

## Research Article

# Performance Evaluation and Optimization of Waterproof Adhesive Layer for Concrete Bridge Deck in Seasonal Frozen Region Using AHP

Weidong Jin , Yu Zhao , Wensheng Wang , and Feng He 

College of Transportation, Jilin University, Changchun 130025, China

Correspondence should be addressed to Wensheng Wang; wangws@jlu.edu.cn and Feng He; hefjlu@126.com

Received 17 February 2021; Revised 19 March 2021; Accepted 20 March 2021; Published 31 March 2021

Academic Editor: Yubo Jiao

Copyright © 2021 Weidong Jin et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The weak connection performances between the waterproof adhesive layer, the bridge deck, and asphalt pavement are important factors that cause the bridge deck slippage and upheaval and affect the safety and durability of the bridge. In this paper, styrene-butadiene-styrene- (SBS-) modified asphalt, SBS-emulsified asphalt, rubber-modified asphalt, and AMP-100 waterproof materials are selected to study the performance of the bridge deck waterproof adhesive layer in the seasonal frozen region. The shear strength and bond strength of the four waterproof adhesive materials were obtained through the shear test and pull-out test of the composite specimens composed of four kinds of adhesive materials, diatomite rubber-particle asphalt mixture, and concrete bridge deck at different dosages and temperatures. According to the priority analysis of the factors including cost, construction difficulty, and environmental protection for the four kinds of materials by using analytic hierarchy process (AHP), SBS-modified asphalt is obtained as the most suitable waterproof adhesive layer of diatomite rubber particle asphalt mixture bridge deck in seasonal frozen region.

## 1. Introduction

With the development of highway traffic in China and the quantity of bridges increasing, the bridge deck pavement has become an important part of the bridge traffic system [1–4]. Among them, the waterproof adhesive layer between asphalt pavement and cement concrete bridge deck cannot only prevent rainwater from penetrating into the bridge deck but also improve the stress condition between the two structures [5]. The weak connection performance between the waterproof adhesive layer, bridge deck, and asphalt pavement layer is an important factor affecting the safety and durability of bridges, which causes bridge deck slippage and upheaval. So more and more attention is paid to the performance of the bridge deck waterproof adhesive layer [6].

In the mid-1970s, Manning D G of the United States systematically studied more than 100 kinds of waterproof adhesive layers at that time and selected 5 kinds of materials as more promising waterproof materials [7]. The study of the

waterproof adhesive layer was carried out in China from 1980s to 1990s [8]. Moisture content in the waterproof adhesive layer is an important factor affecting its performance. Feng et al. studied the effect of moisture content on the strength of the waterproof adhesive layer. The results showed that the shear strength of the waterproof bonding layer increased with the decrease of moisture content [9, 10]. In addition, the performance of the waterproof adhesive layer is not only related to itself but also related to the cement concrete layer and asphalt mixture layer bonded with it. In this regard, Qian et al. studied the influence of the replacement of aggregate in the asphalt mixture with phosphorus slag on the performance of the waterproof adhesive layer and found that phosphorus slag can improve the interlayer bond strength of the waterproof adhesive layer [11]. Wu et al. studied the influence of roughness of the cement concrete bridge deck connected with the adhesive layer and loading speed of the adhesive layer on the performance of the adhesive layer and concluded that the rougher the

concrete bridge deck and the greater the loading speed of the adhesive layer, the greater the adhesive layer performance strength [12]. However, these scholars generally consider the influence of internal factors, without considering the influence of external environment and temperature on the performance of the waterproof adhesive layer in actual laying. Xu et al. studied the bond strength under vehicle load [13]. Liu et al. studied the bond strength under the combined action of load and temperature and obtained that, with the increase of temperature, the performance of the adhesive layer decreased significantly [14]. These scholars considered the influence of vehicles and external temperature on the waterproof adhesive layer, but did not take into account the other structures of bridge deck pavement and asphalt mixture pavement which were paved by them are just common asphalt mixture.

In recent years, to study the performance of different waterproof adhesive layers, Guo et al. selected three different waterproof adhesive layers to do waterproof and shear strength tests, and the results showed that SBS-modified asphalt was better [15, 16]. Wang et al. studied the steel bridge pavement under vehicle load by the pull-out test and direct shear test and studied the effects of temperature, spraying quantity, and environmental conditions. It was concluded that rubber asphalt as the waterproof adhesive layer had good performance [17]. Zhang analyzed the influence of impermeability and aging resistance on the properties of materials through the shear test and pull-out test under different conditions. And, on comparing several adhesive layers, the epoxy asphalt has significant advantages [18]. Liu et al. found that waterborne epoxy-resin emulsified asphalt had good adhesion and waterproof performance through theoretical analysis on cohesion and simulation failure tests of cohesion and waterproof, which could effectively prevent the passage of bridge deck pavement [19]. Some scholars considered other properties of the waterproof adhesive layer. Chen et al. tested the effects of different bond surfaces on shear properties, measured the shear strength of specimens at different temperatures, and carried out fatigue life tests [20]. Fang et al. determined the influence of shear stress and temperature on the fatigue life of the waterproof adhesive layer by the shear fatigue test and discussed the design method and design index of the bridge deck considering the shear fatigue damage of the waterproof adhesive layer [21]. Qiu et al. used five performance indexes, such as tensile strength, direct shear strength, oblique shear strength, fatigue life, and project cost, to evaluate. A suitable waterproof adhesive system was recommended by using the multiobjective grey target decision method as the optimization method [22]. Some scholars considered the relationship between adhesive layer and bridge deck damage. Liu et al. studied two different types of asphalt mixtures and three different types of asphalt waterproof adhesive materials and obtained that the air void and test temperature of the asphalt mixture have different effects on the blister damage performance [23].

Based on the change of temperature difference in the seasonal frozen region, the research group developed a new type of asphalt mixture called diatomite rubber-particle

asphalt mixture [24, 25]. This kind of bridge deck pavement material not only has green ecology but also has strong noise reduction ability and can solve the safety hidden danger of ice and snow pavement. In the seasonal frozen region where the temperature difference between winter and summer is large, laying this new asphalt mixture needs to consider the selection of the waterproof adhesive layer to make the performance of bridge deck pavement more excellent. This paper selects several high-quality waterproof adhesive materials commonly used in seasonal frozen area engineering such as SBS-modified asphalt, SBS emulsified asphalt, rubber-modified asphalt, and AMP-100 waterproof material. It is bonded with this new type of asphalt mixture and cement board to study its shear performance and bond performance at different temperatures. Through comparison combined with some other conditions such as environmental protection and cost, a waterproof adhesive layer material with better bond performance with the diatomite rubber-particle asphalt mixture which is suitable for the environment of the seasonal freezing region is selected.

## 2. Experimental Materials and Methods

*2.1. Experimental Materials.* In this study, the composite bridge deck structure of cement concrete-waterproof adhesive layer-asphalt mixture was used as the experimental object. Cement concrete specimens were made using a common mix proportion provided on-site, i.e., cement: water: river sand: gravel (by quality) is 10:3.8:15:20 [26–28]. C50 concrete was used for cement concrete specimens, and a high-efficiency water reducing agent was added. Four types of waterproof adhesive layers were selected as the waterproof adhesive layer in this paper, including SBS-modified asphalt waterproof adhesive layer, SBS emulsified asphalt waterproof adhesive layer, rubber asphalt waterproof adhesive layer, and AMP-100 waterproof adhesive material. And, the corresponding basic performances are shown in Tables 1–3 following JTG F40-2004, GB/T16777-2008, and JC/T975-2005 [29–31]. The new type of asphalt mixture modified by diatomite and rubber crumb was adopted as asphalt pavement on the bridge deck. According to the Chinese specification JTG F40-2004 “Technical Specifications for Construction of Highway Asphalt Pavements” [29], the median aggregate gradation of stone matrix asphalt (SMA)-13 was used in this paper. The AH-90 # asphalt from Panjin City was also used, and the asphalt-aggregate ratio was designed to be 6.3% in this study. The high-quality diatomite from Changbai Mountain area of Jilin Province was used to replace the mineral powder by equal volume replacement, whose content is 15% of asphalt by quality. The content of rubber crumb is 3% of aggregate by dry weight, and the particle size of rubber crumb is 1–3 mm [24, 25].

