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Review Article

Overview: Application of Resin Waterproof Adhesive Materials in Bridge Deck Pavement in China

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To further promote the research and application of resin type waterproof adhesive layer materials, the types, relevant specifications, and research trends of resin type waterproof adhesive layer in China are comprehensively investigated. The performance evaluation indicators, performance requirement, and requirements in different specifications are systematically analyzed, and the key performance evaluation indicators are recommended. The basic properties of common resin type waterproof adhesive layer materials are studied, and the bonding properties of different resin waterproof adhesive layers were compared and evaluated. The results showed that pull-out strength, shear strength, tensile strength, elongation at break, low temperature flexibility, and impermeability are the key performance evaluation indicators of resin waterproof adhesive layer. The tensile property, corrosion resistance, and water impermeability of resin type waterproof adhesive layer material are good, the flexibility of epoxy resin type waterproof adhesive layer material is poor, and the flexibility of methyl methacrylate (MMA) waterproof adhesive layer material is good. The bonding performance of the epoxy resin waterproof adhesive layer is better than that of the MMA. As the temperature rises, the bonding performance of the two waterproof adhesive layers is significantly reduced. At 60°C, the average pull-out strengths of the epoxy resin and MMA waterproof adhesive layer were 1.83 MPa and 1.47 MPa, respectively.

1. Introduction

Since the 1990s, the construction of long-span bridges in China has entered a peak period, and a large number of long-span bridges have been built one after another [1]. However, it is common for the deck pavement structure of long-span bridges to be damaged within the service life; therefore, the academic and engineering circles attach great importance to it. Over the years, a lot of funds and human and material resources have been invested in the in-depth study of deck pavement [2, 3]. As one of the key technologies of bridge deck pavement, the waterproof adhesive layer plays an important role in connecting the preceding and the following in bridge deck pavement. It can not only connect the bridge deck and pavement structure as a whole, bear force together, and coordinate deformation but also prevent water infiltration from eroding the steel plate, which plays an important role in ensuring the service quality and durability of bridge deck pavement. In recent years, it has also attracted great attention of experts and scholars [4–6].

The research on waterproof adhesive layer was carried out earlier in developed countries. In the 1920s, Denmark and Kansas, United States, began to use relatively primitive waterproof adhesive layer on concrete bridges. From 1940s to 1950s, with the large-scale highway construction in developed countries, waterproof adhesive layer was gradually applied. In the 1960s, the concept of waterproof system officially appeared, and the United States began to study waterproof adhesive layer. In 1976, the National Cooperative Highway Research Program (NCHRP) of the United States

proposed the performance test and road performance evaluation method of waterproof adhesive layer materials. After entering the 1990s, the American Society of Testing and Materials (ASTM) summarized and improved the old test procedures for waterproof adhesive layer materials and put forward test methods and evaluation indicators such as self-performance, static load resistance, and water seepage resistance of waterproof materials [7]. In the 1990s, the British Transportation Research Laboratory (TRL) proposed a unified standard for the test methods and evaluation indicators such as physical properties, adhesion, and durability of bridge deck waterproof adhesive layer materials [8]. The Danish Road Institute also clearly put forward the importance and technical requirements of setting up a waterproof layer in its report no. 106 in 2000 [9]. Generally speaking, developed countries have carried out early research on waterproof adhesive layer materials, and the research results are relatively mature and comprehensive. Based on the shear test, Li et al. found that the shear strength of the epoxy resin waterproof adhesive layer is affected by the thickness of the waterproof adhesive layer, the roughness of the concrete surface, the particle size of the simultaneous crushed stone, and the test temperature [10]. Feng et al. studied the influence of steel bridge deck roughness on the bonding strength of waterproof adhesive layer based on pull-out test and found that when the steel bridge deck roughness is 60 μm, the epoxy waterproof coating has strong bonding strength with steel bridge deck [11].

