sustainability

MDPI

Review

Materials and Performance of Asphalt-Based Waterproof Bonding Layers for Cement Concrete Bridge Decks: A Systematic Review

Feng Gao [1], Xuan Gao [2], Qian Chen [3,*], Yanduo Li [3], Zhiwei Gao [4] and Chaohui Wang [3,*]

[1] Sino Nuclear Northwest Construction Group Co., Ltd., Xi'an 710054, China
[2] CCCC First Highway Consultants Co., Ltd., Xi'an 710075, China
[3] School of Highway, Chang'an University, Xi'an 710064, China
[4] School of Information Engineering, Xizang Minzu University, Xianyang 712082, China
* Correspondence: 2016121160@chd.edu.cn (Q.C.); wchh0205@chd.edu.cn (C.W.)

Abstract: As an important part of the bridge deck pavement system, the waterproof bonding layer plays a vital role in ensuring the integrity and durability of the pavement structure. Asphalt-based waterproof bonding materials have attracted extensive attention from researchers due to their low cost and good combination with asphalt surfaces. However, the existing research results of asphalt waterproof bonding layers are confused and there is a lack of systematic summaries. In addition, there are significant differences in the type, specification, performance, evaluation method, and evaluation index of asphalt materials. The performance evaluation indexes and methods of asphalt waterproof bonding materials need to be further studied and improved. To further promote the research and development of asphalt waterproof bonding layer materials, in this paper, the relevant specifications for the waterproof bonding layer of roads and bridges in China were systematically combed, the key performance index requirements in different specifications were compared and evaluated, the research trends of the asphalt waterproof bonding layer in China and its application in engineering construction were comprehensively reviewed, the performance of different asphalt waterproof bonding materials were systematically investigated, and the construction technology and economy of different asphalt waterproof bonding layer materials were analyzed. This paper provides a useful reference for the specification improvement and quality control of asphalt waterproof bonding layer.

Keywords: road materials; bridge deck pavement; asphalt-based waterproof bonding layer; research progress; working properties

Citation: Gao, F.; Gao, X.; Chen, Q.; Li, Y.; Gao, Z.; Wang, C. Materials and Performance of Asphalt-Based Waterproof Bonding Layers for Cement Concrete Bridge Decks: A Systematic Review. *Sustainability* **2022**, *14*, 15500. https://doi.org/10.3390/su142315500

Academic Editor: Rui Micaelo

Received: 1 September 2022
Accepted: 15 November 2022
Published: 22 November 2022

1. Introduction

A waterproof bonding layer acts as a functional layer between the bridge deck and the paving layer, acting as a bonding and waterproofing layer. A good waterproof bonding layer not only ensures the integrity of the paving structure, but also plays a part in stress absorption, inhibits surface cracking, and offers other effects [1,2]. At present, the commonly used bridge deck waterproof bonding layer materials in China are mainly categorized as asphalt and reactive resin types, and asphalt materials, because of their own water repellent, low cost, and good adhesion with the surface layer, are widely used in the field of bridge deck pavements, while the development of modified asphalt, so that it not only retains the original advantages of asphalt materials, but also has a number of significant characteristics of modified asphalt, is ongoing. In recent years, researchers have carried out a series of studies on the performance of different modified asphalt-based waterproof bonding materials. Scholars represented by Haynes proposed a variety of modified asphalt-based waterproof adhesive materials, with self-healing, crack resistance, impermeability, and other aspects to enhance the performance of waterproof materials [3–6]. Scholars represented by Oh evaluated the service performance of different types of waterproof adhesive layer [7–9]. Scholars represented by Hailesilassie analyzed the bonding and debonding mechanism of waterproof adhesive materials in different situations based on laboratory tests [10–14]. In summary, it can be seen that the current research is mainly focused on the development of waterproofing binder materials and interlayer bonding performance, but the results are complicated, scattered, lack systematic sorting, and engineering applications have not formed a complete system. In order to further promote the research and application of asphalt-based waterproof adhesive layer, it is necessary to more systematically comb the changing rules of the working performance of different asphalt-based waterproof adhesive layers, so as to conduct further targeted research.

Based on above reasons, in this paper, the relevant specifications of asphalt waterproof bonding layer for roads and bridges in China were systematically sorted out, the key technical indicators of waterproof bonding layer in different specifications were compared and evaluated, the research trends and the engineering applications of bridge deck waterproof bonding layer in China were comprehensively investigated, the performance of different asphalt waterproof bonding layer materials was comprehensively summarized, and the construction technology and economy of different asphalt waterproof bonding layer materials were compared and analyzed. This work provides a reference for revising and improving the relevant specifications of asphalt waterproof bonding materials, and lays a foundation for subsequent engineering applications and targeted in-depth research.

2. Survey and Evaluation of Asphalt-Based Waterproof Bonding Layer Specifications

The asphalt-based waterproof bonding layer is effectively bonded with the bridge deck through physical action. The material softens or melts with the increase in temperature, and solidifies with the decrease in temperature. In the project, the asphalt-based waterproof bonding layer is divided into coiled material, coating film, and crushed stone seal according to the structure type [15–17]. Because of the different structures of bridge deck pavement combinations and the wide variety of waterproof bonding materials and specifications, there are significant differences in their corresponding performance index requirements and evaluation methods. In order to comprehensively and objectively evaluate the technical performance of the waterproof bonding layer, this paper comprehensively investigated the relevant specifications of waterproof bonding layer materials for roads and bridges in China, and compared their key performance indicators and specific requirements, as shown in Table 1.

Table 1. Relevant specifications of bonding layers for roads and bridges.

Serial Number	Specification Name	Specification Number
1	Atactic polypropylene(APP) asphalt waterproof roll for roads and bridges	JT/T 536-2004
2	Waterproofing coatings for concrete bridges and road surfaces	JC/T 975-2005
3	Emulsified asphalt waterproof coating	JC/T 408-2005
4	Modified bituminous waterproofing sheets for concrete bridge decks and other concrete surfaces trafficable by vehicles	JC/T 974-2005
5	Technical guide to the design and construction of highway steel box girder bridge decks	[2006] NO.274
6	Standard specification for waterborne epoxy-binder waterproof coating for concrete bridges	DB32/T 2285-2012
7	Technical specifications for asphalt pavement interlayer treatment of highways	DB61/Z 917-2014
8	General specifications of epoxy asphalt materials for paving roads and bridges	GB/T 30598-2014
9	Water quality asphalt waterproof coating for highways	JT/T 535-2015
10	Technical specifications for the construction of ERS steel deck pavements	DB33/T 2012-2016
11	Specifications for the design and construction of pavements on highway steel deck bridges	JTG/T3364-02-2019
12	Technical specification for rapid construction of a waterproof-bonding layer on concrete bridge decks	DB11/T 1680-2019

According to the specifications in Table 1, at the beginning of the application of a waterproof bonding layer for bridge deck pavements, building waterproof coiled materials, the asphalt film, and other materials were mostly used, but the effect was not ideal. At present, the composite waterproof system is mainly composed of a synchronous chip seal, high-performance epoxy materials, and a variety of materials. Considering the characteristics of bonding layer materials and the influence of construction factors, it is proposed that the key technical indicators of a waterproof bonding layer should include drying time, heat resistance, low temperature flexibility, impermeability, and bonding performance.

2.1. Drying Time

There are five specifications in the survey that limit the drying time of asphalt waterproof bonding materials, mainly for solvent asphalt and water emulsion asphalt materials (see Figure 1 for details).

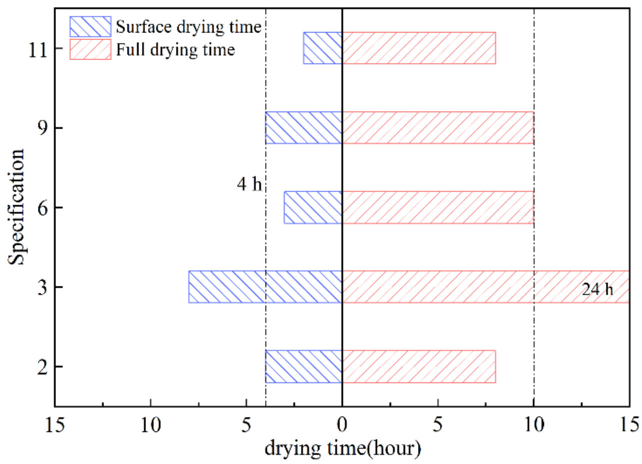

Figure 1. Comparison of relevant specifications for drying time of waterproof bonding layer materials.

Different specifications for asphalt-based waterproof bonding materials' drying time requirements are broader. Among them, specifications 2, 6, 9, and 11 have a surface drying time of basically less than 4 h and a hard drying time of basically less than 8 or 10 h. Compared with the above specifications, the drying time in specification 3 is the longest, and the surface drying time is consistent with the hard drying time in specification 2, both of which are 8 h, while the hard drying time is up to 24 h. As far as the different asphalt types were concerned, solvent asphalt bonding materials have the most stringent drying time requirements; specification 11 requires a surface drying time of less than 2 h, and specifications 2, 3, 6, and 9 require a surface drying time of 3 h, 4 h, or 8 h for emulsified asphalt bonding materials. This indicates that solvent-based bonding materials evaporate into film faster and are relatively more demanding than water-emulsion materials. Generally speaking, the surface drying time is short, the materials easily solidify quickly, and the immediate construction rarely produces the sagging phenomenon, meaning that the project requirements can be met in a short time. However, a too short surface drying time will affect the adhesion of the bonding layer, which will lead to a reduction in the bonding performance between layers. Therefore, the surface drying and hard drying time can be determined according to the actual situation to obtain a better interlayer bonding effect.

In summary, when solvent asphalt waterproof bonding materials are applied to bridge deck pavements, the surface drying time shall be less than 2 h and the hard drying time shall be less than 8 h, while the emulsion asphalt bonding materials shall meet the requirements of a surface drying time of less than 4 h and a hard drying time of less than 10 h. According to specification 2, a thermal-modified asphalt binder shall meet the requirements that the surface drying time is less than 4 h and the hard drying time is less than 8 h.

2.2. Heat-Resistant Properties

There are seven specifications in China that put forward requirements on the heat resistance of asphalt waterproof bonding layer materials, mainly for modified asphalt waterproof rolls, water emulsion asphalt materials, heat-modified asphalt materials, and epoxy asphalt. See Figure 2 for details.

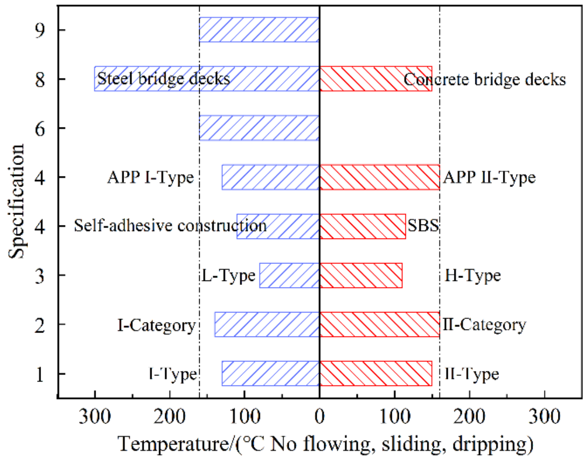

Figure 2. Comparison of relevant specifications for heat-resistant properties of waterproof bonding layer materials.

In Figure 2, the four specifications for heat-resistant property requirements are 160 °C with no flow, sliding, and dripping, while this is also in addition to specification 8 in the steel bridge deck epoxy asphalt waterproof bonding layer, namely that 300 °C does not melt outside the highest requirements. Parts of the specification requirements for heat-resistant properties of 150 °C and below, especially in the specification 3 requirements of high-performance (H-type) waterproof bonding material with a heat resistance of 110 °C, are relatively general for the visible water emulsion type asphalt waterproof bonding material, with a low performance (L-type) of only 80 °C. However, with the increase in engineering requirements and the development of modified asphalt, waterproof bonding material requirements for heat-resistant properties have also gradually increased. For example, rubber-modified asphalt mixes can be paved at temperatures of around 180 °C, although there is a significant temperature difference between the waterproof bonding layer and the asphalt mix, and the lower thermal limits make it difficult to meet the growing demand. Therefore, in order to avoid the asphalt paving process due to high temperature caused by excessive softness and flow of waterproof bonding material caused by hot aggregate puncture phenomenon, while taking into account the appropriate softening of bonding material or the slight flow that is conducive to improving the adhesion, waterproof bonding material heat-resisting properties should meet the following technical conditions: 160 °C conditions, bonding material without sliding, flowing, dripping.