*2.2. Specimen Preparation.* According to the requirements of the Chinese specification JTG 3420-2020 “Testing Methods of Cement and Concrete for Highway Engineering” [32], the cement concrete specimens of  $\phi 101.6 \text{ mm} \times 50 \text{ mm}$  were

TABLE 1: Basic properties of SBS-modified asphalt and rubber-modified asphalt.

Properties	SBS-asphalt	Rubber-asphalt	Standard	Method
Penetration at 25°C, 100 g, 5 s (0.1 mm)	69	65	60–80	T 0604
Ductility at 5°C, 5 cm/min (cm)	31	33	≥30	T 0605
Softening point (°C)	75	71	≥55	T 0606
Brookfield viscosity at 135°C (Pa·s)	1.912	2.032	≤3	T 0625

TABLE 2: Basic properties of SBS-modified emulsified asphalt.

Properties	Test value	Standard	Method
Ion charge	+	+	T 0653
Residue on sieve (%)	0.05	≤0.1	T 0652
Enguera viscosity at 25°C	18	2–30	T 0622
Storage stability (%)	0.64	≤1	T 0655
	Solid content (%)	≥55	T 0651
Evaporation residue	Penetration (0.1 mm)	45–150	T 0604
	Ductility at 5°C (cm)	≥20	T 0605
	Softening point (°C)	≥50	T 0606

TABLE 3: Basic properties of the AMP-100 waterproof adhesive material.

Properties	Test value	Standard
Appearance (before curing)	Black liquid	—
Moisture content (%)	2.2	≤3
Extensibility (mm)	850	≥600
Water tightness at 0.3 MPa, 30 min	No seepage	No seepage
Heat resistance at 160 ± 2°C	No flowing and sliding	No flowing and sliding
Frost resistance at -25°C	No cracks after 20 times	No cracks after 20 times
Dryness at 25°C	Surface dry	1.5 h
	Hard dry	2.8 h

prepared using the vibration compaction method, in which the specimen mold was made separately. After demolding, the specimens were made to undergo shot blasting, and their surfaces were chiseled, cleaned, and dried. The specimens were then subjected to the standard curing preservation for 28 days to achieve a good strength. Subsequently, the waterproof bonding layer was spread twice, and each spreading requires about 4 h natural drying. This is because the amounts of waterproof adhesive materials were relatively large. It is easy to flow when spraying too much on Marshall specimens once, which would make the amount of waterproof adhesive layer materials inaccurate. Two small spreading of waterproof adhesive layer materials makes the amount of material more accurate and the coating more uniform [26]. According to the Chinese specification JTG E20-2011 “Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering” [33], the SMA-13 asphalt mixture Marshall specimen was formed by the compaction method [34]. Then, put the prepared asphalt mixture specimen on the surface of the cement concrete specimen which has been sprinkled with the waterproof adhesive layer. The specimen was compacted on the compaction instrument by the compaction method so that the waterproof adhesive layer can be fully bonded. Due to the high density of asphalt concrete containing rubber particles, the porosity of the specimen prepared by the

compaction method was smaller than that prepared by the wheel pressure method, leading to a better performance; then, the compaction method was used here [35]. Finally, the composite specimen of the cement concrete-waterproof adhesive layer-asphalt mixture structure would be prepared in Figure 1. There are four different types of waterproof adhesive layers, and the corresponding amount of each adhesive layer was in their respective optimal dosage range [14, 36, 37]. In the study, four dosage gradients for each type of waterproof adhesive layer were set, as listed in Table 4.

### 2.3. Experimental Methods

**2.3.1. Shear Test.** In order to study the influence of waterproof adhesive layer types on the shear performance between the cement concrete layer and asphalt mixture layer on bridge decks, the laboratory shear test was carried out by using the indoor-formed composite shear specimen. Refer to the Chinese specification CJJ 139-2010 “Technical Specification for Waterproof of City Bridge Decks” [38], the shear strength test method was adopted. The test instrument adopted YAW series microcomputer-controlled electro-hydraulic servo pressure testing machine for shear tests. The specimen was placed in the premade test mold, and the test

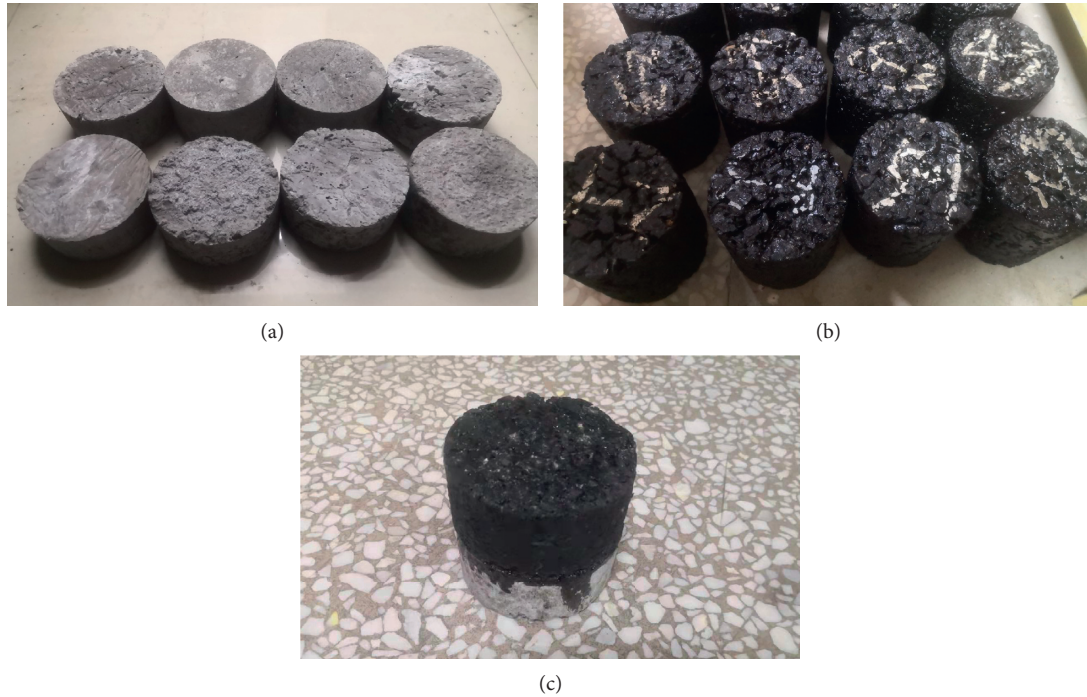


FIGURE 1: Preparation of the composite specimen. (a) Cement concrete specimens. (b) Asphalt mixture specimens. (c) Composite specimen of the cement concrete-waterproof adhesive layer-asphalt mixture.

TABLE 4: Design of the waterproof adhesive layer for shear and pull-out tests.

