Level II indices of the exhaust emitted by the construction machine is $W_{B2} = (0.17, 0.28, 0.55)^T$. The weight vectors of Level II indices of the pollutant emissions of the asphalt mixture are $W_{B3} = (0.40, 0.40, 0.20)^T$ and $W_{B3} = (0.29, 0.29, 0.29, 0.13)^T$. The weights of all the indices are shown in Table 1.

4.2.4. *Rating System for Pollutant Emission Reduction.* The rating system includes two ranking level indices. Thus, the approximation method of interval numbers is adopted to approach the Level I index during the rating process. The score set of Level II indices within Level I index are assumed to be

$$I = \{I_1, I_2, \dots, I_m\}. \tag{14}$$

$\{C_1, C_2, \dots, C_p\}$ C_e ($e = 1, 2, \dots, p$) refers to the level of function effect.

The score set of the function effect of the future rating project (or index) is $\{[x_{01}^L, x_{01}^U], [x_{02}^L, x_{02}^U], \dots, [x_{0n}^L, x_{0n}^U]\}$, $\{[x_{01}^L, x_{01}^U], [x_{02}^L, x_{02}^U], \dots, [x_{0n}^L, x_{0n}^U]\}$, and $x_{0i}^L \leq x_{0i}^U$. Thus, the decision matrix is expressed as follows:

$$\begin{bmatrix} [x_{01}^L, x_{01}^U] & [x_{02}^L, x_{02}^U] & \cdots & [x_{0n}^L, x_{0n}^U] \\ [x_{11}^L, x_{11}^U] & [x_{12}^L, x_{12}^U] & \cdots & [x_{1n}^L, x_{1n}^U] \\ [x_{21}^L, x_{21}^U] & [x_{22}^L, x_{22}^U] & \cdots & [x_{2n}^L, x_{2n}^U] \\ \vdots & \vdots & \vdots & \vdots \\ [x_{m1}^L, x_{m1}^U] & [x_{m2}^L, x_{m2}^U] & \cdots & [x_{mn}^L, x_{mn}^U] \end{bmatrix} \begin{matrix} C_X \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} \tag{15}$$

Conducting dimensionless treatment of original indices is necessary because dimensions and magnitudes may vary. The treatment formula is expressed as follows:

$$\begin{aligned}
y_{ij}^L &= \frac{x_{ij}^L}{\sum_{i=0}^m x_{ij}^U}, \\
y_{ij}^U &= \frac{x_{ij}^U}{\sum_{i=0}^m x_{ij}^L}, \\
y_{ij}^L &= \frac{1/x_{ij}^U}{\sum_{i=0}^m (1/x_{ij}^L)}, \\
y_{ij}^U &= \frac{1/x_{ij}^L}{\sum_{i=0}^m (1/x_{ij}^U)}, \\
i &= 0, 1, 2, \dots, n; \quad j = 1, 2, \dots, m.
\end{aligned} \tag{16}$$

After nominalizing the original indices, these indices are transformed into dimensionless values $y_{ij}, y_{ij} \in [0, 1]$.

Thus, decision matrix X becomes decision matrix Y . Decision matrix Y is multiplied by weight vector $\theta = (\theta_1, \theta_2, \dots, \theta_m)$, and discriminant matrix R is obtained as follows:

$$\begin{bmatrix} [y_{01}^L \theta_1, y_{01}^U \theta_1] & [y_{02}^L \theta_2, y_{02}^U \theta_2] & \cdots & [y_{0n}^L \theta_n, y_{0n}^U \theta_n] \\ [y_{11}^L \theta_1, y_{11}^U \theta_1] & [y_{12}^L \theta_2, y_{12}^U \theta_2] & \cdots & [y_{1n}^L \theta_n, y_{1n}^U \theta_n] \\ [y_{21}^L \theta_1, y_{21}^U \theta_1] & [y_{22}^L \theta_2, y_{22}^U \theta_2] & \cdots & [y_{2n}^L \theta_n, y_{2n}^U \theta_n] \\ \vdots & \vdots & \vdots & \vdots \\ [y_{m1}^L \theta_1, y_{m1}^U \theta_1] & [y_{m2}^L \theta_2, y_{m2}^U \theta_2] & \cdots & [y_{mn}^L \theta_n, y_{mn}^U \theta_n] \end{bmatrix} \begin{matrix} C_X \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} \quad (17)$$