2.3. Low-Temperature Flexibility

There are six specifications in the survey that limit the low temperature flexibility of asphalt waterproof bonding layer materials, mainly for modified asphalt waterproof coiled materials and water emulsion asphalt materials, as shown in Figure 3.

In Figure 3, the low-temperature flexibility of asphalt materials was more strictly controlled, with more attention paid to the effects of heat treatment, corrosion, and aging on them. Under standard conditions, the three specifications for low-temperature flexibility are the same, with no cracks or fractures at −25/−15 °C. Specification 1 for hot mix asphalt pavement APP asphalt waterproofing membrane and specification 3 in the H-type emulsified asphalt material requirements is relatively low, at only −10 and 0 °C without cracking or fracture. Most high-performance water-based asphalt materials and SBS-modified asphalt waterproofing roll-roofing are mainly between −25–−20 °C. In different corrosive and aging environments, the requirements for low-temperature performance were mostly relaxed by 5 to 10 °C. As the temperature drops, the brittleness of the asphalt material increases, and shrinkage can lead to cracks or fractures, so this property was often considered in cold areas and the requirements could be relaxed in hot and humid climates. In summary, in hot and humid climatic conditions, requirements can be relaxed to −15 °C without cracks and fractures; cold climatic conditions should meet −25 °C without cracks and fractures; corrosion and aging conditions can be relaxed by 5 °C.

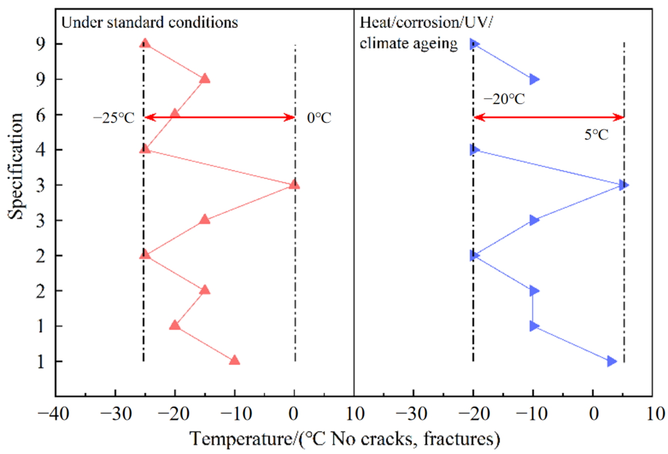

Figure 3. Comparison of relevant specifications for the low-temperature flexibility of waterproof bonding layer materials.

2.4. Waterproof Properties

A total of 10 specifications in China require waterproof properties for asphalt-based waterproof bonding layer materials, as shown in Figure 4.

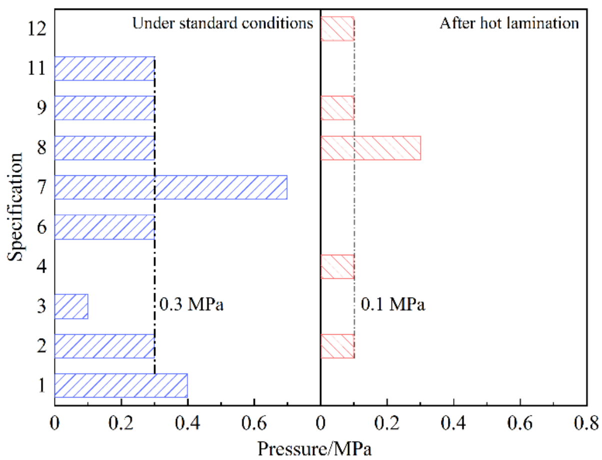

Figure 4. Comparison of relevant specifications for the waterproof properties of waterproof bonding layer materials.

In Figure 4, five specifications have the same waterproof performance requirements for asphalt materials, which is 0.3 MPa and that it is impermeable within 30 min. In other specifications, the same test conditions only require the film to maintain a high impermeable pressure; for example, the pressure in specification 1 and specification 7 is 0.4 and 0.7 MPa, respectively. This also shows that compared with the coating materials, such as emulsion asphalt, heat-modified asphalt, and solvent asphalt, the modified asphalt waterproof coiled material has higher requirements for water resistance and a better waterproofing effect. In addition, since the superstructure of the waterproof bonding layer is vulnerable to the impact of construction machinery or hot aggregate paving during the construction process, resulting in the asphalt film being punctured and damaged and affecting its performance, the five specifications have added hot rolling conditions to the waterproof performance test. Four of them require that the waterproof performance after hot rolling is 0.1 MPa, and that it is impermeable within 30 min. The highest requirement in specification 8 is 0.3 MPa, and that it is impermeable within 30 min. Considering that the resistance to construction damage of the waterproof bonding layer is extremely important, the waterproof performance requirements should generally meet the following technical conditions: 0.3 MPa after hot rolling, and 30 min impermeable.

2.5. Bonding Properties

Bonding performance is the most important road performance index of the waterproof bonding layer, which is generally characterized by adhesion pull-out, interlayer pull-out and interlayer shear. There are seven specifications in China that put forward requirements for the bonding performance of asphalt waterproof bonding layer materials, as shown in Figure 5.

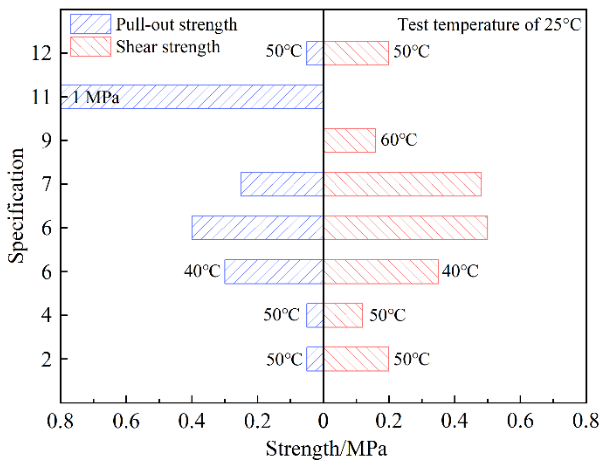

Figure 5. Comparison of relevant specifications for the bonding properties of waterproof bonding layers.

For the interlayer bonding properties of asphalt-based waterproof bonding materials, different specifications respectively limit the water emulsion asphalt, hot melt asphalt, modified asphalt roll, waterborne epoxy asphalt, SBS-modified asphalt seal, rubber-modified asphalt seal, solvent asphalt, and fiber reinforced rubber asphalt waterproof bonding layer. Analysis of Figure 5 shows that for the shear strength, specifications 6 and 7 require that waterborne epoxy asphalt, SBS-, and rubber-modified asphalt seals should be higher than 0.5 or 0.48 MPa at 25 °C. Specifications 2, 9, and 12 require high-temperature conditions (40–60 °C) for water emulsion asphalt and that the modified asphalt waterproof bonding layer should be higher than 0.16 or 0.2 MPa. Specification 4 for the modified asphalt membrane shear strength requirements requests minimum high-temperature conditions higher than 0.12 MPa. This is mainly due to the coil-type material on the concrete interface treatment requirements being high, and the coil material joints' fragile shear deformation resistance being poor, so its requirements are broader. For the pull strength, in addition to specification 11 in the solvent asphalt class of material requirements are relatively high, but the rest of the difference is not much, while specifications 6 and 7 require the waterproof bonding layer at 25 °C to have a pull strength higher than 0.25–0.4 MPa. Specifications 2, 4, and 11 require that the high temperature (50 °C) pull-out strength should be higher than 0.05 MPa.

In conclusion, when the modified asphalt is used as the waterproof bonding layer, pull strength should be higher than 0.3 MPa, and the shear strength should be higher than 0.05 MPa. When the emulsion asphalt is used as the waterproof bonding layer, the shear strength at 50 °C must be higher than 0.05 MPa. The bonding performance of waterborne epoxy asphalt, SBS-, and rubber-modified asphalt seal coat is excellent, so the requirements can be appropriately raised, that is, that the shear strength at 25 °C is not less than 0.5 MPa, and that the shear strength at high temperatures is not less than 0.35 MPa.

3. Investigation and Evaluation of the Working Properties of Asphalt-Based Waterproof Bonding Layer Materials

A comprehensive survey of China's roads and bridges with asphalt-based waterproof bonding layer material research dynamics and physical engineering application status, based on mathematical and statistical principles [18], was carried out. It summarized the application of asphalt-based waterproof bonding layer material technical indicators, clarified the level of performance of different asphalt-based waterproof bonding layer materials and their differences, and provided a reference for subsequent targeted in-depth research. For statistical purposes, data that were too fragmented were excluded from the statistics.

3.1. Basic Properties of Asphalt-Based Waterproof Bonding Layer Materials

According to the specifications, the basic properties of asphalt-based waterproof bonding materials mainly include pull-out strength, heat resistance, low temperature flexibility, water permeability resistance, and other properties. When applied to the surface of bridge concrete or steel plate, the amount of waterproof materials should be 0.7–1.0 kg/m^3 [19–32]. We have carried out investigation and statistics on the above properties of the waterproof bonding layer, as shown in Figure 6.

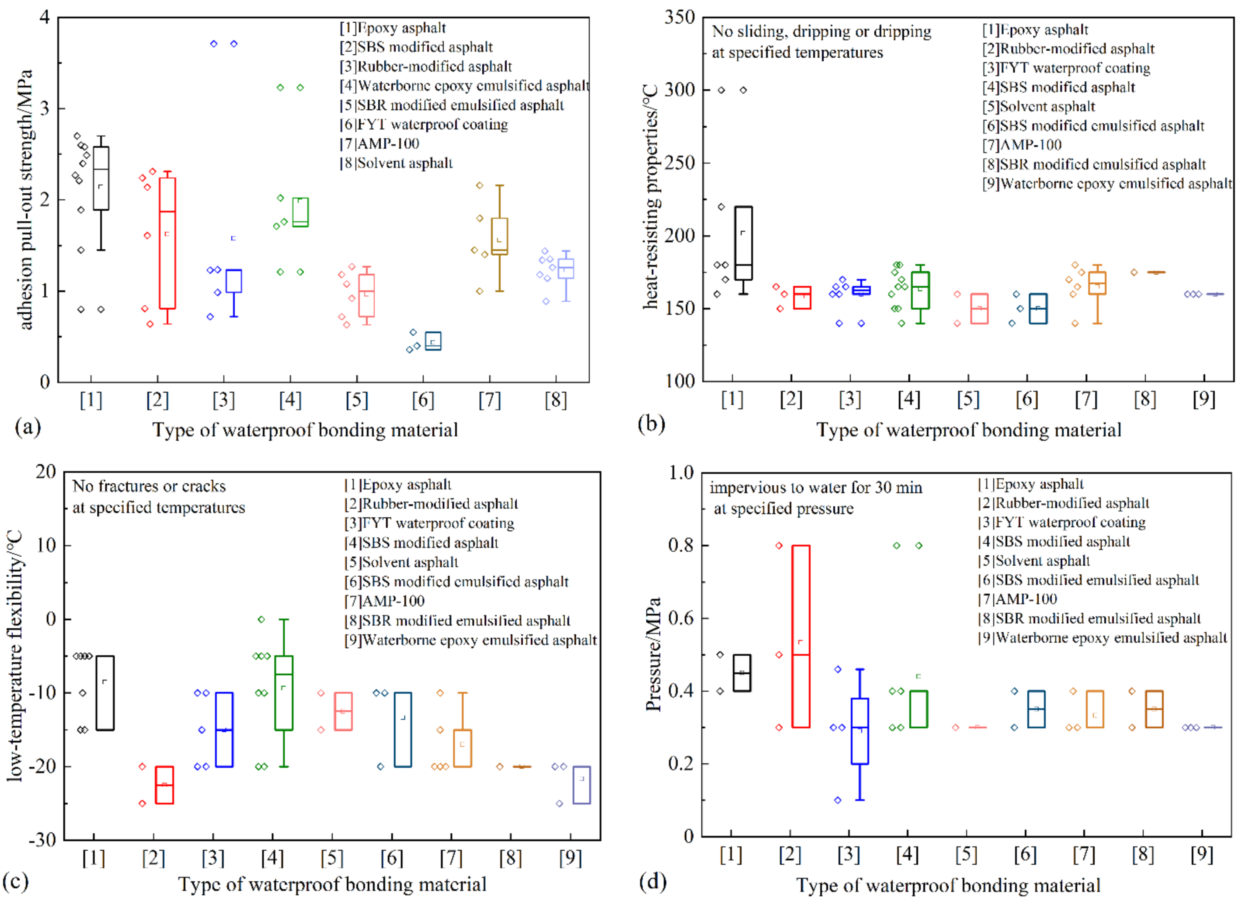

Figure 6. Basic properties of the asphalt waterproof bonding layer materials. (**a**) Mechanical properties, (**b**) heat-resistant properties, (**c**) low-temperature flexibility, and (**d**) waterproof properties.