Waterproof adhesive layer types	The dosage gradient design (kg/m <sup>2</sup> )			
Rubber-modified asphalt [36]	2.0	2.2	2.4	2.6
SBS-modified asphalt [14]	1.6	1.8	2.0	2.2
SBS emulsified asphalt [36]	0.4	0.6	0.8	1.0
AMP-100 waterproof materials [37]	0.6	0.8	1.0	1.2

mold was placed in the center of the instrument. During the test, the prepared composite specimen was placed in the iron mold in the order of the concrete layer below and asphalt mixture layer above. The position of the specimen was adjusted to make the adhesive layer exactly located in the shear plane, and the press was dropped to the upper surface of the iron mold. The shear rate was controlled at 45 mm/min. After starting the instrument, record the pressure curve over time. When the specimen was destroyed, stop the shear test and record the maximum pressure value as well as the displacement value.

The shear test specimens were divided into two groups: (1) the first group of specimens was tested for four types of waterproof adhesive layers with different dosages in Table 4 at room temperature of 25°C. (2) The second group of specimens with the optimum dosage was tested at four temperature gradients of -5°C, 10°C, 25°C, and 40°C, simulating the temperature variation range of pavement in the northern region during cold and summer. The specimens at -5°C were placed in the refrigerator for 4 h to control the temperature, and the specimens at 10°C, 25°C, and 40°C were placed in the constant-temperature water bath pot for 4 h to control the temperature. The shear tests

were carried out, respectively, and the pressure was converted to shear force after the test. The shear strength of each waterproof adhesive layer at different temperatures can be also obtained. There are three parallel specimens under each different parallel condition. Finally, the specimen failure was taken as the test termination condition. The shear test is shown in Figure 2.

The principle of the shear test in this paper is that the pressure plate of the test machine is applied from above to the test mold, and the test mold transmits the pressure to asphalt concrete and divides the pressure into a pressure normal and a shear force. The shear force provides a downward sliding effect on the asphalt mixture, in which the effect of pressure normal is ignored so that the waterproof adhesive layer is subjected to shear force. Finally, the shear force at failure is obtained, and the shear force is divided by the area of the waterproof adhesive layer, which is the shear strength.

In general, the shear strength is calculated by  $\tau = (L/A)$ ,  $\tau$  = shear strength (kPa),  $L$  = applied load (kN), and  $A$  = applied area (m<sup>2</sup>). In this study, the shear strength of the waterproof adhesive layer measured as in Figure 1 can be calculated by

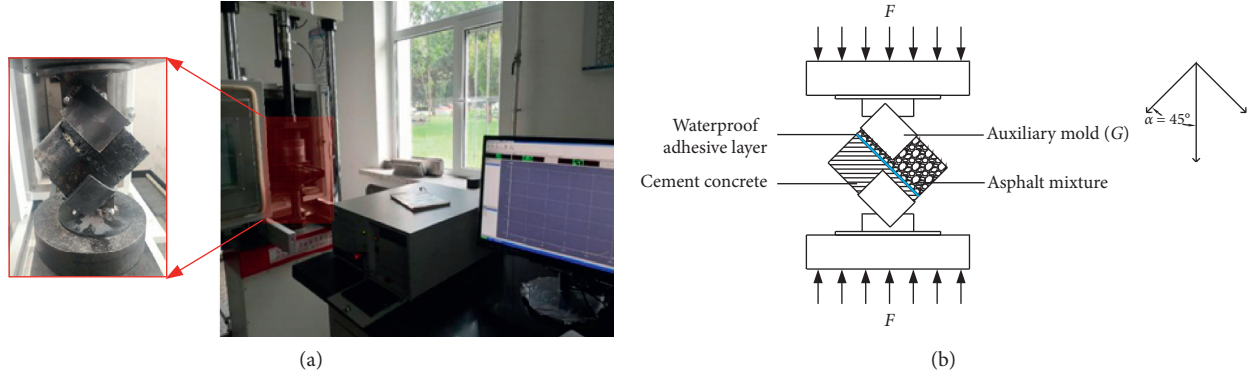


FIGURE 2: Shear test of the composite bridge deck structure. (a) Shear test in this paper. (b) The diagram of the shear test.

$$\tau = \frac{(F_S + G)\sin \alpha}{A_S}, \quad (1)$$

where  $\tau$  = shear strength of the waterproof adhesive layer (kPa),  $F_S$  = external load applied by the testing machine (kN),  $G$  = weight of the auxiliary test mold (kN),  $\alpha$  = angle between load and specimen (here, it is  $45^\circ$ ), and  $A_S$  = area of the waterproof adhesive layer on the cement concrete slab ( $\text{m}^2$ ).

**2.3.2. Pull-Out Test.** Similar to the shear test, the bond strength of the waterproof adhesive layer is also an important evaluation index of the adhesive layer. Referring to CJJ 139-2010 “Technical Specification for Waterproof Engineering of Urban Bridge Deck” [38], pull-out tests were conducted for evaluating the bond strength. In order to determine the bond strength of the waterproof adhesive layer, the CMT-100 electronic universal testing machine was used in this paper to conduct the pull-out test of the composite specimen with a specially fabricated mold. During the pull-out test, the epoxy AB adhesive was used to bond the iron mold to the surface of the composite specimen, and the mechanical clamping specimen was connected to the mold, which was placed without pressure for 12 h to wait for the glue to provide enough strength. The drawing rate was controlled at 10 mm/min. When the test value would no longer increase, stop the test and record the final maximum value.

The pull-out test specimens were also divided into two groups. The first group of specimens was tested for four types of waterproof adhesive layers with different dosages in Table 4 at room temperature of  $25^\circ\text{C}$ . As for the second group, the specimens with the optimum dosage were tested at  $-5^\circ\text{C}$ ,  $10^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $40^\circ\text{C}$ . The condition treatments of specimens were the same as those of the shear test specimens [26]. Then, pull-out tests were carried out to record the test data. There are three parallel specimens under each different parallel condition. Finally, the specimen failure is taken as the test termination condition. The pull-out test is shown in Figure 3.

The principle of the pull-out test is that the testing machine applies a pull upward to the test mold, the test mold

transmits tension to asphalt concrete, and asphalt concrete transmits tensile force to the waterproof adhesive layer so that it is subjected to tensile force. Finally, the tensile force at failure is obtained. The required bond strength is divided by tensile force by the area of the waterproof adhesive layer. According to the specification, the bond strength can be calculated by

$$p = \frac{F_T}{A_T}, \quad (2)$$

where  $p$  = bond strength (kPa),  $F_T$  = tensile force (kN), and  $A_T$  = tension area ( $\text{m}^2$ ).

### 2.3.3. Analytic Hierarchy Process (AHP) Method.

Analytic hierarchy process (AHP) [39, 40] is a method to solve complex multicriteria decision-making problems, which has the advantage of systematic analysis. It takes the research object as a system and makes decisions according to the way of decomposition, comparative judgment and comprehensive thinking. AHP requires decision-makers to judge the relative importance of each standard and use each standard to make the preference of each decision scheme. Finally, a list of schemes based on overall evaluation is formed. The specific steps are as follows:

- (1) Building hierarchical structure model
- (2) Constructing importance judgment matrix of hierarchy
- (3) Hierarchical consistency analysis
- (4) Final hierarchical ranking

After the hierarchical structure model is established, its judgment matrix is constructed. The judgment matrix is used to describe the importance between the two factors. In order to accurately describe the proportion of importance among different factors, the scale method is introduced in the analytic hierarchy process in Table 5.