The decision rating principle states that a shorter distance is closer to the ranking level. The level with the minimum distance is the ranking level. The calculation formula of the distance from future rating set C_x to ranking level C_i is expressed as follows:

$$d_i = d(C_x, C_i) = \sqrt{(d_{i1}^+)^2 + (d_{i1}^-)^2 + \cdots + (d_{in}^+)^2}. \quad (18)$$

In the formula, $d_{ij}^+ = \max(|r_{0j}^L - r_{ij}^L|, |r_{0j}^U - r_{ij}^U|)$, $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$.

The ranking level can be determined according to minimum distance d_i .

5. Results and Discussions

5.1. Individual Ranking for Pollutant Emission Reductions. The pollutants included in this study include NO_x , CO_x , SO_2 , CO , and CO_2 . The reduction rate can be classified into five ranking levels recorded as $V = (V_1, V_2, V_3, V_4, V_5) = (\text{excellent}, \text{good}, \text{fair}, \text{poor}, \text{and very poor})$. The classification of pollutant emissions can be conducted using the method mentioned previously. The classification process of the reduction rate of NO_x is shown as follows.

Based on the hierarchical clustering method, the field collected data and laboratory test data obtained are classified using SPSS. The classification results are shown in Figure 2.

The clustering results are examined by Bayesian discriminant analysis to verify its reasonability. Regarding the posterior probability of erroneous judgment, 97.4% of the original data are clustered correctly and the classification is highly accurate. The linear discriminant models are established according to the coefficient table:

$$\begin{aligned} y_1 &= 1.821x_1 - 53.590, \\ y_2 &= 1.374x_2 - 31.183, \\ y_3 &= 2.276x_3 - 82.805, \\ y_4 &= 0.245x_4 - 2.547, \\ y_5 &= 0.908x_5 - 14.525. \end{aligned} \quad (19)$$

The discriminant values of all ranking levels can be obtained by adopting formula (19). Critical value U is calculated by using the discriminant function. The critical values of adjacent levels are $U_{12} = 50.13$, $U_{23} = 57.23$, $U_{34} = 39.52$, and $U_{45} = 18.07$. The classification standard of the reduction rate

of NO_x will be obtained by integrating the critical values and considering the testing errors.

The classification standards of the reduction rates of CO_x , SO_2 , CO , and CO_2 are determined based on the same method, and the results are shown in Table 8.

5.2. Individual Ranking for Energy Consumption

5.2.1. Energy Conservation. This study classifies the data of the energy-saving effect in the mixing process of the WMA mixture into five ranking levels by hierarchical clustering method based on Ward method, recorded as $V = (V_1, V_2, V_3, V_4, V_5) = (\text{excellent}, \text{good}, \text{fair}, \text{poor}, \text{and very poor})$. Linear discriminant models are established according to the coefficient table:

$$\begin{aligned} y_1 &= 2.988x_1 - 58.947, \\ y_2 &= 2.344x_2 - 36.885, \\ y_3 &= 1.639x_3 - 18.858, \\ y_4 &= 4.116x_4 - 110.381, \\ y_5 &= 5.443x_5 - 191.847. \end{aligned} \quad (20)$$

According to formula (20), the discriminant values of all the ranking levels can be calculated using the discriminant function expression of the energy-saving effect classification. The critical values of adjacent levels are $U_{12} = 34.26$, $U_{23} = 25.57$, $U_{34} = 36.95$, and $U_{45} = 61.39$. The classification standard of reduction rate of NO_x will be obtained by integrating the critical values and considering testing errors, as indicated as follows: excellent [61, 100), good [37, 61), fair [34, 37), poor [26, 34), and very poor (0, 25).

5.2.2. Energy Consumption

(1) Mixing Process. The traditional energy sources that are used in the mixing process of asphalt mixtures are coal and heavy oil. New energy sources include coal gasification and natural gas. The energy consumption in the mixing process can be divided into five ranking levels, namely, excellent, good, fair, poor, and very poor, according to energy consumption and energy types. The classification methods are shown as follows: excellent (theoretical consumption of natural gas), good (theoretical consumption of coal gasification), fair and poor (theoretical consumption of heavy oil), and very poor (raw coal).