In Figure 6a, the epoxy asphalt adhesion pull-out strength is the highest, with 75% of the epoxy asphalt data having a strength higher than 1.89 MPa, and mainly concentrated between 1.89~2.58 MPa. Waterborne epoxy emulsified asphalt adhesion pull-out strength has an average value of 1.99 MPa, the overall strength is slightly lower than the epoxy asphalt, and the data is mainly concentrated in the range of 1.71~2.02 MPa. Rubber-modified asphalt, SBS-modified asphalt, and AMP waterproof coating adhesion's pull-out strengths are relatively similar, in the range of 1.56~1.62 MPa. The SBR-modified emulsified asphalt and FYT waterproof coating's overall strength is low, the former having 50% of the data concentrated between 0.72~1.18 MPa, while the latter's values are mainly concentrated in 0.36~0.55 MPa. It can be seen that, in addition to waterborne epoxy emulsified asphalt, the mechanical properties of the remaining water-emulsified asphalt-like materials are low, which is mainly due to the small asphalt content as a result of the general emulsified asphalt-like materials' low viscosity, and the coating breaking because the emulsion curing film thickness is thin, which affects the adhesion with the concrete panel.

In Figure 6b, as a thermosetting material, epoxy asphalt has the best heat resistance, with its heat resistance mainly concentrated between 170 and 220 °C. The mean and median heat resistance of the remaining materials can meet the specification of 160 °C without flowing, sliding, or dripping. Analysis of Figure 6c shows that for low-temperature flexibility performance, the rubber asphalt temperature was mainly concentrated between −20 to −25 °C, which meets the requirements of specification 2 for no cracking and fracture at −15/−25 °C for hot melt type asphalt. A total of 50% of the data for SBS-modified asphalt was concentrated between −5 and −15 °C, which is lower than the specification requirement. The FYT waterproof coating and AMP-100 average value of −15 °C and −17 °C, respectively, can meet the needs of the specification 9 in the case of warm conditions. Waterborne epoxy emulsified asphalt and SBR-modified emulsified asphalt meet the requirements of specification 9 for waterborne asphalt materials under cold conditions. It shows that the waterborne epoxy emulsified asphalt and SBR-modified emulsified asphalt have excellent low-temperature performance among the water emulsion asphalt type materials. In addition, the low-temperature performance of epoxy bitumen is poor, with data mainly concentrated between −5 and −15 °C. In terms of impermeability, most materials meet the specification of 0.3 MPa pressure for 30 min without water penetration, but because the waterproofing bonding layer's resistance to construction damage is more important, it should be considered in conjunction with the study of the material's own resistance to water penetration. For the drying times, in the examples investigated, the surface and actual drying times were 3.5 h and 7.5 h for solvent asphalt, and 4 h and 8 h for both AMP-100 and waterborne epoxy emulsified asphalt, respectively.

To further ensure the long-term performance of the waterproofing binder material, the researchers also tested the corrosion resistance of the asphalt-based waterproof bonding material. Gao, Guo, Guo et al. studied the acid and alkali corrosion resistance of AMP-100, FYT, SBS-modified asphalt, and epoxy asphalt materials by immersing the materials in 2% H_2SO_4, 1% NaOH or 2% NaOH, and 20% NaCl solutions for 7~15 d. It was found that the four materials had good acid and alkali resistance [33–35]. Zhou immersed the epoxy asphalt specimens into 20% HCl, 20% NaOH, 20% NaCl, and 20% CH_3COONa solutions for 15 d, followed by tensile properties tests, respectively, and found that the epoxy asphalt specimens soaked in the solutions showed a small magnitude of mass change and a slight decrease in tensile strength and elongation at break [26].

3.2. Investigation and Evaluation of the Bonding Performance of Asphalt-Based Waterproof Bonding Layers

Due to poor shear resistance and complex construction processes, the coil-type waterproof bonding layer currently used in road engineering was relatively small. At the same time, temperature is the key factor affecting the performance of the waterproof bonding layer. Therefore, based on temperature, we have combed the research work of asphalt coating types and gravel sealed waterproof bonding layers for bridge deck pavements in China. The difference in adhesive properties of asphalt binder course materials is clarified.

3.2.1. Modified Asphalt Waterproof Bonding Layer Materials Bonding Properties

Bonding property statistics for epoxy asphalt at different temperatures can be seen in Figure 7. Bonding property statistics for SBS-modified asphalt can be seen in Figure 8. Rubber-modified asphalt bonding property statistics are shown in Figure 9. All data are from literature [5,9,10,13,22,26–50].

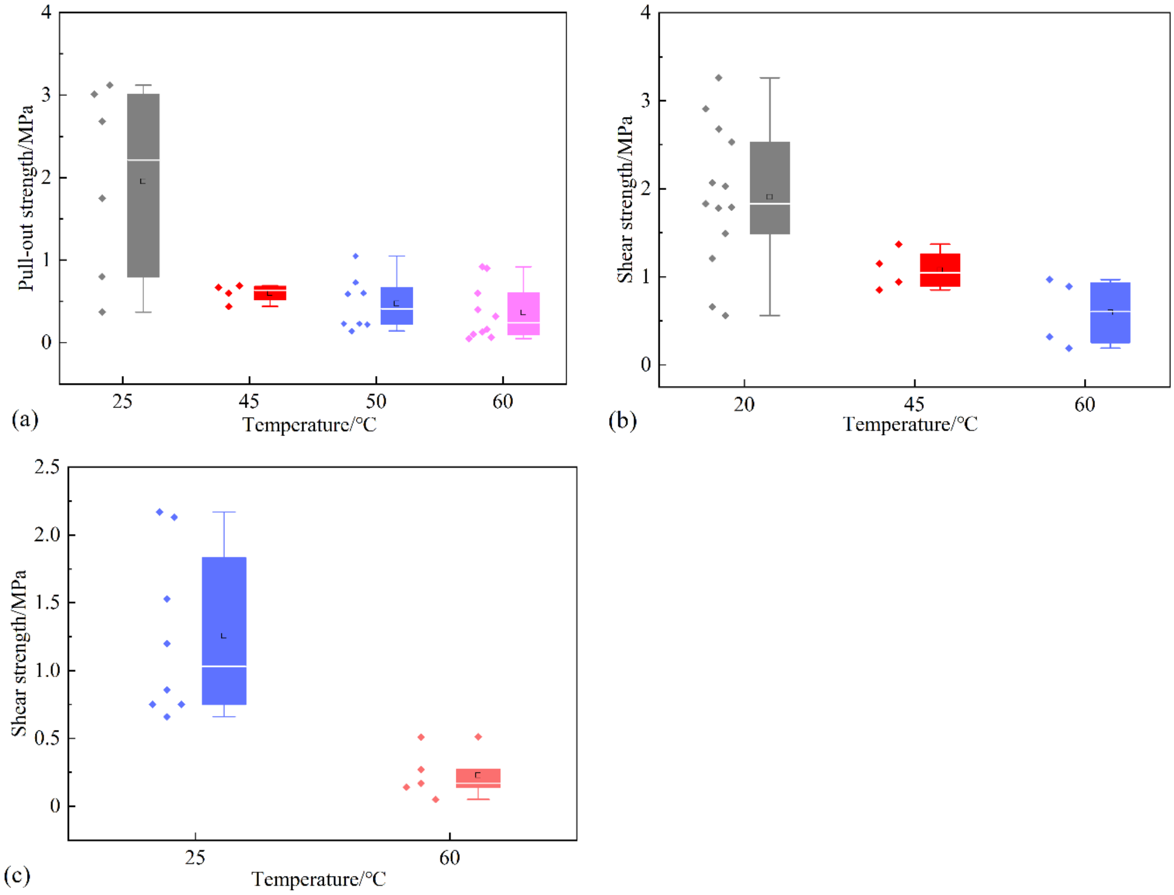

Figure 7. Bonding properties of the epoxy asphalt waterproof bonding layer materials. (**a**) Pull-out strength, (**b**) shear strength (direct shear), and (**c**) shear strength (40° oblique shear).

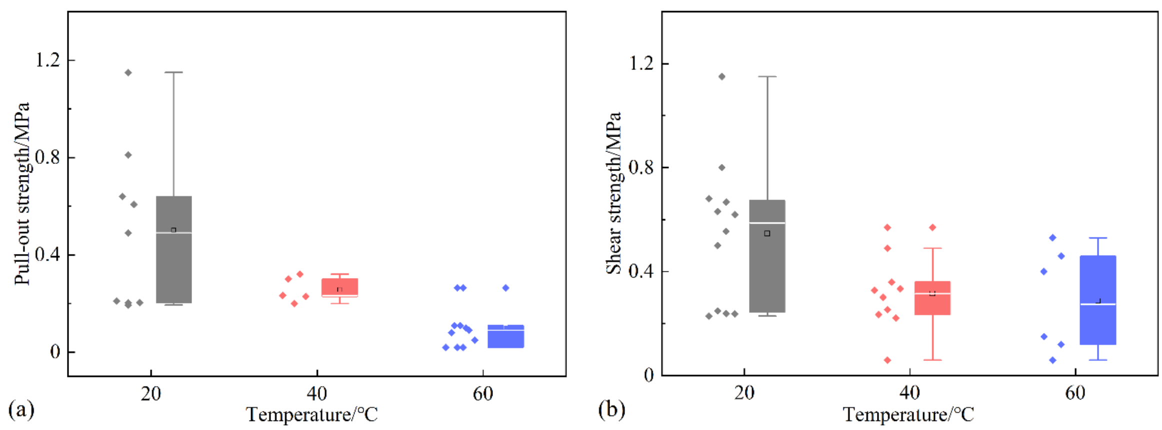

Figure 8. *Cont.*

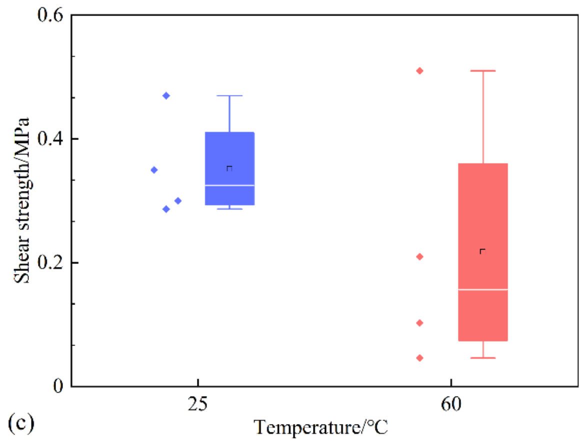

Figure 8. Bonding the properties of SBS-modified asphalt waterproof bonding layer materials. (**a**) Pull-out strength, (**b**) shear strength (direct shear), and (**c**) shear strength (45° oblique shear).