The priority tables of the various influencing factors are obtained through Table 5. Then, the influence factors in the table are normalized so that the sum of each column element is 1:

$$b_{ij} = \frac{\sum_i d_{ij}}{n} d_{ij}, \quad (3)$$

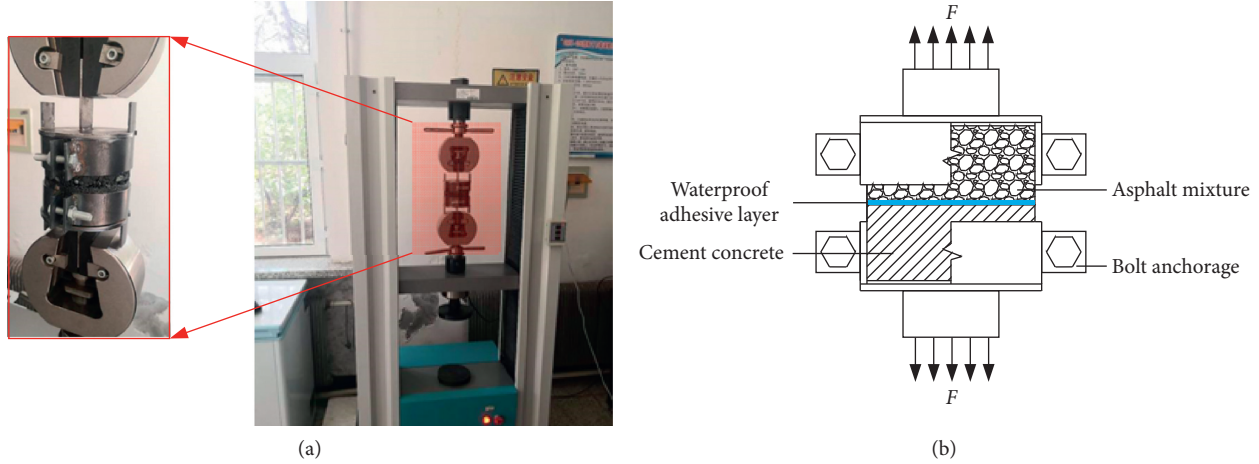


FIGURE 3: Pull-out test of the composite bridge deck structure. (a) Pull-out test in this paper. (b) The diagram of the pull-out test.

TABLE 5: Definition of the judgment matrix scale.

Scale	Meaning
1	Comparing the two factors, two factors are equally important
3	Compared with the two factors, the former is slightly important
5	Compared with the two factors, the former is obviously important
7	Compared with the two factors, the former is very important
9	Comparing the two factors, the former is extremely important
2, 4, 6, and 8	Median of adjacent scales

where  $d_{ij}$  = the  $i$ th row and  $j$ th column elements in the influence factor priority table,  $b_{ij}$  = the  $j$ th column element of the  $i$ th row in the priority normalization table, and  $n$  = the number of influencing factors of the waterproof adhesive layer.

Then, the average value of each row of the priority normalization table is taken to calculate the priority  $\alpha$ :

$$\alpha_i = \frac{\sum_j b_{ij}}{n} \quad (4)$$

Consistency analysis is performed after the judgment matrix is constructed. Consistency analysis is used to measure whether the judgment matrix obtained before is consistent. If the final value is less than 0.1, it would indicate that the consistency of the judgment matrix is acceptable. If not, it proves that the judgment matrix is unreasonable. The consistency ratio can be calculated by

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (5)$$

where  $\lambda_{\max}$  = the maximum eigenvalue of the judgment matrix and  $CI$  = the consistency ratio:

$$\lambda_{\max} = \frac{\sum_i \sum_j \alpha_i a_{ij} / \alpha_i}{n}, \quad (6)$$

where  $\alpha_i$  = the elements of the  $i$ th line in the judgment matrix and  $a_{ij}$  = the elements of the  $i$ th row and  $j$ th column in the judgment matrix.

The revised consistency ratio can be calculated by

$$CR = \frac{CI}{RI}, \quad (7)$$

where  $CR$  = the revised consistency ratio and  $RI$  = correction factor.

Finally, the final ranking of the hierarchy is obtained by the judgment matrix.

### 3. Results and Discussion

**3.1. Comparative Analysis of Shear Properties of Four Types of Waterproof Adhesive Layers.** The interlayer shear strength curves of different types of waterproof adhesive layers at 25°C are shown in Figure 4. From Figure 4, the shear strength values at room temperature 25°C of four types of waterproof adhesive layers increase first and then decrease with the increase of dosage, and there is maximum shear strength. Because the amount of the waterproof adhesive layer is less, there is not enough bond strength to resist the effect of external force. With the increase of the amount of the adhesive layer, the shear strength increases gradually. After reaching a limit, as the amount of the adhesive layer continues to increase, the waterproof adhesive layer will accumulate between the cement concrete layer and asphalt mixture layer, which cannot play a good bonding role, and the shear strength between the layers decreases gradually. Therefore, it can be considered that there is an optimal amount of the waterproof adhesive layer. And, with the increase of the amount of the adhesive layer, the shear strength gradually tends to a constant value. It indicates that the shear strength between layers is completely provided by

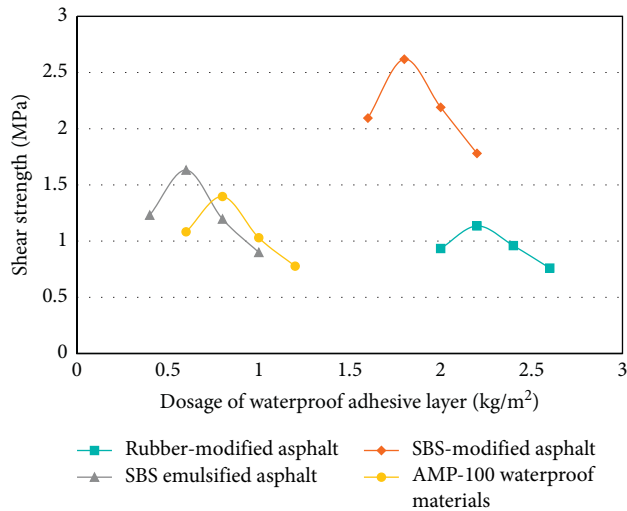


FIGURE 4: Shear strength of four types of waterproof adhesive layers with different dosages.

the shear strength of the adhesive layer itself, and it is not attached to concrete and asphalt mixture.

SBS-modified asphalt has a two-phase separation structure so that it can form a spatial three-dimensional network structure with the asphalt matrix and has a strong cohesion. It can be well adsorbed on the diatomite rubber-particle asphalt mixture, so the shear strength is larger [41]. When the rubber asphalt is bonded with the asphalt mixture, there are rubber particles added on the surface of the asphalt mixture, which accumulates with the rubber powder of the rubber asphalt itself. Too many rubber powders cannot be well compatible with the asphalt matrix, and the intermolecular force is weakened. And, rubber asphalt is not easy to combine with the dense cement concrete layer, the interface friction resistance is small, and the bond effect is poor, so the shear strength is small [42–45]. SBS emulsified asphalt has good fluidity, which can fully contact with the adhesive surface. Because of its own modifier and emulsifier, the relative bonding ability is weak, so the shear strength is small [45–47]. AMP-100 materials can accelerate construction due to second-order reactions and high fluidity. But because asphalt content is not high, its own bond performance is general [37].