The classification results of ranking levels in the mixing process are shown as follows: when the upper limit of natural gas consumption is calculated, the mixing temperature will select a higher temperature, which is 175°C , and aggregate heating temperature is 190°C . In the process of calculating theoretical minimum natural gas consumption, the specific heat capacity of aggregate is selected as the lower limit with the mixing temperature and aggregate heating temperature of 160°C and 190°C , respectively. Fuel is heavy oil, and the asphalt-aggregate ratio is 5%. The measuring parameters are shown in Table 9.

FIGURE 2: Cluster pedigree chart of NO_x reduction rate.

The calculated amount of heavy oil consumption in the mixing process of modified asphalt mixture is 7.86 kg/t according to previously presented parameters. The conversion coefficient of heavy oil to standard coal is 1.4286,

whereas the conversion coefficient of natural gas to coal is 1.2143. The converted consumption of heavy oil into natural gas by using the conversion coefficient of standard coal is 9.25 m³/t. This value is the maximum theoretical natural

TABLE 8: Score limits of ranking levels of reduction rate.

Reduction rate ranking levels	Excellent	Good	Fair	Poor	Very poor
NO _x	[57, 100)	[50, 57)	[40, 50)	[19, 40)	(0, 19)
CO _x	[69, 100)	[59, 69)	[47, 59)	[23, 47)	(0, 23)
SO ₂	[70, 100)	[62, 70)	[54, 62)	[52, 54)	(0, 52)
CO	[71, 100)	[51, 71)	[38, 51)	[20, 38)	(0, 20)
CO ₂	[68, 100)	[52, 68)	[49, 52)	[40, 49)	(0, 40)

TABLE 9: Calculation parameters of energy consumption in mixing process.

Measuring parameters	Value
Specific heat capacity (kJ/kg·°C)	Aggregate 1.0 Water 4.2
Specific heat capacity of aggregate [kJ/(kg·°C)]	0.8
Asphalt-aggregate ratio (%)	5
Moisture content of aggregate (%)	4
Original temperature of aggregate (°C)	25
Heavy oil	
Net calorific power (kJ)	41820
Combustion efficiency (%)	90
Roller heat transfer rate (%)	60
Natural gas	
Net calorific power (kJ)	35567.5
Combustion efficiency (%)	100
Roller heat transfer rate (%)	100

gas consumption, which is used to calculate the minimum natural gas consumption in the mixing process of asphalt mixtures. The minimum consumption is 3.26 m³/t.

The excellent level ranges from 3.26 m³/t to 9.25 m³/t of natural gas consumption in the asphalt mixing process. The final results of other classes calculated by the same method are shown in Table 10.

(2) *Transportation, Paving, and Compaction Processes.* Energy consumption is categorized into five ranking levels in transporting asphalt mixture, which are excellent, good, fair, poor, and very poor. Hierarchical cluster analysis and Bayesian discriminant analysis are used to establish discriminant models based on the field collected data of unit energy consumption during transportation. The analyses are shown as follows:

$$\begin{aligned}
 y_1 &= 3313.845x - 51.317, \\
 y_2 &= 6627.689x - 200.44, \\
 y_3 &= 2187.137x - 23.262, \\
 y_4 &= 4676.203x - 100.589, \\
 y_5 &= 1087.544x - 6.9630.
 \end{aligned} \tag{21}$$

The discriminant values of all ranking levels can be calculated using formula (21). Critical value U will be calculated using the discriminant function. The critical values of the adjacent levels are $U_{12} = 0.045$, $U_{23} = 0.035$, $U_{34} = 0.031$, and $U_{45} = 0.015$. Thus, the classification standards of energy consumption in transporting of the asphalt mixture are obtained.

The classification standards of energy consumption in the paving and compaction process are determined by using the same calculating method, as shown in Table 11.