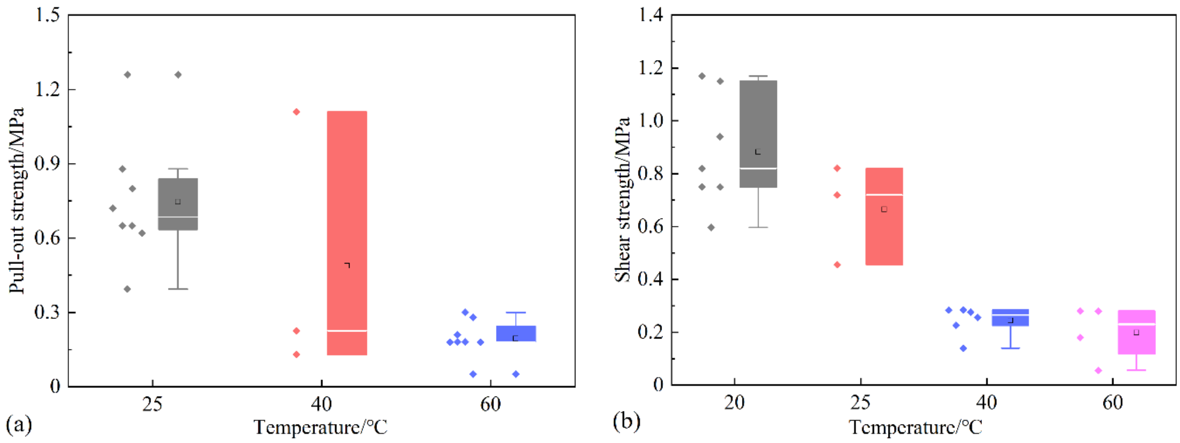

Figure 9. Bonding properties of the rubber-modified asphalt waterproof bonding layer materials. (**a**) Pull-out strength, and (**b**) shear strength (direct shear).

Epoxy asphalt is mainly applied to the coating of concrete bridge, making it a small part of the epoxy asphalt gravel waterproof bonding layer. In Figure 7, for the pull-out strength, which is highest at 25 °C, the mean value is approximately 1.96 MPa, meeting the specification of above 1.0 MPa. As the temperature rises, the overall trend of interlaminar drawing strength decreases, remaining at around 0.6 MPa at 45 °C, with an average value of only 0.36 MPa at 60 °C. For shear strength, the direct shear strength is mainly distributed between 1.49 and 2.53 MPa at 20 °C and remains at around 0.59 MPa at 60 °C. A total of 50% of the data for oblique shear strength at 25 °C are concentrated in the range of 0.75 to 1.83 MPa, while the average value at 60 °C is only 0.23 MPa. The pattern is basically the same as that for drawing strength, which decreases with increasing temperature. It can be seen that even though the asphalt and epoxy resin form a highly cross-linked mesh structure to improve strength and high temperature properties, as a temperature sensitive material, there is a certain degradation of mechanical properties when the temperature increases.

At present, the SBS-modified asphalt bonding material in the actual project is used with a single particle size of gravel together with the spread of a SBS-modified asphalt synchronous gravel waterproof bonding layer. Compared to coated materials, this structure not only has a good ability to coordinate deformation, but also effectively reduces construction costs and greatly improves the controllability of construction quality. In Figure 8, for the pull-out strength, the mean value is as high as 0.50 MPa at 20 °C. The pull-out strength decreases significantly with increasing temperature and only remains at 0.10 MPa at 60 °C.

As the median value is lower than the mean value, this indicates that the overall bonding performance is low at high temperatures. The shear strength is consistent with the above pattern, with the direct shear strength concentrated between 0.24–0.67 MPa at 20 °C, with a lower variation during the rise from 40 °C to 60 °C. The 45° oblique shear strength is mainly distributed between 0.29 and 0.41 MPa at 20 °C and concentrated between 0.07 and 0.36 MPa at 60 °C. In fact, when the asphalt surface paving uses a SBS-modified asphalt bonding material in the role of high temperature melting, the excess part is squeezed into the pores of the surface layer, and the surface layer shares the role of waterproofing, but the process is mainly physical bonding, and thermal stability is poor, as is the bonding layer of high-temperature adhesion performance in general.

Analysis of Figure 9 shows that the pull-out strength of the rubber-modified asphalt bonding material at 25 °C was mainly distributed in the range of 0.64–0.84 MPa, and as more concentrated in the range of 0.64~0.69 MPa. With the increase in temperature, pull-out strength decreases significantly, as the average value of strength at 60 °C is only 26.7% of that at 25 °C, which is about 0.20 MPa. The shear strength also decreases with increasing temperature, while the overall shear strength at 40 °C and 60 °C is relatively similar, with the former having a mean value of 0.24 MPa and the latter a mean value of 0.20 MPa. As the rubber particles become slightly loose and soft at high temperatures, the particles regain a certain degree of plasticity and adhesion, allowing them to maintain good adhesion at high temperatures.

3.2.2. Water Emulsion Type Asphalt Waterproof Bonding Layer Materials Bonding Properties

Statistics on the bonding properties of waterborne epoxy emulsified asphalt at different temperatures [10,32,51–57] were shown in Figure 10. Binding property statistics for SBS-modified emulsified asphalt [26,40,42,47,48,50] can be seen in Figure 11. The SBR-modified emulsified asphalt bonding property statistics [13,22,40,58,59] can be seen in Figure 12. The FYT bonding property statistics [13,24,25,34,60–62] can be seen in Figure 13. The AWP and AMP waterproofing adhesive material bonding property statistics [25,27,29,30,62,63] see Figure 14. In addition, some data are from literature [64–76].

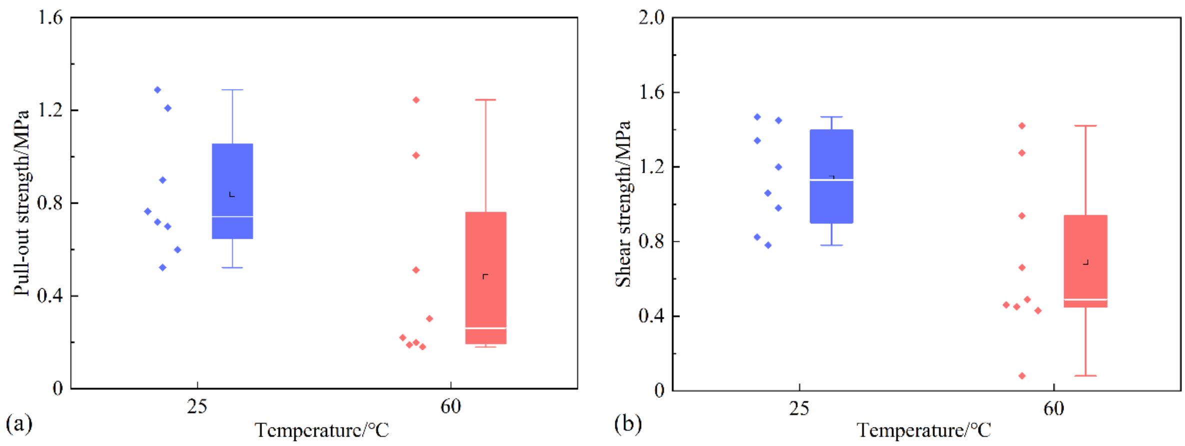

Figure 10. Bonding properties of the waterborne epoxy emulsified asphalt waterproof bonding layer materials. (**a**) Pull-out strength; (**b**) shear strength (direct shear).

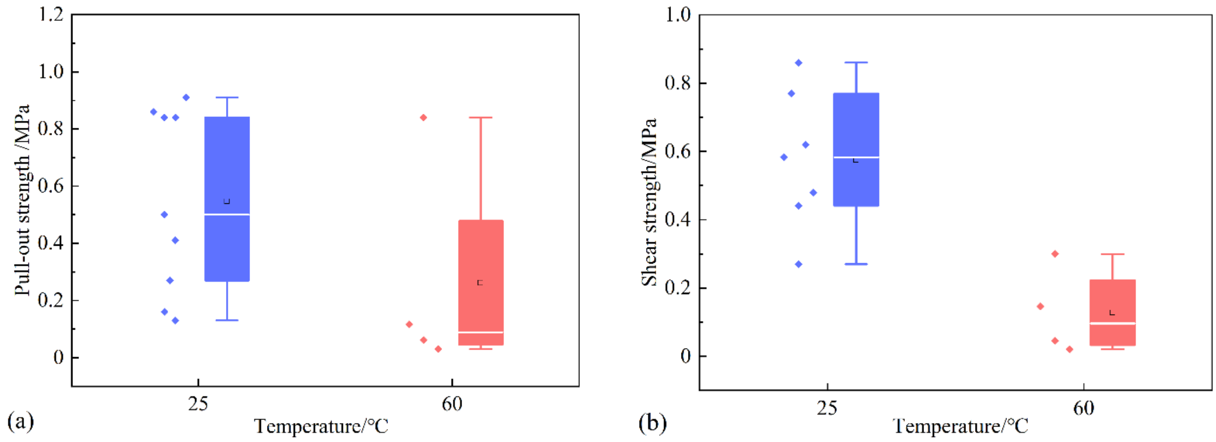

Figure 11. Bonding properties of the SBS-modified emulsified asphalt waterproof bonding layer materials. (**a**) Pull strength; (**b**) Shear strength (Direct shear).

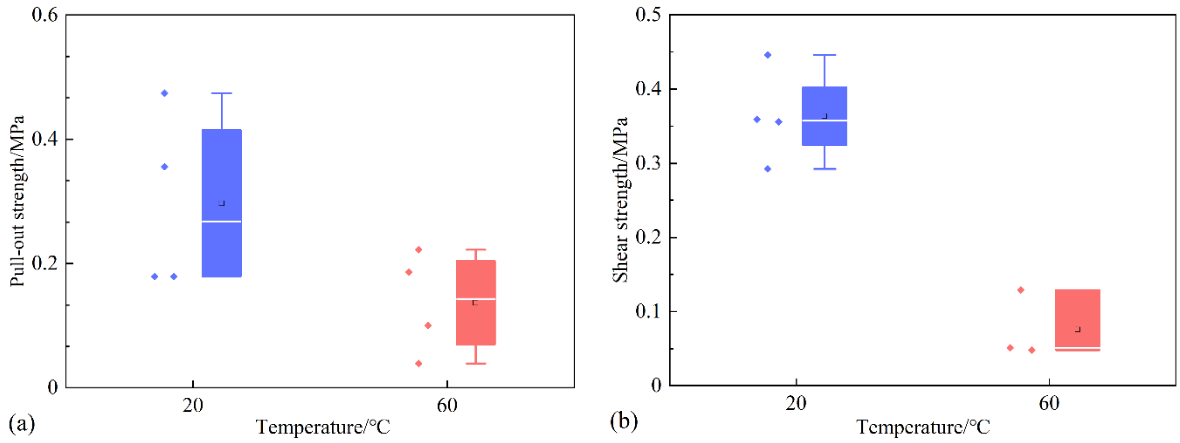

Figure 12. Bonding properties of the SBR-modified emulsified asphalt waterproof bonding layer materials. (**a**) Pull-out strength; (**b**) shear strength (direct shear).

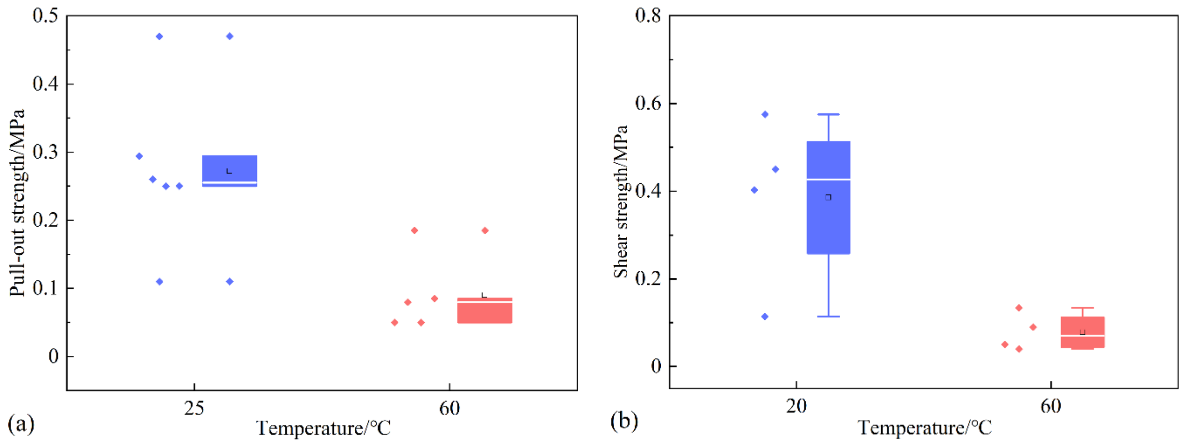

Figure 13. Bonding properties of the FYT waterproof bonding layer. (**a**) Pull-out strength; (**b**) shear strength (direct shear).