When the amount of rubber asphalt is  $2.2 \text{ kg/m}^2$ , the shear strength is the largest. When the dosage of SBS-modified asphalt is  $1.8 \text{ kg/m}^2$ , the shear strength is the highest. When the dosage of SBS emulsified asphalt is  $0.6 \text{ kg/m}^2$ , the shear strength is the highest. The maximum shear strength was obtained when AMP-100 waterproof materials' content was  $0.8 \text{ kg/m}^2$ . Among them, the maximum shear strength of SBS-modified asphalt is  $2.61 \text{ MPa}$ , which is higher than the other three kinds of adhesive layers, and its shear resistance is better than the other three adhesive layers.

**3.2. Comparative Analysis of Pull-Out Properties of Four Types of Waterproof Adhesive Layers.** Figure 5 is the bond strength curve of different types of waterproof adhesive layers at  $25^\circ\text{C}$ .

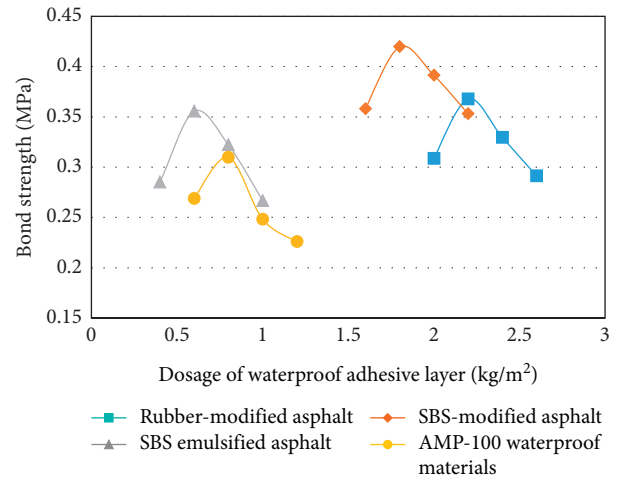


FIGURE 5: Bond strength of four types of waterproof adhesive layers with different dosages.

It can be seen from Figure 5 that, at room temperature of  $25^\circ\text{C}$ , with the increase of the amount of the four waterproof adhesive layers, the bond strength increases first and then decreases, and there is maximum bond strength. This is due to the less amount of the adhesive layer and the weaker bond capacity of the adhesive layer with cement concrete and asphalt mixture. With the increase of the amount of the adhesive layer, the bond ability gradually increases and reaches a peak value. At this point, the waterproof bonding layer obtains the optimal amount of the material when the bond strength is maximum. The waterproof bonding layer not only has the bonding effect between layers but also can repair the cracks on the surface of the upper and lower structural layers. Thus, the friction and meshing between layers are increased, and the bond ability between layers is increased [48]. When the amount of the waterproof bonding layer exceeds the optimal amount, too much bonding layer material makes the overall thickness of the bonding layer larger, reducing the friction and meshing between cement concrete and asphalt mixture. At this time, only the bonding effect of the waterproof bonding layer material is left, so the overall bonding strength is reduced.

The shear strength and bond strength of the waterproof bonding layer are from the bonding ability of the adhesive layer itself and the bond effect between the layers. In addition, the shear strength partly comes from the friction resistance of the interface, and the bond strength has little correlation with it. So the range dosage and optimum dosage of shear strength and bond strength are the same, and shear strength is greater than bond strength [37]. Rubber asphalt mainly enhances its bond performance by adding the rubber powder and modifier. An appropriate amount of the rubber powder can adsorb asphalt molecules and have a large cohesive force. Because the interface friction resistance is small and the bond effect is poor, the bonding performance of rubber asphalt is small. But the bond ability is large, so the bond performance is large [37]. The bond strength principle of other adhesive layers is the same as the shear strength principle.

When the rubber asphalt content is  $2.2 \text{ kg/m}^2$ , the bond strength is the highest. When the dosage of SBS-modified asphalt is  $1.8 \text{ kg/m}^2$ , the bond strength is maximum. The maximum bond strength was obtained when SBS emulsified asphalt content was  $0.6 \text{ kg/m}^2$ . When AMP-100 material dosage was  $0.8 \text{ kg/m}^2$ , the bond strength was the highest. The maximum bond strength of SBS-modified asphalt is  $0.42 \text{ MPa}$ , and its bond performance is better than the other three adhesive layers. The bond ability of SBS emulsified asphalt is similar to rubber asphalt.

**3.3. Influences of Temperature on the Shear and Pull-Out Properties of the Waterproof Adhesive Layer.** Generally, the waterproof adhesive layer is mostly asphalt mixture, with a certain temperature sensitivity. Therefore, in the seasonal frozen region, the influence of temperature on the waterproof adhesive layer should be considered. Figure 6 shows the interlaminar shear strength curves of different waterproof adhesive layers at different temperatures under the optimum dosage.

It can be seen from Figure 6 that, with the increase of temperature, the shear strength of the four adhesive layers decreases by varying degrees, which indicates that the waterproof adhesive layer is temperature sensitive. As the temperature rises, the internal structure of the adhesive layers becomes unstable and the shear strength decreases. At low temperature, the shear strength is large, indicating that the low-temperature performance of these waterproof adhesive layers is excellent, and the internal stability is very stable. At high temperature, the shear strength is very low, indicating that the internal shear layer has been very unstable and lost its proper strength.

Physical entanglement or chemical cementation of SBS-modified asphalt due to continuous polymerization of SBS modifier particles with increasing temperature reduces the temperature sensitivity of materials. And, energy is needed to destroy the three-dimensional network structure of SBS-modified asphalt. SBS-modified asphalt has better temperature performance [49]. The rubber powder of rubber asphalt is added to the matrix asphalt, changing the asphalt colloid structure. Under the change of temperature, a uniform and insoluble phase solution system was formed. Therefore, the temperature sensitivity is also low, and the temperature performance is good [42, 45, 50]. SBS emulsified asphalt has high temperature sensitivity because the emulsifier has high temperature sensitivity. With the increase of temperature, the internal particles are more active, so the temperature performance is low [45, 46]. The AMP-100 material can adsorb asphalt molecules because of its internal macromolecular structure when temperature changes, so the temperature sensitivity is low. But because its shear strength is low, the overall strength is low [37].

At different temperatures, the shear properties of the four materials are greatly different. The maximum shear strength of SBS-modified asphalt is  $5.41 \text{ MPa}$  at  $-5^\circ\text{C}$  higher than other adhesive layers, and the minimum shear strength of SBS emulsified asphalt is  $0.27 \text{ MPa}$  at  $40^\circ\text{C}$  lower than other adhesive layers. The shear strength of the AMP-100

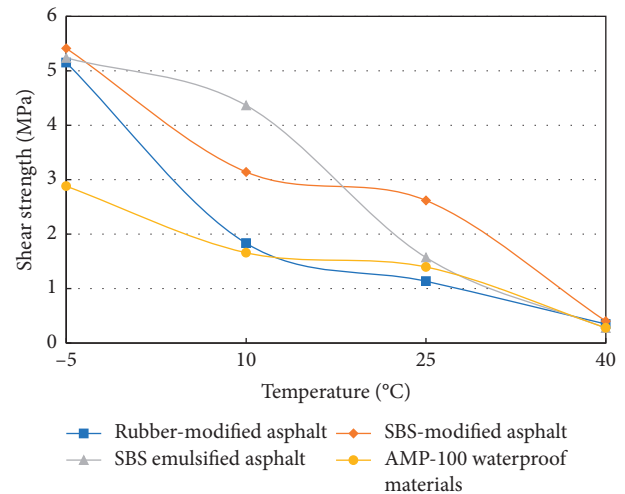


FIGURE 6: Shear strength of four types of waterproof adhesive layers at different temperatures.

material decreased least at different temperatures. In the seasonal frozen region, the temperature of bridge deck pavement varies from  $0^\circ\text{C}$  to  $30^\circ\text{C}$ . In this range, rubber asphalt and AMP-100 materials have low shear strength. Although the shear strength of SBS emulsified asphalt is high, the strength decreases greatly with the increase of temperature. The shear strength of SBS-modified asphalt is relatively high, and the strength changes little with the increase of temperature. Therefore, the overall performance of SBS-modified asphalt is better.