5.3. Exhaust Pollutants. The regulations on the limits for exhaust pollutants from diesel engines of nonroad mobile machinery are indicated in the Chinese national *Standard Limits and Measurement Methods for Exhaust Pollutants from Diesel Engines of Non-Road Mobile Machinery* (I, II) (GB 20891-2007). This standard is appropriate for diesel engines of nonroad mobile machinery with less than 560 kW net power under unsteady speed. Five ranking levels ranging from excellent to very poor are used to classify the rating index for mechanical exhaust of asphalt pavement derived from transportation, paving, and compaction process.

Five ranking levels ranging from excellent to very poor are used to classify the rating index for mechanical exhaust of asphalt pavement derived from transportation, paving, and compaction process. Regarding the ranking levels of mechanical exhaust, if four items reach the standard, the ranking level is excellent. The ranking level is good, if three items reach the standard. The ranking level is fair or poor with three or two items reaching the standard. If there is no item reaching the standard, the ranking level is very poor.

5.4. Case Study

5.4.1. Rating by Single Index. The average energy consumption and reduction effect of pollutant emissions in all processes can be obtained based on the test results of the WMA-flame retardant pavement of Haihe Tunnel in Tianjin Province during the construction process. The data shown in Table 12 are obtained using interval estimation.

Five expert scores for the qualitative indices of mechanical exhausts and the relevant interval estimations are shown in Table 13.

The approximation method of interval numbers is adopted to elevate all single indices, and the calculation process of the energy-saving effect is introduced as an example. The interval estimation is [56, 79], which is between

TABLE 10: Score limits of ranking levels of energy consumption in mixing process.

Ranking levels	Consumption of unit asphalt mixture in mixing process
Excellent	[3.26, 9.25] (natural gas: m ³ /t)
Good	[11.10, 31.44] (coal gasification: m ³ /t) or (9.25, ∞) (natural gas: m ³ /t)
Fair	[2.77, 6.08] (heavy oil: kg/t) or (31.44, ∞) (coal gasification: m ³ /t)
Poor	[6.08, 7.86] (heavy oil: kg/t)
Very poor	(5.55, ∞) (raw coal: kg/t) or (7.86, ∞) (heavy oil: kg/t)

TABLE 11: Score limits of ranking levels of energy consumption in transportation, paving, and compaction.

Unit energy consumption ranking levels	Excellent	Good	Fair	Poor	Very poor
Transportation process	(0, 0.015]	(0.015, 0.031]	(0.031, 0.035]	(0.035, 0.045]	(0.045, ∞)
Paving process	(0, 0.131]	(0.131, 0.176]	(0.17, 0.219]	(0.219, 0.263]	(0.263, ∞)
Compaction process	(0, 0.103]	(0.103, 0.188]	(0.188, 0.251]	(0.251, 0.336]	(0.336, ∞)

TABLE 12: Interval estimation of single indices of energy consumption and pollutant emissions.

Level II index	Energy-saving effect	Unit energy consumption in transportation process	Unit energy consumption in paving process	Unit energy consumption in compaction process	Reduction rate of NO _x	Reduction rate of CO _x	Reduction rate of SO ₂
Interval estimation	[56, 79]	[0.013, 0.020]	[0.12, 0.15]	[0.08, 0.13]	[51.0, 63.2]	[60.80, 76.5]	[62.80, 66.55]

TABLE 13: Values of rating indices effect.

Level I index	Mechanical exhaust		
Level II index	Transportation process	Paving process	Compaction process
Average value	89.8	89.8	90.6
Interval value	86.6–93.0	87.9–91.7	88.7–92.5

[61, 100) and [37, 61) representing excellent and good. Thus, the distance between the index and excellent level is derived as follows:

$$d_1 = \sqrt{(56 - 61)^2 + (79 - 100)^2} = 21.59. \quad (22)$$

The distance between the index and good level is derived as follows:

$$d_2 = \sqrt{(56 - 37)^2 + (79 - 61)^2} = 26.17. \quad (23)$$

The calculation and comparison result indicate that the energy-saving index is excellent. The rating result of energy-saving effect is excellent and those of ranking Level II indices are good. The rating result of mechanical exhaust in construction process is excellent. The rating result of reduction rate of CO_x is excellent and those of NO_x and SO₂ are good.