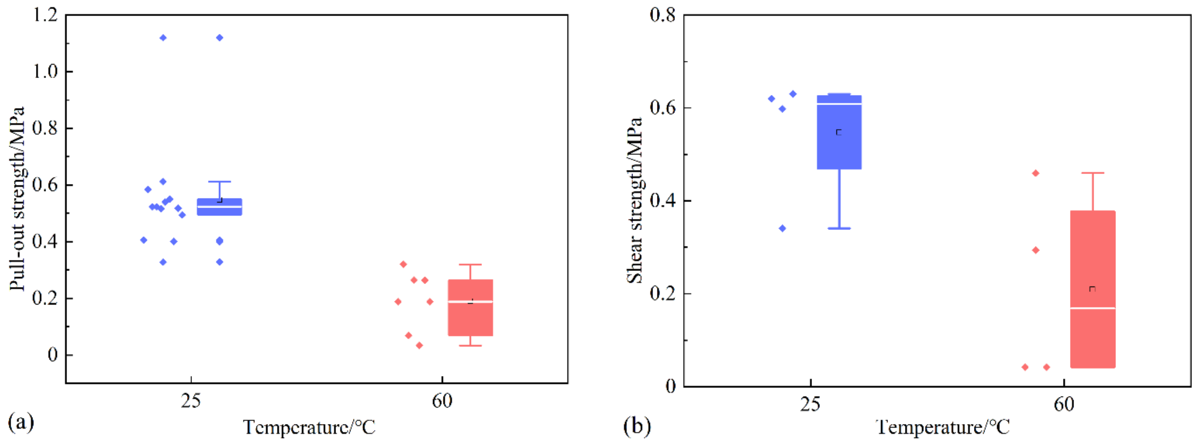

Figure 14. Bonding properties of the AWP and AMP waterproof bonding layer. (**a**) Pull strength; (**b**) shear strength (direct shear).

In Figure 10, for the pull-out strength, it was mainly concentrated between 0.65~1.05 MPa at 25 °C and maintained at 0.48 MPa at 60 °C. Among these values, a few data have higher pull-out strength at high temperature, which is mainly due to the higher admixture of epoxy resin; the epoxy resin can form more reticulation with asphalt to improve the strength, or the admixture of other viscosity increasing modified materials can also play a role. For shear strength, the mean value of direct shear strength at 25 °C is approximately 1.14 MPa, compared to 0.69 MPa at 60 °C. The data was more concentrated in the range of 0.45 to 0.49 MPa, but there are still some materials with good high temperature properties.

Analysis of Figure 11 shows that the pull-out strength of the SBS-modified emulsified asphalt bonding material at 25 °C was mainly concentrated in the range of 0.27–0.84 MPa, with a high degree of data dispersion (not concentrated). At 60 °C, it mainly remains at 0.26 MPa, but its median is only 0.09 MPa, which shows a high degree of overall attenuation of its pull-out strength at high temperatures. At 25 °C, the shear strength was mainly distributed between 0.44 and 0.77 MPa, and at 60 °C there is also a significant reduction, with the shear strength remaining at only 0.13 MPa.

Analysis of Figure 12 shows that, at 20 °C, the SBR-modified emulsified asphalt waterproof bonding layer's pull-out strength was mainly distributed between 0.18~0.41 MPa, and the data was more scattered. At 60 °C, when the strength dropped significantly, the data were mainly distributed between 0.07~0.20 MPa. A shear strength at 20 °C was mainly maintained at 0.36 MPa. At 60 °C when the strength is low, its average value is only 0.08 MPa, compared with at 20 °C. The mean value of strength decreased by about 77.8% compared with 20 °C. It can be seen that although SBR can improve the viscosity and toughness of asphalt, its high temperature stability is poor and it is difficult to apply in high temperature areas.

Analysis of Figure 13 shows that, at 25 °C, the FYT waterproof coating's pull-out strength was mainly concentrated between 0.25~0.29 MPa. At 60 °C, when the pull-out strength was mainly distributed in 0.05~0.09 MPa, the strength is relatively low. Shear strength versus the temperature is decreasing trend, sd its strength at 25 °C is 0.39 MPa but, at 60 °C, it reduced to 0.08 MPa. Thus, it can be seen that the high temperature performance of general water emulsion asphalt materials is poor.

The AWP and AMP waterproof coating was mainly based on asphalt, with rubber, resin, and other polymer materials used in the prepared water-based waterproof coating. It uses a polymer emulsion as the main film-forming substances, which include the main types of AWP-2000, AWP-2000F fiber-reinforced waterproofing materials and AMP-100, etc. Among them, AMP-100 has a unique first- and second-order reaction process, and construction can facilitate a certain degree of repair to concrete bridge deck micro-cracks. After curing, they can form a highly elastic plastic coating film. In addition, the material and asphalt surface compatibility is good, the bonding ability, and waterproofing effect are relatively strong, and the AWP-2000 type in the coating after curing can have a certain degree of elasticity, allowing it to play a stress absorption role. In Figure 14, the pull-out strength is mainly maintained at 0.55 MPa at 25 °C and decreases to 0.19 Mpa at 60 °C; the shear strength is consistent with the overall pattern of pull-out strength, with the average value decreasing from 0.55 Mpa at 25 °C to 0.21 Mpa at 60 °C.

In addition to the above commonly used types, researchers have also conducted studies on other types of modified emulsified asphalt, such as CR and EVA and modified emulsified asphalt thin slurry sealers, etc. Therefore, statistical summaries of the bonding performance of other types of modified emulsified asphalt waterproofing binder materials other than those mentioned above [14,27,40,55,60,64–66] are shown in Figure 15.

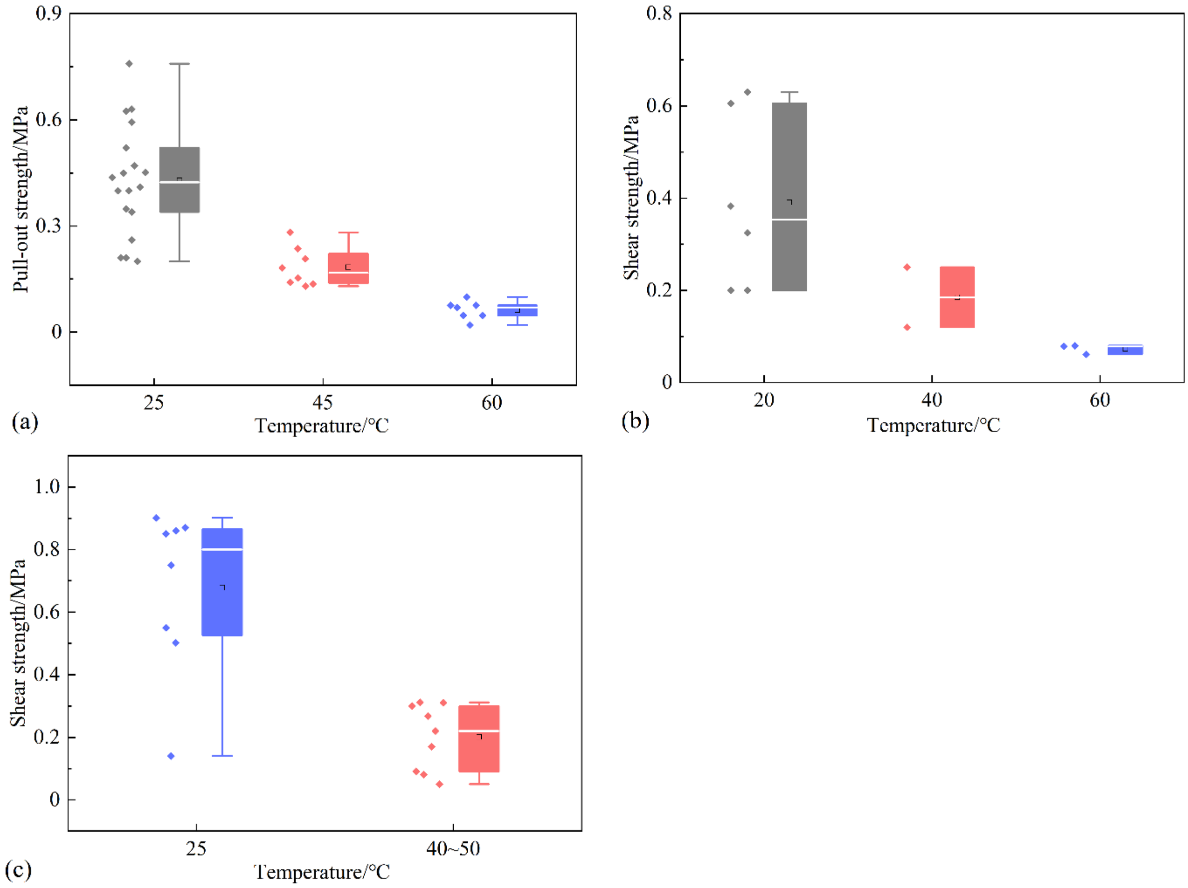

Figure 15. Bonding properties of other types of modified emulsified asphalt waterproof bonding layer materials. (**a**) Pull strength; (**b**) shear strength (direct shear); (**c**) shear strength (40° oblique shear).

Analysis of Figure 15 shows that for the drawing strength, the most data were collected at 25 °C and were mainly distributed in the range of 0.34~0.52 MPa, with the temperature increasing against the overall decreasing trend of strength. The average value was about 0.18 MPa at 45 °C and was only maintained at 0.06 MPa at 60 °C; the pattern of interlayer shear strength and drawing strength is basically the same, as the most data were collected at 20 °C for the direct shear strength, but its dispersion was high. The degree of the shear angle was higher with the temperature of 60 °C, as it was only 0.07 MPa; at the shear angle of 40 °, the average value of shear strength from 25 °C at 0.68 MPa decreased to 40~50 °C at 0.20 MPa. Overall, the modified emulsified asphalt waterproofing binder layer offers a low performance at high temperatures.

3.2.3. Solvent Asphalt Waterproof Bonding Layer Materials Bonding Properties

Solvent asphalt was generally not used alone as a waterproof bonding layer, but with epoxy resin and rubber asphalt sand adhesive together to form a waterproof bonding system. Its bonding performance statistics [23,27,28,31,67–69,75,76] can be seen in Figure 16.