Figure 7 is the bond strength curve of different kinds of waterproof adhesive layers at different temperatures under the optimal dosage. It can be seen from Figure 7 that the bond strength of the waterproof adhesive layer gradually decreases with the increase of temperature. The adhesive layer is larger at low temperature than at high temperature, indicating that the adhesive layer is temperature sensitive. And, it is not active at low temperature, so the bond strength is higher. With the increase of temperature, the internal adhesive layer is becoming more and more unstable, so the bond strength decreases. And, with temperature to rise, the adhesive layer is melting, which would destroy its bond performance.

Shear performance and bond performance principles are similar, determined by their own bonding ability and interlayer bond effect. SBS-modified asphalt has good bond property because SBS modifier particles have good adsorption property [49]. The AMP-100 material has low overall bond strength because of low asphalt content. The bond strength of rubber asphalt and SBS emulsified asphalt is basically the same. However, because rubber asphalt contains rubber, whose low-temperature stability is greater and adsorption capacity is stronger, its low-temperature bond strength is greater [50].

At different temperatures, the bond strength of the waterproof adhesive layer is very different. The maximum bond strength of rubber asphalt is  $0.81 \text{ MPa}$  at  $-5^\circ\text{C}$ , and the minimum bond strength of the AMP-100 material is



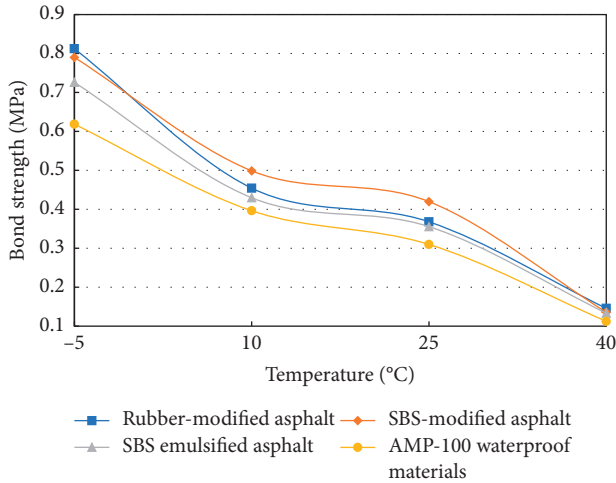


FIGURE 7: Bond strength of four types of waterproof adhesive layers at different temperatures.

0.11 MPa at 40°C. The bond strength of the AMP-100 material is little low, and the bond strength of SBS-modified asphalt is excellent.

**3.4. Evaluation Analysis and Optimization Based on Comprehensive Performances of the Waterproof Adhesive Layer Using AHP.** According to the previous strength test and temperature test of the waterproof adhesive layer, it is not enough to give a waterproof adhesive layer which has enough advantages to bond with the diatomite rubber-particle asphalt mixture. There are many external factors to be considered in the practical projects, such as the cost of each waterproof adhesive layer, the construction difficulty during the construction, and the time taken to block public transportation, which is the problem that should be considered when paving the bridge deck. Therefore, to get a better waterproof adhesive layer, the performance value obtained above and external factors such as the cost of waterproof adhesive layer, construction difficulty, environmental protection, and energy saving are considered for analysis.

According to the research and analysis of multi-objective grey target decision theory, some scholars have obtained the priority relationship among shear performance, bond performance, and cost. According to priority size, shear performance  $\geq$  bonding performance  $\geq$  cost [51]. For temperature, some scholars believe that the waterproof bonding layer has been under the influence of high temperature from the beginning of laying, which is the main reason affecting the bond performance [14, 17]. So the temperature should be the highest priority, which is higher than the bond performance and shear performance. Construction difficulty and environmental protection are not factors affecting the overall performance of the waterproof bonding layer, so their priority is low. And, in the construction, some defects of construction difference may be caused by the long and difficult construction

process, so the priority of construction difficulty is higher than environmental protection [52]. Here, the analytic hierarchy process (AHP) [39, 40] was used to process the data. First, the priority of each factor is determined in Table 6.

Then, carry out normalized processing and calculate the priority. The priority here is the proportion of each influencing factor for the waterproof adhesive layer, as listed in Table 7.

Next, calculate the priority consistency to determine whether the previous comparison between any two means is consistent:

$$\sum \alpha_i A_i = \sum \begin{pmatrix} \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \end{pmatrix} = \begin{bmatrix} 0.528 \\ 0.290 \\ 0.190 \\ 0.986 \\ 1.593 \\ 2.523 \end{bmatrix}, \quad (8)$$

where  $A_i$  = normalized matrix of influencing factors in Table 7, and  $a_{ij}$  = normalized values of each influencing factor in Table 7. Therefore, the consistency ratio can be calculated by equation (5), i.e.,  $CI = ((\lambda_{\max} - n)/(n - 1))$ , where  $\lambda_{\max} = 6.073$ .

The revised consistency ratio calculated by equation (7) is  $CR = CI/RI = 0.012 \leq 0.1$ . Here, the value of  $RI$  is 1.24. So the consistency ratio meets the requirements. Therefore, the priority of the waterproof adhesive layer under various influencing factors is shown in Table 8.

Priority of the waterproof adhesive layer can be calculated by

$$\mu = \sum_i \alpha_i b_{ij}, \quad (9)$$

where  $b_{ij}$  = normalized values of each waterproof adhesive layer under different factors in Table 8. So the priority of rubber-modified asphalt  $\mu = 0.131$ , the priority of SBS-modified asphalt  $\mu = 0.376$ , the priority of SBS emulsified asphalt  $\mu = 0.210$ , and the priority of SBS AMP-100 waterproof materials  $\mu = 0.282$ .

Therefore, considering the cost, bond strength, shear strength, construction difficulty, environmental protection, energy saving, and temperature performance of the waterproof adhesive layer, according to the priority order of performance analysis, SBS-modified asphalt has the best comprehensive performance, and its bond properties and shear properties are better; the second is AMP-100, which has better temperature performance than other materials; the third is the performance of SBS emulsified asphalt, and the overall performance is more common; and, the last is the rubber asphalt performance, and its temperature performance is poor. So the SBS-modified asphalt waterproof adhesive layer is the most suitable for laying on diatomite rubber-particle asphalt mixture pavement.

TABLE 6: Priority determination of influencing factors of the waterproof adhesive layer.

Priority	Cost	Construction difficulty	Environmental protection	Bond property	Shear property	Temperature
Cost	1	2	3	1/2	1/3	1/5
Construction difficulty	1/2	1	2	1/4	1/6	1/8
Environmental protection	1/3	1/2	1	1/6	1/8	1/9
Bond property	2	4	6	1	1/2	1/3
Shear property	3	6	8	2	1	1/2
Temperature	5	8	9	3	2	1

TABLE 7: Priority normalization of influencing factors of the waterproof adhesive layer.