5.4.2. Comprehensive Rating

(1) *Level I Indices.* The rating by ranking Level I indices will be introduced by utilizing the rating of pollutant emissions as an example. Decision matrix X of pollutant emissions is shown as follows:

$$X = \begin{bmatrix} [51.0, 63.2] & [60.8, 76.5] & [62.8, 66.55] \\ [57.0, 100.0] & [69.0, 100.0] & [70.0, 100.0] \\ [50.0, 57.0] & [59.0, 69.0] & [62.0, 70.0] \\ [40.0, 50.0] & [47.0, 59.0] & [54.0, 62.0] \\ [19.0, 40.0] & [23.0, 47.0] & [52.0, 54.0] \\ [0.0, 19.0] & [0.0, 23.0] & [0, 52.0] \end{bmatrix} \begin{matrix} C_x \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{matrix} \quad (24)$$

These three indicators of Level I indices are benefit indicators. After normalization, normalized matrix Y could

be obtained. Decision rating matrix R could be determined by multiplying normalized matrix Y by weight θ .

$$R = \begin{bmatrix} [0.060, 0.116] & [0.065, 0.119] & [0.031, 0.044] \\ [0.069, 0.184] & [0.074, 0.155] & [0.035, 0.066] \\ [0.060, 0.105] & [0.063, 0.107] & [0.031, 0.047] \\ [0.049, 0.092] & [0.050, 0.091] & [0.027, 0.041] \\ [0.023, 0.074] & [0.025, 0.073] & [0.026, 0.036] \\ [0.0, 0.035] & [0.0, 0.036] & [0.0, 0.035] \end{bmatrix} \begin{matrix} C_x \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{matrix} \quad (25)$$

The distance between all levels and rating indices set of pollutant emissions can be calculated as follows: $d_1 = 0.080$,

$$X = \begin{bmatrix} [56.0, 79.0] & [0.013, 0.020] & [0.120, 0.150] & [0.080, 0.130] & [86.6, 93.0] & [87.9, 91.7] & [88.7, 92.5] & [51.0, 63.2] & [60.8, 76.5] & [62.8, 66.55] \\ [61.0, 100.0] & [0.0, 0.015] & [0.0, 0.131] & [0.0, 0.103] & [90.0, 100.0] & [90.0, 100.0] & [90.0, 100.0] & [57.0, 100.0] & [69.0, 100.0] & [70.0, 100.0] \\ [37.0, 61.0] & [0.015, 0.031] & [0.131, 0.176] & [0.103, 0.188] & [80.0, 90.0] & [80.0, 90.0] & [80.0, 90.0] & [50.0, 57.0] & [59.0, 69.0] & [62.0, 70.0] \\ [34.0, 37.0] & [0.031, 0.035] & [0.176, 0.219] & [0.188, 0.251] & [60.0, 80.0] & [60.0, 80.0] & [60.0, 80.0] & [40.0, 50.0] & [47.0, 59.0] & [54.0, 62.0] \\ [26.0, 34.0] & [0.035, 0.045] & [0.219, 0.263] & [0.251, 0.336] & [50.0, 60.0] & [50.0, 60.0] & [50.0, 60.0] & [19.0, 40.0] & [23.0, 47.0] & [52.0, 54.0] \\ [0, 26.0] & [0.045, \infty] & [0.263, \infty] & [0.336, \infty] & [0.0, 50.0] & [0.0, 50.0] & [0.0, 50.0] & [0.0, 19.0] & [0.0, 23.0] & [0, 52.0] \end{bmatrix} \begin{matrix} C_x \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{matrix} \quad (26)$$

All the single indices are normalized, and normalized matrix Y can be obtained according to the calculation result.