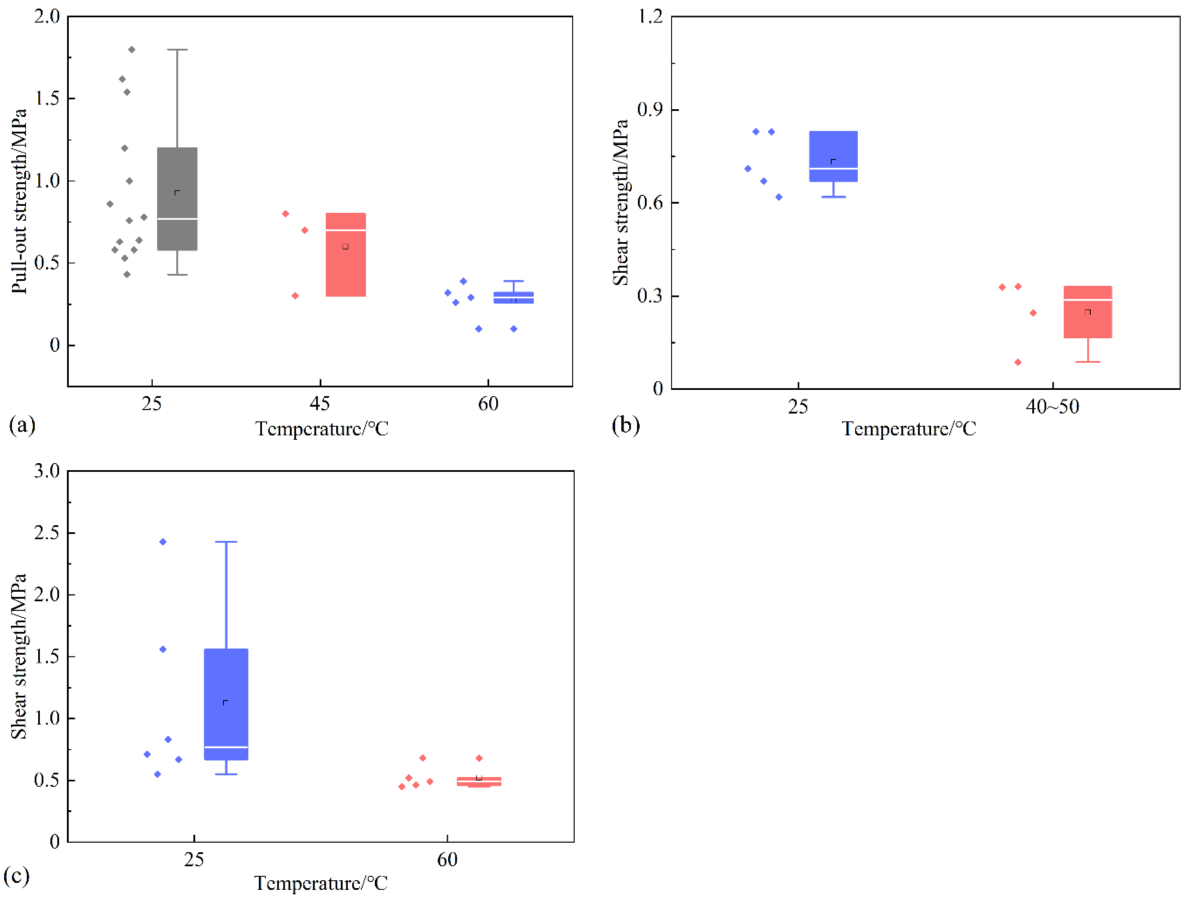

Figure 16. The bonding properties of solvent asphalt waterproof bonding layer materials (**a**) Pull strength; (**b**) shear strength (direct shear); (**c**) shear strength (40° oblique shear).

Analysis of Figure 16 shows that the most data were collected at 25 °C, and the pull-out strength was mainly distributed in the range of 0.58~1.20 MPa, with a high degree of data dispersion, and a few parts were higher than 1.5 MPa, which was mainly due to the improvement of interlayer bonding performance by setting epoxy resin as the underseal layer. The pull-out strength showed a decreasing trend as the temperature rose, maintaining at 0.6 MPa at 45 °C, and mainly concentrated between 0.26~0.32 MPa at 60 °C. Shear strength also decreased with the rise in temperature, as direct shear strength at 25 °C is mainly concentrated between 0.67~0.83 MPa, while at 40~50 °C it is at 0.25 MPa. With a shear angle of 40 °, the shear strength changes from 1.13 MPa at 25 °C to 0.52 MPa at 60 °C. In addition, by including the rubber asphalt sand rubber, it can also play a role in protecting the waterproof bonding layer and absorbing stress.

3.3. Comparison of Bonding Properties of Different Asphalt-Based Waterproof Bonding Layers

According to the data from Figures 7–16, a comparative analysis of different types of waterproof bonding layer bonding performance indicators can be determined. Specific indicators include 25 °C and 60 °C pull-out strength, and shear strength (direct shear), as can be seen in Figures 17 and 18.

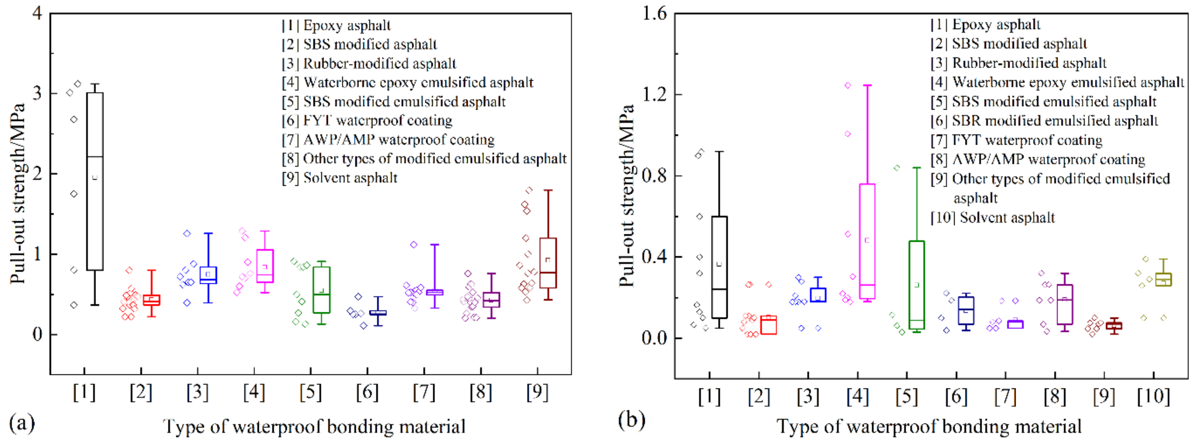

Figure 17. Comparison of pull strength of different asphalt waterproof bond layers. (**a**) Pull-out strength (25 °C); (**b**) pull-out strength (60 °C).

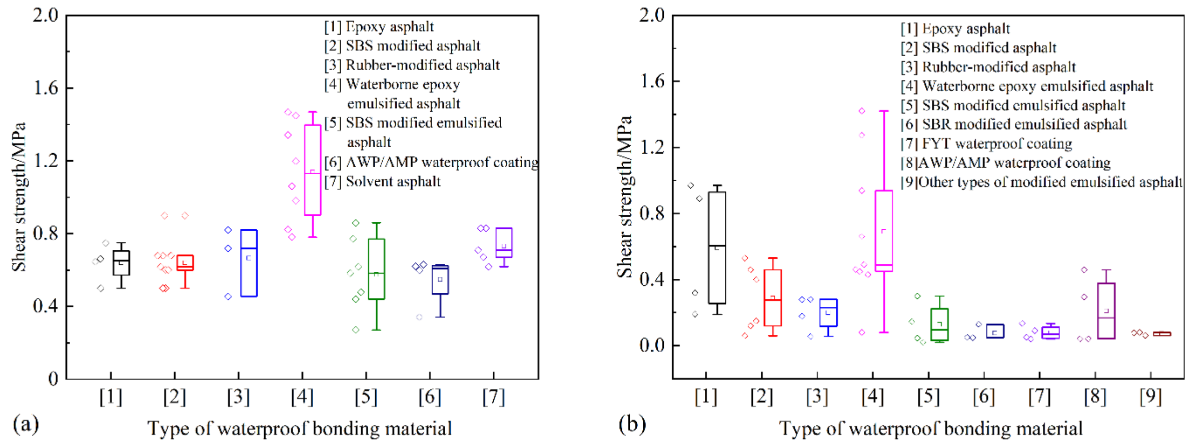

Figure 18. Comparison of shear strength of different asphalt waterproof bond layers. (**a**) Shear strength (direct shear 25 °C); (**b**) shear strength (direct shear 60 °C).

Analysis of Figure 17a shows that the epoxy asphalt mean and median are highest, followed by the solvent asphalt waterproofing system, then the waterborne epoxy emulsified asphalt, indicating that the epoxy resin and solvent-based asphalt constitute a composite structure which can greatly enhance the adhesion and flexibility of the material. Rubber-modified asphalt synchronous gravel waterproofing bonding layer has a high interlayer pull-out strength, and is overall higher than SBS-modified asphalt, mainly due to the fact that the overall amount of SBS-modified asphalt is less, and the gravel spreading bonding material coating is not uniform, resulting in more voids which affect the bond strength. In addition, it can be seen that of the water emulsion asphalt materials, except in the analysis of Figure 17a, epoxy asphalt has the highest mean and median, followed by the solvent asphalt waterproofing system, then the waterborne epoxy emulsified asphalt, indicating that the epoxy resin and solvent asphalt constitute a composite structure, which can greatly enhance the adhesion and flexibility of the material. Rubber-modified asphalt synchronous gravel waterproof bonding layer has a high interlayer pull-out strength, and is overall higher than SBS-modified asphalt, mainly due to the fact that the overall amount of SBS-modified asphalt is less, and the gravel spreading bonding material coating is not uniform, resulting in more voids which affect the bond strength. In addition, for water emulsion asphalt materials, except waterborne epoxy emulsified asphalt, the overall pull-out strength is low. This includes FYT and other types of modified emulsified asphalt bonding, meaning that the performance is poor. This is mainly because the general water emulsion asphalt materials contain about 40% water, so that the formation of the thin asphalt film after curing affects the bonding performance. Analysis of Figure 17b shows that as asphalt is by nature a highly temperature sensitive viscoelastic material, the properties will decay to a certain extent at high temperatures, resulting in a higher decay in pull-out strength at 60 °C compared to 25 °C for different asphalt materials. The average pull-out strength of waterborne epoxy emulsified asphalt is the highest, at 0.48 MPa, followed by epoxy asphalt, solvent asphalt, and SBS-modified emulsified asphalt, at 0.37 MPa, 0.27 MPa, and 0.26 MPa, respectively, while the pull-out strength of rubber-modified asphalt binder materials is mainly concentrated between 0.18~0.25 MPa, lower than the above four categories. The other water emulsion asphalt, AWP and AMP, have a relatively high waterproof coating performance, as its pull-out strength is maintained at 0.19 MPa, while FYT and other types of modified emulsified asphalt can only be maintained at 0.10 MPa, 0.09 MPa and 0.06 MPa.

From Figure 18a it can be seen, the overall shear strength from high to low for waterborne epoxy emulsified asphalt, solvent asphalt, epoxy asphalt, rubber-modified asphalt, SBS-modified asphalt, SBS-modified emulsified asphalt and AWP and AMP are relatively similar, except for waterborne epoxy emulsified asphalt and solvent asphalt. Analysis of Figure 18b shows that waterborne epoxy emulsified asphalt and epoxy asphalt has the best high temperature shear strength, followed by SBS-modified asphalt and rubber-modified asphalt, meaning that a synchronous gravel waterproofing bonding layer at high temperatures offers good coordination for shear deformation resistance. The remaining materials in the AWP and AMP waterproof coating offer relatively good high temperature performance, but its cost is higher.

The epoxy asphalt, waterborne epoxy emulsified asphalt, and solvent asphalt waterproof bonding system have the best interlayer bonding performance, because the epoxy resin has good mechanical properties, so that the three-dimensional interpenetrating mesh structure formed with the asphalt, which fundamentally changed the ordinary asphalt thermoplastic, greatly enhancing the high temperature stability of the material [77]. In addition, waterborne epoxy emulsified asphalt can be used for cement concrete bridge decks to repair micro-cracks during the construction period due to its good fluidity and permeability. The SBS-modified asphalt and rubber-modified asphalt synchronous gravel waterproof bonding layer with the advatanges of convenient construction, quality control, low cost and good interlayer shear resistance and other advantages were widely paid attention to by researchers. However, compared with the coating class materials, its high internal void ratio leads to low bonding performance and its waterproofing performance is average [78]. The reason for this is that it is difficult to form an effective embedding structure after spreading single-grain gravel, which makes it easy for the gravel to be incompletely coated during construction, resulting in a high porosity and susceptibility to water infiltration and ponding. The water emulsified asphalt, when used as a coating material, has average interlayer bonding properties. The subsequent study can be improved by mixing the appropriate grade of coarse and fine aggregates to improve the interlayer shear resistance. In addition, as the emulsified asphalt has an electrical charge on its surface, the asphalt particles can be closely adsorbed to the aggregate surface, which not only reduces the void ratio but also increases the adhesion to the aggregate, giving it a good waterproofing effect.