Priority	Normalization						Priority $\alpha$	
	Average	Cost	Construction difficulty	Environmental protection	Bond property	Shear property		Temperature
Cost		0.085	0.093	0.103	0.072	0.081	0.088	0.087
Construction difficulty		0.042	0.047	0.069	0.036	0.040	0.055	0.048
Environmental protection		0.028	0.023	0.034	0.024	0.030	0.049	0.032
Bond property		0.169	0.186	0.207	0.145	0.121	0.147	0.162
Shear property		0.254	0.279	0.276	0.289	0.242	0.220	0.260
Temperature		0.423	0.372	0.310	0.434	0.485	0.441	0.411

TABLE 8: Priority normalization of the waterproof adhesive layer under various influencing factors.

	Cost	Construction difficulty	Environmental protection	Bond property	Shear property	Temperature
Rubber-asphalt	0.167	0.167	0.423	0.227	0.074	0.096
SBS-asphalt	0.333	0.167	0.123	0.423	0.586	0.277
SBS-emulsified asphalt	0.333	0.333	0.227	0.227	0.212	0.161
AMP-100 materials	0.167	0.333	0.227	0.123	0.128	0.466

## 4. Conclusions

Some conclusions are obtained by testing the properties of these four waterproof adhesive layers bonded with diatomite rubber-particle asphalt mixture and cement concrete.

- (1) At 25°C, the maximum shear strength of SBS-modified asphalt is 2.61 MPa at 1.8 kg/m<sup>2</sup>, whose shear resistance is better than the other three adhesive layers, and the maximum adhesive strength is 0.42 MPa at 1.8 kg/m<sup>2</sup>, which is better than the other three adhesive layers. For shear and bond properties, the optimum dosage of rubber asphalt is 2.2 kg/m<sup>2</sup>, and the optimum dosage of SBS-modified asphalt is 1.8 kg/m<sup>2</sup>. The optimum dosage of SBS emulsified asphalt is 0.6 kg/m<sup>2</sup>, and the optimum dosage of AMP-100 materials was 0.8 kg/m<sup>2</sup>.
- (2) At the same temperature, with the increase of the amount of the waterproof adhesive layer, the bond strength and shear strength both increased first, then decreased, and gradually stabilized.
- (3) At different temperatures, the shear strength of AMP-100 materials has the least reduction. The shear strength of rubber asphalt and SBS-modified asphalt is very high, but the overall performance of SBS-modified asphalt is better. The bond strength of the AMP-100 material is low, and the bond

strength of SBS-modified asphalt is excellent as a whole.

- (4) Compared with other adhesive layer materials, SBS-modified asphalt has the best comprehensive performance, which is more suitable for the climate with large temperature difference in winter and summer in the seasonal frozen region and has a better bond effect in the seasonal frozen region. Therefore, this paper selects the SBS-modified asphalt material as the most suitable waterproof adhesive layer bonded with diatomite rubber-particle asphalt mixture.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

This research was funded by Scientific and Technological Project of Science and Technology Department of Jilin Province (Grant no. 20190303052SF).

## References

- [1] C. Raab and M. N. Partl, "Mechanical evaluation of concrete bridge deck pavement systems," *Journal of Testing and Evaluation*, vol. 48, no. 1, pp. 211–222, 2020.
- [2] L. Chen, Z. Qian, D. Chen, and Y. Wei, "Feasibility evaluation of a long-life asphalt pavement for steel bridge deck," *Advances in Civil Engineering*, vol. 2020, Article ID 5890945, 8 pages, 2020.
- [3] L. Chen, G. Liu, Z. Qian, and X. Zhang, "Determination of allowable rutting depth based on driving safety analysis," *Journal of Transportation Engineering, Part B: Pavements*, vol. 146, no. 2, 2020.
- [4] L. Chen, Z. Qian, and Q. Lu, "Crack initiation and propagation in epoxy asphalt concrete in the three-point bending test," *Road Materials and Pavement Design*, vol. 15, no. 3, pp. 507–520, 2014.
- [5] H. Zhang, P. Gao, Z. Zhang, and Y. Pan, "Experimental study of the performance of a stress-absorbing waterproof layer for use in asphalt pavements on bridge decks," *Construction and Building Materials*, vol. 254, Article ID 119290, 2020.
- [6] Y. Guan, C. Han, M. Li, and L. Yan, "Performance of modified epoxy resin waterproof adhesive layer on cement concrete bridge surface," *Journal of Building Materials*, vol. 16, no. 5, pp. 894–902, 2013.
- [7] F. Mazzotta, C. Lantieri, V. Vignali, A. Simone, G. Dondi, and C. Sangiorgi, "Performance evaluation of recycled rubber waterproofing bituminous membranes for concrete bridge decks and other surfaces," *Construction and Building Materials*, vol. 136, pp. 524–532, 2017.
- [8] J. S. Gong, H. L. Zhou, and H. L. Zhang, "Development and application of modified asphalt," *Petroleum Engineering Construction*, vol. 51987, in Chinese.
- [9] D.-c. Feng, M. Xu, and W.-d. Wei, "Analysis of the influence of cement concrete deck moisture content on the bonding performance of waterproof adhesion layer," *Journal of Highway and Transportation Research and Development (English Edition)*, vol. 8, no. 2, pp. 31–36, 2014.
- [10] M. Guo, M. Liang, Y. Jiao, W. Zhao, Y. Duan, and H. Liu, "A review of phase change materials in asphalt binder and asphalt mixture," *Construction and Building Materials*, vol. 258, Article ID 119565, 2020.
- [11] G. P. Qian, S. J. Li, H. N. Yu et al., "Interlaminar bonding properties on cement concrete deck and phosphorous slag asphalt pavement," *Materials*, vol. 12, no. 9, 2019.
- [12] S. P. Wu, H. Wang, J. Han, and J. T. Lin, "Research on waterproof-adhesive layer's shearing strength in cement concrete bridge pavement," *Key Engineering Materials*, vol. 417–418, pp. 849–852, 2009.
- [13] Q. Xu, Q. Zhou, C. Medina, G. K. Chang, and D. K. Rozycki, "Experimental and numerical analysis of a waterproofing adhesive layer used on concrete-bridge decks," *International Journal of Adhesion and Adhesives*, vol. 29, no. 5, pp. 525–534, 2009.
- [14] Y. Liu, J. Wu, and J. Chen, "Mechanical properties of a waterproofing adhesive layer used on concrete bridges under heavy traffic and temperature loading," *International Journal of Adhesion and Adhesives*, vol. 48, pp. 102–109, 2014.
- [15] M. Guo, Y. Tan, L. Wang et al., "Study on water permeability, shear and pull-off performance of waterproof bonding layer for highway bridge," *International Journal of Pavement Research and Technology*, vol. 11, no. 4, pp. 396–400, 2018.
- [16] Y. Jiao, Y. Zhang, L. Fu, M. Guo, and L. Zhang, "Influence of crumb rubber and tpa-pack super on performances of SBS modified porous asphalt mixtures," *Road Materials and Pavement Design*, vol. 20, 2019.
- [17] H. Wang, C. Jin, H. Liu, and Z. Xue, "Rubber asphalt waterproof adhesive layer for steel bridge gussasphalt pavement," *International Journal of Structural Integrity*, vol. 12, no. 2, 2020.
- [18] K. Zhang, "Interlaminar performance of waterproof and cohesive materials for concrete bridge deck under specific test conditions," *Journal of Materials in Civil Engineering*, vol. 30, no. 8, 2018.
- [19] M. Liu, S. Han, J. Pan, and W. Ren, "Study on cohesion performance of waterborne epoxy resin emulsified asphalt as interlayer materials," *Construction and Building Materials*, vol. 177, pp. 72–82, 2018.
- [20] J. Chen, C. Yao, H. Wang, W. Huang, X. Ma, and J. Qian, "Interface shear performance between porous polyurethane mixture and asphalt sublayer," *Applied Sciences*, vol. 8, no. 4, p. 623, 2018.
- [21] N. Fang, X. Wang, H. Ye et al., "Study on fatigue characteristics and interlayer design method of waterproof cohesive bridge deck layer," *Applied Sciences*, vol. 9, no. 10, 2019.
- [22] Y. Qiu, S. An, A. Rahman, and C. Ai, "Evaluation and optimization of bridge deck waterproof bonding system using multi-objective grey target decision method," *Road Materials and Pavement Design*, vol. 21, no. 7, pp. 1844–1858, 2020.
- [23] H. Liu, G. Yuan, Q. Zhang, P. Hao, S. Dong, and H. Zhang, "Study on influence factors of asphalt mixtures pavement blistering on portland cement concrete bridge deck," *International Journal of Pavement Engineering*, vol. 22, no. 2, pp. 249–256, 2021.
- [24] M. Z. Pei, *Research on the Optimized Preparation Process and Anti-aging Property of Diatomite-Crumb Rubber Compound Modified Asphalt*, Jilin University, Changchun, China, 2016, in Chinese.
- [25] Y. Q. Zhao, H. D. Kuai, F. Chen et al., "Study on factors influencing the viscosity of diatomite+rubber powder modified bitumen," *Technology of Highway and Transport*, vol. 3, no. 1, pp. 37–40, 2018, in Chinese.
- [26] F. Zhang and M. Li, "Performance of composite waterproof cohesive layer on cement concrete bridge," *Journal of Harbin Institute of Technology*, vol. 52, no. 3, pp. 26–32, 2020, in Chinese.
- [27] Y. Jiao, Y. Zhang, M. Guo, L. Zhang, H. Ning, and S. Liu, "Mechanical and fracture properties of ultra-high performance concrete (UHPC) containing waste glass sand as partial replacement material," *Journal of Cleaner Production*, vol. 277, Article ID 123501, 2020.
- [28] G. Tan, Z. Zhu, W. Wang et al., "Flexural ductility and crack-controlling capacity of polypropylene fiber reinforced ECC thin sheet with waste superfine river sand based on acoustic emission analysis," *Construction and Building Materials*, vol. 277, Article ID 122321, 2021.
- [29] JTG F40-2004, *Technical Specifications for Construction of Highway Asphalt Pavements (Explanation)*, China Communications Press, Beijing, China, 2004, in Chinese.
- [30] GB/T16777-2008, *Test Methods for Building Waterproofing Coatings*, Standardization Administration of China, Beijing, China, 2008, in Chinese.
- [31] JC/T975-2005, *Waterproofing Coating for Concrete Bridge and Road Surface*, National Development and Reform Commission of the PRC, Beijing, China, 2005, in Chinese.
- [32] JTG 3420-2020, *Testing Methods of Cement and Concrete for Highway Engineering*, Ministry of Communications of the PRC, Beijing, China, 2020, in Chinese.