$$R = \begin{bmatrix} [0.042, 0.093] & [0.007, 0.0] & [0.294, 0.0] & [0.023, 0.0] & [0.002, 0.002] & [0.003, 0.003] & [0.005, 0.007] & [0.037, 0.069] & [0.038, 0.070] & [0.018, 0.026] \\ [0.046, 0.118] & [\infty, 0.0] & [\infty, 0.0] & [\infty, 0.0] & [0.002, 0.002] & [0.003, 0.004] & [0.005, 0.007] & [0.041, 0.109] & [0.043, 0.091] & [0.020, 0.039] \\ [0.028, 0.072] & [0.006, 0.0] & [0.010, 0.0] & [0.018, 0.0] & [0.001, 0.002] & [0.002, 0.003] & [0.005, 0.007] & [0.036, 0.062] & [0.037, 0.063] & [0.018, 0.027] \\ [0.025, 0.044] & [0.003, 0.0] & [0.007, 0.0] & [0.010, 0.0] & [0.001, 0.002] & [0.002, 0.003] & [0.003, 0.006] & [0.029, 0.054] & [0.030, 0.054] & [0.016, 0.024] \\ [0.019, 0.040] & [0.003, 0.0] & [0.006, 0.0] & [0.007, 0.0] & [0.001, 0.001] & [0.001, 0.002] & [0.003, 0.004] & [0.014, 0.044] & [0.014, 0.043] & [0.015, 0.021] \\ [0, 0.031] & [0.002, 0.0] & [0.005, 0.0] & [0.005, 0.0] & [0.0, 0.001] & [0.0, 0.002] & [0.0, 0.004] & [0.0, 0.021] & [0.0, 0.021] & [0.0, 0.020] \end{bmatrix} \begin{matrix} C_x \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{matrix} \quad (27)$$

The distance between all levels and pollutant emission reduction and energy consumption effect of Haihe Tunnel in Tianjin Province can be calculated as follows: $d_1 = \infty$, $d_2 = 0.024$, $d_3 = 0.056$, $d_4 = 0.067$, and $d_5 = 0.096$. According to the rating principles, the ranking level can be determined based on minimum d_i . The calculation results indicate that the minimum value is d_2 , which determines the distance between Level II and pollutant emission reduction effect in Haihe Tunnel project in Tianjin Province is minimum. The rating of the comprehensive effect of pollutant emission reduction is classified as "good."

6. Conclusions

This study develops a comprehensive rating system for pollutant emission reduction and energy-saving effect of asphalt

$d_2 = 0.016$, $d_3 = 0.036$, $d_4 = 0.063$, and $d_5 = 0.120$. According to the rating principles, the ranking level by minimum d_i can be determined. The calculation results indicate that the minimum value is d_2 , which indicates that the distance between Level II and the rating indices set is the minimum. Therefore the ranking level is good. The remaining indices are evaluated by using the same method and the results of energy consumption, quantitative mechanical exhaust, and pollutant emissions of asphalt mixture are excellent, excellent, and good, respectively.

(2) *Comprehensive Ranking.* Decision matrix X of pollutant emission reduction and energy-saving effect on the Haihe Tunnel project in Tianjin Province is expressed as follows:

Decision rating matrix R will be obtained by multiplying weight θ and normalized matrix Y :

pavement construction regarding energy conservation, quantitative mechanical emission discharges, and reduction rate of pollutant emissions of asphalt mixtures with the following key contributions.

(i) Reduction rates of pollutant emissions are measured through laboratory testing for three types of pollutant reduction modifiers. The energy consumption data of all periods during the construction of 58 highways from 10 provinces are collected.

(ii) Based on the hierarchical clustering method and Bayesian discriminant analysis, this paper has established a rigorous ranking system to quantify the reduction effects of pollutant emissions of asphalt mixtures, mechanical energy consumption, and mechanical exhausts using the five ranking levels from excellent to very poor.

(iii) This study presents a rating framework for the comprehensive pollutant emission reduction effect of asphalt mixtures based on the AHP and approximation methods. The pollutant emission reduction effects of WMA-flame retardant mixture used in the Haihe Tunnel project in Tianjin Province are evaluated in accordance with the proposed rating system to demonstrate its feasibility for real-world applications.

This paper provides reference for evaluating the pollutant emission and energy conservation effect of asphalt pavement construction. Future work includes the update of system data and the development of relevant software interfaces for production application.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This paper describes research activities mainly requested and sponsored by the *Science and Technology Projects of Ministry of Housing and Urban-Rural Development of China* (Program 2014-R1-019), *Natural Science Basic Research Plan in Shaanxi Province of China* (Program no. 2014JM2-5045), *Key Scientific and Technological Project in Henan Province of China* (Program no. 152102210113), and *Fundamental Research Funds for the Central Universities* (Program no. 310821162013). That sponsorship and interest are gratefully acknowledged.

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