3.4. Construction Process of Asphalt-Based Waterproof Bonding Layer Materials

The construction process of waterproof bonding materials is one of the important factors affecting the quality of the project. At present, there are many different types of adhesive materials and different bonding principles and applicable conditions, resulting in different types of waterproof bonding layer construction process differences. According to existing research results [79–85], the construction process of the waterproof bonding layer can be distinguished by coil, coating, and a gravel sealing layer. The thickness of the coiled material is high, and the construction is mostly carried out by manual on-site baking. After the asphalt is melted and rolled, it is bonded to the concrete panel. The coating materials are constructed through an asphalt distributor, an intelligent distributor, mechanical spraying, and manual scraping. Among these, SBS-modified asphalt, SBR-modified emulsified asphalt, and other materials are sprayed on-site by asphalt distributors. The temperature, speed, and dosage of asphalt spraying should be kept stable and artificial spraying should be carried out in time. Epoxy asphalt and waterborne epoxy emulsified asphalt are generally spread by intelligent spreaders to ensure uniform, continuous, and accurate dosage. To ensure uniformity, continuity, and accurate dosage, the binder materials, such as AMP-100, AWP-2000, and solvent-type asphalt are applied by mechanical spraying or manual scraping, etc. To avoid holes in the drying process of the binder materials, the construction is generally applied in two layers. Synchronous gravel sealer is mostly constructed by a synchronous gravel sealer truck, which should be driven smoothly and evenly and that ensure the temperature of asphalt sprinkling is between 160~180 °C. After the synchronous gravel sealer is sprinkled, it is rolled by rubber roller in time.

It is worth noting that there is a significant difference between the construction interval time of different asphalt binder materials. The upper surface layer construction can be carried out after the completion of the bonding, and the interval time is almost zero. The construction interval of heat-modified asphalt bonding materials and a synchronous crushed stone seal is relatively short. The SBS- and SBR-modified emulsified asphalt and other water emulsion materials should be carried out on the upper surface layer after the demulsification of emulsified asphalt and the complete evaporation of water, and the interval time is about 8~4 h. The drying time of epoxy and waterborne epoxy emulsified asphalt binder should be controlled between 3~5 h. The interval between the first and second coating construction of AMP-100 is 2~8 h, and the asphalt surface layer construction is carried out after the complete drying. The solvent-based asphalt is the second layer coating after the first layer is dry. In addition, the coil has higher requirements on the flatness of the bridge deck, which needs to be baked while rolling; synchronous crushed stone seals are prone to incomplete gravel coating during construction. The coating rate can be improved by spraying asphalt twice before and after gravel spreading.

4. Conclusions and Prospects

(1) For the asphalt waterproof bonding layer, the epoxy asphalt waterproof adhesive material interlayer bonding has the best performance. The waterborne epoxy emulsified asphalt has good high-temperature performance and excellent fluidity and permeability. The SBS and rubber-modified asphalt synchronous crushed stone seal has the advantages of convenient construction, controllable quality, low cost, and good high-temperature coordination shear resistance.

(2) Key performance indicators of asphalt-based waterproof bonding layers material include heat resistance, low-temperature flexibility, impermeability, and bonding.

(3) Epoxy asphalt, solvent asphalt, and waterborne epoxy emulsified asphalt bonding performances are high, with the average value of pull-out strength of 1.96, 0.92, 0.84 MPa, respectively. Epoxy asphalt, waterborne epoxy emulsified asphalt, and solvent-based asphalt waterproof bonding systems have the best high-temperature performance, followed by SBS-modified asphalt and a rubber-modified asphalt synchronous crushed stone waterproof bonding layer.

In the future, more in-depth research and exploration should be carried out in the following aspects: (1) Scientific and reasonable index evaluation systems and advanced test methods for the bridge waterproof adhesive layer should be further put forward; (2) Based on the existing engineering experience and research results, the performance evaluation system of the waterproof adhesive layer suitable for different regions and different material types should be established.

Author Contributions: Conceptualization, F.G., Q.C. and C.W.; methodology, Z.G.; validation, X.G.; formal analysis, F.G.; investigation, X.G.; resources, C.W.; data curation, Y.L.; writing—original draft preparation, F.G.; writing—review and editing, Q.C. and C.W.; supervision, X.G.; project administration, C.W. and Q.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by the Innovation Capability Support Program of Shaanxi (2022TD-07).

Data Availability Statement: All data, models, and code generated or used during the study appear in the published article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fu, H.; Wang, C.; Niu, L.; Yang, G.; Liu, L. Composition optimisation and performance evaluation of waterborne epoxy resin emulsified asphalt tack coat binder for pavement. *Int. J. Pavement Eng.* **2021**, *2021*, 1932878. [CrossRef]
2. Liu, L.Q.; Wang, C.H.; Liang, Q. Preparation of a heat insulation bonding layer for roads and its heat insulation effect. *J. Clean. Prod.* **2022**, *365*, 132828. [CrossRef]
3. Chen, Q.; Wang, C.; Hu, X.; Guo, C.; Liu, F. Preparation and property optimization of road basic energy-absorbing materials based on balanced control. *Acta Mater. Compos. Sin.* **2022**, *39*, 3356–3368.
4. Haynes, M.A.; Coleri, E.; Sreedlhar, S. Impermeable Asphalt Concrete Layer to Protect and Seal Concrete Bridge Decks. *Transp. Res. Rec.* **2019**, *2673*, 355–367. [CrossRef]
5. Kang, H.; Oh, K.; Ahn, K.; Jiang, B.; He, X.; Oh, S. Property Analysis of Double-Sided Composite Waterproofing Sheet for Simultaneous Application on Asphalt Concrete and Latex-Modified Concrete Pavements for Bridge Decks. *Appl. Sci.* **2022**, *12*, 9779. [CrossRef]
6. Mazzotta, F.; Lantieri, C.; Vignali, V.; Simone, A.; Dondi, G.; Sangiorgi, C. Performance evaluation of recycled rubber waterproofing bituminous membranes for concrete bridge decks and other surfaces. *Constr. Build. Mater.* **2017**, *136*, 524–532. [CrossRef]
7. Oh, K.H.; Kim, S.Y.; Park, Y.G. Joint- or Crack-Opening Resistance Evaluation of Waterproofing Material and System for Structural Sustainability in Railroad Bridge Deck. *Materials* **2020**, *13*, 4229. [CrossRef]
8. Zhang, F.; Li, M.Q.; Wang, T.Y.; Feng, D.C. Performance of composite waterproof cohesive layer on cement concrete bridge. *J. Harbin Inst. Technol.* **2020**, *52*, 26–32.
9. Wan, C.G.; Shen, A.Q.; Zhao, X.Y. Xun, C. Grey target optimization of waterproof adhesive materials for bridge deck pavement with comprehensive. *J. Build. Mater.* **2017**, *20*, 406–410.
10. Hailesilassie, B.W.; Hean, S.; Partl, M.N. Testing of blister propagation and peeling of orthotropic bituminous waterproofing membranes. *Mater. Struct.* **2015**, *48*, 1095–1108. [CrossRef]
11. Chen, Q.; Wang, C.H.; Fu, H.; Yang, G.; Sun, Z. Optimization of construction method of waterborne epoxy asphalt cape seal based on performance evolution. *China J. Highw. Transp.* **2021**, *34*, 236–245.
12. Zhang, H.; Gao, P.; Zhang, Z.; Pan, Y. Experimental study of the performance of a stress-absorbing waterproof layer for use in asphalt pavements on bridge decks. *Constr. Build. Mater.* **2020**, *254*, 119290. [CrossRef]
13. Liu, M.M.; Han, S.; Yang, H.; Wu, X. The applicability of different waterproof adhesive interlayer for bridge deck pavement. *J. Shenzhen Univ. (Sci. Eng.)* **2020**, *37*, 103–110. [CrossRef]
14. Editorial Department of China Journal of Highway and Transport. Review on China's bridge engineering research: 2014. *China J. Highw. Transp.* **2014**, *27*, 1–96.
15. Huang, X.M. Research status summary of asphalt pavement technology on cement concrete bridge deck. *J. Traffic Transp. Eng.* **2014**, *14*, 1–10.
16. Chen, Q.; Wang, C.H.; Yu, S.X.; Song, Z.; Fu, H.; An, T. Low-temperature mechanical properties of polyurethane-modified waterborne epoxy resin for pavement coating. *Int. J. Pavement Eng.* **2022**, 1–13. [CrossRef]
17. Wang, C.H.; Shu, C.; Han, B.; Fu, Y.; Zhou, L. Research progress of high modulus asphalt concrete. *J. Chang. Univ. (Nat. Sci. Ed.)* **2020**, *40*, 1–15.
18. *DB32/T 2285-2012*; Waterborne Epoxy-Binder Waterproof Coating for Concrete Bridges. Jiangsu Provincial Bureau of Quality and Technical Supervision: Nanjing China, 2012.
19. *JC/T 408-2005*; Emulsified Asphalt Waterproof Coating. China Chemical Building Materials Co., Ltd.; Suzhou Waterproof Material Research and Design Institute; National Development and Reform Commission of the People's Republic of China: Beijing, China, 2005.
20. Chen, Z.Y. Study on the Waterproof Binding Layer of Long Span Orthogonal Intersection Steel Bridge Deck. Master's Thesis, Chang'an University, Xi'an, China, 2008.
21. Liu, Z.Y. Research on Concrete Bridge Deck Waterproofing in Cold Regions. Master's Thesis, Chang'an University, Xi'an, China, 2008.
22. Zhang, J. Study on the Waterproofing and Bonding Layer of Concrete Bridge Deck. Master's Thesis, Chang'an University, Xi'an, China, 2008.
23. Zhou, J.W. Experimental Study on Waterproof Binding Course of Concrete Bridge Deck. Master's Thesis, Nanjing Forestry University, Nanjing, China, 2009.