- [33] JTG E20-2011, *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering*, China Communications Press, Beijing, China, 2011, in Chinese.
- [34] J. Yubo, L. Zhang, G. Qinglin et al., "Acoustic emission-based reinforcement evaluation of basalt and steel fibers on low-temperature fracture resistance of asphalt concrete," *Journal of Materials in Civil Engineering*, vol. 32, no. 5, Article ID 04020104, 2020.
- [35] P. Li, M. Z. Lu, and H. R. Wu, "Influence analysis of Marshall molding method and rolling molding method on the volume parameters of asphalt mixture," *Science Technology and Engineering*, vol. 11, pp. 3049–3051, 2008, in Chinese.
- [36] DB11/T 1680-2019, *Technical Specification for Rapid Construction of Waterproof-Bonding Layer on Concrete Bridge Deck*, Beijing Municipal Bureau of Market Supervision, Beijing, China, 2019, in Chinese.
- [37] W. H. Zhang, *Study on Waterproof and Cohesive Layer of Asphalt Concrete Pavement for Cement Concrete Bridge under the Condition of Warm-Wet and Heavy Load*, Guangzhou University, Guangzhou, China, 2017, in Chinese.
- [38] CJJ 139-2010, *Technical Specification for Waterproofing of City Bridge Decks*, Ministry of Housing and Urban-Rural Construction of the PRC, Beijing, China, 2010, in Chinese.
- [39] D. Wu, Z. Yang, N. Wang, C. Li, and Y. Yang, "An integrated multi-criteria decision making model and AHP weighting uncertainty analysis for sustainability assessment of coal-fired power units," *Sustainability*, vol. 10, no. 6, p. 1700, 2018.
- [40] W. Xiang, S. Xue, S. Qin, L. Xiao, F. Liu, and Z. Yi, "Development of a multi-criteria decision making model for evaluating the energy potential of Miscanthus germplasms for bioenergy production," *Industrial Crops and Products*, vol. 125, pp. 602–615, 2018.
- [41] X. Gao, *Research on Asphalt Deck of Binzhou Three-Cable-Stayed Bridge over Yellow River*, Southeast University, Nanjing, China, 2006, in Chinese.
- [42] S. Liu, "Analysis of the performance and mechanism of desulfurized rubber and low-density polyethylene compound-modified asphalt," *Journal of Applied Polymer Science*, vol. 136, no. 45, 2019.
- [43] H. Liu, Z. Chen, W. Wang, H. Wang, and P. Hao, "Investigation of the rheological modification mechanism of crumb rubber modified asphalt (CRMA) containing TOR additive," *Construction and Building Materials*, vol. 67, pp. 225–233, 2014.
- [44] X. F. Wang, "Study of rubber asphalt modification mechanism," *Advanced Materials Research*, vol. 194–196, pp. 844–847, 2011.
- [45] Y. Li, S. Li, R. Lv et al., "Research on failure mode and mechanism of different types of waterproof adhesive materials for bridge deck," *International Journal of Pavement Engineering*, vol. 16, no. 7, pp. 602–608, 2015.
- [46] R. Gong, "The influence of SBS modifier on the performance of modified emulsified asphalt," *Petroleum Asphalt*, vol. 15, no. 529, pp. 4–6, 2017, in Chinese.
- [47] L. Xu, "Chemical, morphological and rheological investigations of SBR/SBS modified asphalt emulsions with waterborne acrylate and polyurethane," *Construction and Building Materials*, vol. 272, 2021.
- [48] C. H. Liu, *Research on Properties of Several Waterproof and Cohesive Layers for Concrete Bridge Deck*, Wuhan University of Technology, Wuhan, China, 2009, in Chinese.
- [49] C. Yang, "The mechanism analysis of SBS modified asphalt by GPC method," *Urban Construction Theory Research*, vol. 10, pp. 1–8, 2012, in Chinese.
- [50] J. Lu, *Performance Influence Factors and Mechanism of Rubber Asphalt*, Chang'an University, Xi'an, China, 2010, in Chinese.
- [51] Y. Qiu, S. An, R. Ali, and C. Ai, "Evaluation and optimization of bridge deck waterproof bonding system using multi-objective grey target decision method," *Road Materials and Pavement Design*, vol. 21, no. 7, 2020.
- [52] H. Fan, *Selection and Application of Waterproof Adhesive Layer for Cement Concrete Bridge Deck*, Beijing University of Technology, Beijing, China, 2019, in Chinese.