24. Cai, Y.X. Study on Composite Bridge Deck Waterproof Adhesive Layer for Humid and Rainy Area. Master's Thesis, Chang'an University, Xi'an, China, 2011.
25. Zhou, B. Epoxy-Based Waterproof and Adhesive Materials Development for Concrete Bridge Deck. Master's Thesis, Chang'an University, Xi'an, China, 2012.
26. Yang, Y. Waterproofing Adhesive Material of Expressway Concrete Bridge Deck and Performance Study in East of Gansu Province. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2012.
27. Zhang, D.L. Deck Assessment and Application of Waterproof and Adhesive Layer Material Properties. Master's Thesis, South China University of Technology, Guangzhou, China, 2016.
28. Guo, J.B. Cement Concrete Bridge Deck Waterproofing Adhesive Layer Performance Research and Application. Master's Thesis, South China University of Technology, Guangzhou, China, 2014.
29. Shi, C.G. Research on Performance of Bridge Deck Material Structure Combination and Waterproof Adhesive Layer. Master's Thesis, Jilin University, Jilin, China, 2015.
30. Huang, X.X. The Applied Research of Waterproof Bonding Layer of Asphalt Rubber in the Highway of Tanluo to Baise in Guangxi. Master's Thesis, Guangxi University, Xining, China, 2012.
31. Li, A.F. Research on the Application of New Water-Based Epoxy Waterproof Adhesive Layer in Cement Concrete Bridge Deck Pavement in Guizhou Mountain Area. Master's Thesis, Southeast University, Nanjing, China, 2016.
32. Gao, X.C.; Huang, X.M.; Wang, S.G. Research on waterproof and cohesive layer for long-span prestressed concrete bridge desk. *J. Highw. Transp. Res. Dev.* **2005**, *8*, 70–73.
33. Guo, Z.; Zhou, Z.G.; Deng, C.Q.; Yu, W.; Luo, G. Performance analysis of waterproof bonding layer of asphalt pavement on different cement concrete bridge deck. *Highway* **2018**, *63*, 87–93.
34. Guo, P. Research on Water-Proof Layer in Concrete Bridge Deck. Master's Thesis, Chang'an University, Xi'an, China, 2012.
35. Zhang, Z.Q.; Lei, Z.J.; Yang, B. Study on the performance of waterproof bonding layer of glass fiber asphalt bridge deck. *Highway* **2011**, *9*, 34–37.
36. Wang, J.; Zhou, B.; Chen, S.F.; Wang, J.; Lei, Y. Study on road performance of domestic epoxy asphalt bridge deck waterproof bonding material. *Highway* **2012**, *7*, 35–38.
37. Su, R.R.; Song, Z.J.; Song, X.D. Experimental research on waterproof binding course of epoxy asphalt deck. *Road Mach. Constr. Mech.* **2015**, *32*, 84–86+91.
38. Zhang, Z.Q.; Tao, J.; Zhang, S.T. Experiment and evaluation on performance of epoxy asphalt waterproof cohesive layer on bridge deck pavement. *J. Chang. Univ. (Nat. Sci. Ed.)* **2011**, *31*, 1–6.
39. Ma, Y.Q.; Liang, Z.L. Study on the selection and properties of bonding waterproof layer materials for bridge deck pavement. *Highway* **2007**, *6*, 101–103.
40. Zhang, J. Shear Performance of Waterproofing and Bonding Layer for Concrete Bridge Deck. *J. Highw. Transp. Res. Dev.* **2011**, *28*, 29–34.
41. Yu, X.; Li, Y.T.; Liu, Y. Grey Target Optimization of Waterproof Adhesive Material for Concrete Bridge Deck Pavement Based on Mechanical Analysis. *J. Southwest Jiaotong Univ.* **2012**, *47*, 1086–1091.
42. Wan, C.G.; Shen, A.Q.; Fan, L. Composite behavier of waterproof binding course on cement concrete bridge deck. *J. Hefei Univ. Technol. (Nat. Sci.)* **2016**, *39*, 960–964.
43. Hou, D.H.; Han, M.Z.; Muhammad, Y.; Liu, Y.; Zhang, F.; Yin, Y.; Duan, S.; Li, L. Performance evaluation of modified asphalt based trackless tack coat materials. *Constr. Build. Mater.* **2018**, *165*, 385–394. [CrossRef]
44. Li, Z.D.; Huang, X.M.; Chen, G.X.; Chen, X. On Modified Temperature Model for Synchronous Chip Seal Waterproof Binder Course on the Concrete Bridge. *J. Chongqing Jiaotong Univ. (Nat. Sci.)* **2011**, *30*, 957–964.
45. Yang, Y.S.; Li, Z.X.; Wang, R.D.; Gao, Z. Technology Research on "Two Asphalt One Aggregate" Waterproof Based on Synchronous Crushed Stone. *J. Hebei Univ. Technol.* **2010**, *39*, 92–95.
46. Yang, Y.S.; Li, Z.X.; Wang, X.C. Road performance of synchronous crushed stone waterproof binding course of bridge pavement. *J. Chang. Univ. (Nat. Sci. Ed.)* **2009**, *29*, 19–23+58.
47. Duan, B.D.; Li, J.; Li, M.L.; Cao, D.; Chen, F. Research on material parameters of waterproof adhesive layer for porous asphalt pavement based on interlayer adhesive performance. *Highw. Eng.* **2019**, *44*, 45–49+137.
48. Cao, M.M.; Huang, W.Q.; Lu, Y.; Wu, M.; Li, Y. Test and Evaluation method of Interlaminar Shear Property of Composite Pavement. *J. Highw. Transp. Res. Dev.* **2018**, *35*, 40–48.
49. Bao, C.F.; Yuan, M.Y.; Yu, J.M.; Wang, G.; Wang, J. Study on performance evaluation of bridge deck waterproof bond layer based on interlaminar shear test. *Highway* **2016**, *61*, 212–217.
50. Liang, J.; Xu, H.; Guo, H.; Han, S.; Xia, J. Research on influence of water-based epoxy resin modifier on performance and structure of emulsified asphalt. *Bull. Chin. Ceram. Soc.* **2020**, *39*, 1998–2004.
51. Wang, Q.Z.; Ma, X.J.; Xu, D.W.; Yang, Z. Study on the performance of waterborne epoxy modified emulsified asphalt bridge deck adhesive layer. *Thermosetting Resin* **2020**, *35*, 59–63.
52. Chang, Y.T.; Chen, Z.D.; Niu, X.H.; Zhou, Z. Test of shear resistance of modified emulsified asphalt by waterborne epoxy resin. *J. Jiangsu Univ. (Nat. Sci. Ed.)* **2017**, *38*, 224–229. [CrossRef]
53. Yang, G.L.; Wang, C.H.; Fu, H.; Yan, Z.; Yin, W. Waterborne epoxy resin-polyurethane-emulsified asphalt: Preparation and properties. *J. Mater. Civ. Eng.* **2019**, *31*, 04019265.1–04019265.11. [CrossRef]

54. Wang, M.; Wu, X.L.; Li, B.; Xiao, L.; Peng, Z. Experimental Research on Waterproof Adhesive Layer Material of Concrete Bridge Slab. *Highw. Eng.* **2021**, *47*, 91–96.
55. Ji, J.; Liu, L.H.; Suo, Z.; Xu, Y.; Yang, S.; Xu, S. Performances of Micro-Surfacing with Waterborne Epoxy Resin Modified Emulsified Asphalt. *J. Chang. Univ. (Nat. Sci. Ed.)* **2017**, *37*, 23–30.
56. Chen, Q.; Lu, Y.F.; Wang, C.H.; Han, B.; Fu, H. Effect of raw material composition on the working performance of waterborne epoxy resin for road. *Int. J. Pavement Eng.* **2022**, *23*, 2380–2391. [CrossRef]
57. Ma, L. Study on material performance of high-permeability bridge deck waterproof adhesive layer. *New Build. Mater.* **2020**, *47*, 164–168.
58. Yi, X.J. A Weighted multi-objective decision model for selecting optimum waterproof material of cement concrete bridge. *J. China Foreign Highw.* **2020**, *40*, 298–302.
59. Wang, Y.L.; Zhou, Y.L.; Yao, A.L.; Zhang, Y. Test of shear and pull-off between asphalt and concrete on bridge deck pavement structure. *J. Chang. Univ. (Nat. Sci. Ed.)* **2009**, *29*, 15–18.
60. Liu, S.H. Application of FYT(coating) bridge deck waterproof layer on binbo expressway. *J. China Foreign Highw.* **2005**, *2*, 128–130.
61. Meng, C.C. Optimization of waterproof bond system for concrete deck pavement in rainy and damp-heat area. *Road Mach. Constr. Mech.* **2018**, *35*, 108–111.
62. Liu, L.L.; Li, Y.S.; Zong, J.Y.; Wu, C. Comparative study on the properties of waterproof binding materials for rigid and flexible composite pavement of steel bridge deck. *China Adhes.* **2021**, *30*, 50–53+58.
63. Guo, W.H.; Chen, F.; Li, Y.; Chi, H. Performance test on waterproof binding layer of deck pavement of prestress concrete box-girders bridge with corrugated steel webs. *J. Xihua Univ. (Nat. Sci. Ed.)* **2017**, *36*, 103–106.
64. Li, Q.L.; Tian, Y.; Zhang, M. Study on factors affecting adhesive strength of emulsified asphalt water-proof coating. *New Build. Mater.* **2019**, *46*, 96–98. [CrossRef]
65. Ma, T.; Huang, X.M.; Ju, H. Research on the Performance of Waterproof and Cohesive Layer. *J. Highw. Transp. Res. Dev.* **2007**, *1*, 43–46.
66. Jiang, S.W. Sensitivity analysis of interlayer performance of waterproof bond with different gravel size range. *J. China Foreign Highw.* **2017**, *37*, 290–293.
67. Zhao, Z.Y.; Chen, F.L.; Liu, G.P. Material selection and analysis of waterproof bonding layer for steel bridge deck pavement. *Highway* **2017**, *62*, 288–291.
68. Zhang, D.J.; Zhu, H.P.; Pan, Y.Q. Tests for waterproof binding layer of steel bridge deck pavement of Fourth Nanjing Changjiang River Bridge and the paving technique. *World Bridges* **2014**, *42*, 44–48.
69. Jin, W.; Zhao, Y.; Wang, W.; He, F. Performance evaluation and optimization of waterproof adhesive layer for concrete bridge deck in seasonal frozen region using AHP. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 5555535. [CrossRef]
70. Liu, W.; Yan, K.; Ji, H. Bonding performance evaluation on WTR-APAO composite modified asphalt as waterproof adhesive layer for concrete bridge. *Constr. Build. Mater.* **2022**, *349*, 128667. [CrossRef]
71. Fen, Y.; Kong, Z.; Xiao-yang, J.; Lu, Q.; Yan, J. Evaluation of shear performance of flexible waterproof-adhesive layer in concrete bridge pavement based on grey correlation analysis. *Road Mater. Pavement Des.* **2009**, *10* (Suppl. S1), 349–360. [CrossRef]
72. Qian, G.; Li, S.; Yu, H.; Gong, X. Interlaminar bonding properties on cement concrete deck and phosphorous slag asphalt pavement. *Materials* **2019**, *12*, 1427. [CrossRef]
73. Zha, X.; Lv, R.; Hu, H.; Chen, H.; Wang, Z. Preparation and experimental research on the properties of neodymium iron boron magnetic powder modified asphalt. *Constr. Build. Mater.* **2022**, *321*, 126392. [CrossRef]
74. Sun, Y.; Liu, Y.; Gong, J.; Han, X.; Xi, Z.; Zhang, J.; Wang, Q.; Xie, H. Thermal and bonding properties of epoxy asphalt bond coats. *J. Therm. Anal. Calorim.* **2022**, *147*, 2013–2025. [CrossRef]
75. Chen, Q.; Wang, S.; Wang, C.; Wang, F.; Fu, H.; Yang, X. Modified waterborne epoxy as a cold pavement binder:preparation and long-term working properties. *J. Mater. Civ. Eng.* **2021**, *33*, 04021079. [CrossRef]
76. Chen, Q.; Wang, C.H.; Fu, H.; Fan, Z.; Liu, L. Prediction and extreme value optimization of tensile strength of waterborne epoxy resin for road. *Mater. Rep.* **2021**, *35*, 16172–16177.
77. Zhou, Y.Y.; Ma, G.Z.; Wang, H.D.; Li, G.; Chen, S.; Wang, H.; Liu, M. Research status of pores in thermally sprayed coatings and their effects on coating performance. *Mater. Rep.* **2016**, *30*, 90–96+119.
78. Liu, L.H. Development and Application of a New Waterproof Adhesive Layer Material for Heavy Traffic Concrete Bridge Deck. Master's Thesis, Beijing University of Civil Engineering and Architecture, Beijing, China, 2018.
79. Dai, L. Effect of Temperature and Roughness on the Mechanical Properties of Concrete Bridge Deck Pavement. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2017.
80. Chen, Z.C. Study on Pavement's Waterproofness of Concrete Bridge. Master's Thesis, Chang'an University, Xi'an, China, 2011.
81. Chen, B.; Yang, X.P.; Han, G.X. Study on the influence of bridge deck roughness on the performance of waterproof bonding layer. *Highway* **2021**, *66*, 199–204.
82. Wang, J.J.; Zhang, H.C.; Zhu, L.G. Shotblasting treatment technology for concrete bridge deck pavement. *J. China Foreign Highw.* **2011**, *31*, 170–173.
83. Wang, D.X. Research on Waterproof and Cohesive Layer of Concrete Bridge Deck Asphalt Pavement. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2012.

84. Hu, H.B.; Liu, G.; Qian, Z.D.; Liu, Y.; Wu, X. Experimental study of waterproof bonding layer for concrete deck of Qingshan Changjiang River Highway Bridge in Wuhan. *Bridge Constr.* **2020**, *50* (Suppl. S1), 57–62.
85. Meng, C.C. Test study of waterproof binding layer for deck pavement of Poyang Lake Bridge. *World Bridges* **2011**, *2*, 57–60.