Compared with developed countries, the research and application of bridge deck pavement waterproof adhesive layer in China started late. After entering the 1980s, due to serious early bridge diseases [12, 13], researchers gradually realized the importance of setting up a bridge deck pavement waterproof adhesive layer and began to apply waterproof in physical projects in Beijing, Henan, Anhui, Guangdong, and other places [14, 15]. Due to lack of experience in the research and application of bridge deck waterproofing materials, the initial application of the bridge deck pavement waterproof adhesive layer in China mainly used building waterproof membranes and evaluated the waterproof materials with reference to the "Technical Code for Roof Engineering." However, bridge deck waterproofing is much more complex than roof waterproofing. In addition to requiring the waterproof adhesive layer material to have the properties of impermeability, high temperature resistance, low temperature resistance, corrosion resistance, aging resistance, and good bonding with the upper and lower contact layers, it is more important that the bridge deck waterproof adhesive material will also be affected by the comprehensive action of horizontal and vertical forces of vehicle load, high temperature rolling, impact of dynamic load, reflected cracks of bridge deck, and so forth. Therefore, the application effect of roof waterproof material in bridge deck waterproof is not ideal. With the in-depth research of researchers on bridge deck pavement waterproof adhesive layer materials, resin type waterproof adhesive materials have better adhesion, corrosion resistance, and impermeability, and they have been increasingly used in the field of bridge deck pavement in recent years [16, 17]. Among them, epoxy resin type waterproof adhesive layer and methyl methacrylate (MMA) waterproof adhesive layer are the most common. Diao and Huang explored the influence of different epoxy dosages and the scattered amount of gravel on the bonding strength of epoxy resin waterproof adhesive layer based on pull-out tests and shear tests and found that increasing the amount of epoxy resin or sprinkling gravel can significantly improve the tensile strength and shear strength of the waterproof adhesive layer [18]. Chen and Wang studied the influence of the roughness of the steel bridge deck on the bonding strength of the MMA waterproof adhesive layer based on the pull-out test and the shear test and found that the rough steel plate has higher pull-out strength with the waterproof adhesive layer [19]. Gong et al. studied the construction temperature and humidity of the MMA waterproof adhesive system based on the pull-out test and the shear test and found that the construction temperature should be 25°C, and the relative humidity should not exceed 60% [20]. Long studied and compared the properties of SBS modified asphalt sealing layer, modified emulsified asphalt, and MMA waterproof adhesive layer based on the pull-out test and low temperature bending test. It was found that the toughness, heat resistance, and bonding strength of MMA were higher than those of the other two asphalt waterproof adhesive layers [21].

To sum up, China and other countries have carried out more research on the waterproof adhesive layer of bridge deck pavement. The research in developed countries is earlier and the results are relatively mature. There are specific provisions and construction rules for the setting of waterproof adhesive layer, but some of the test methods used are complex and have poor operability. The technical evaluation standards are mostly qualitative indicators and lack of quantitative indicators. The test interference is also large. The research on waterproof adhesive layer in China started a little late. Although there are many achievements, the research mainly focuses on its basic performance and bonding performance, and there is less research on its durability. Moreover, the research results are scattered and unsystematic. At the same time, China has not formed a complete standard or specification that can be used to guide the quality control in the construction process, resulting in the unclear evaluation index of bridge deck pavement in China. Therefore, it is necessary to systematically sort out the relevant specifications, as well as research and application results of different types of resin type waterproof adhesive layers, so as to further reveal the bonding performance of different types of resin type waterproof adhesive layers and clarify their key performance evaluation indicators.

Based on this, the relevant specifications and research trends of resin type waterproof adhesive materials in China are comprehensively investigated. The performance evaluation indicators and requirements of relevant specifications are systematically sorted out, and the key performance evaluation indicators are clarified. The basic properties and adhesive properties of resin type waterproof adhesive layer materials are compared and evaluated, in order to lay a foundation for the further research and application of resin type waterproof adhesive materials for bridge deck pavement.

2. Methodology

This paper is a review paper, in which the literature survey is carried out using four databases: Web of Science, China National Knowledge Infrastructure, Baidu Search, and Baidu Academic. For each search engine, the following phrase characters and keywords are used: bridge deck pavement waterproof adhesive layer, epoxy resin waterproof adhesive layer, MMA waterproof adhesive layer, and deck waterproofing. The tensile properties, environmental adaptability, impermeability, and bonding properties of resin type waterproof adhesive layer were investigated. After the literature survey, origin was used to draw the diagram for data analysis and processing, and the basic properties and bonding properties of resin waterproof adhesive layer were systematically studied.

3. Types and Technical Requirements of Resin Type Waterproof Adhesive Layer

3.1. Type of Resin Type Waterproof Adhesive Layer. Commonly used resin type waterproof adhesive layers are mainly divided into epoxy resin type waterproof adhesive layers and MMA waterproof adhesive layers. In addition, there are currently less used water-based epoxy resin waterproof adhesive layers, polyurethane waterproof adhesive layers, and so forth.

3.1.1. Epoxy Resin Waterproof Adhesive Layer. The epoxy resin waterproof adhesive materials mainly use epoxy resin (the bisphenol A epoxy resin structural formula is shown in Figure 1), reactive diluent, and modifier as the main components and react with the curing agent to form a structure with a three-dimensional network structure.

The biggest advantage of epoxy resin material is its high bonding strength, good bonding force with the bridge deck, and the ability to consolidate loose bridge deck materials [22]. The impermeability performance is good; it can effectively prevent the ground underwater from seeping and corroding the bridge deck and has good acid, alkali, and salt corrosion resistance [23]. The application of epoxy resin in bridge deck pavement is shown in Figure 2. China applied epoxy resin waterproof adhesive layer to Donghai Bridge in 2002. Subsequently, it has been applied in several bridge projects such as Chongqing Shibanpo Bridge and Xiling Yangtze River Bridge. However, the epoxy resin adhesive layer material also has disadvantages. Its cost is relatively high, the construction is greatly affected by the weather, and the construction cannot be carried out when the temperature is lower than 10°C or in rainy days. Generally, it is only suitable for important bridge projects.

3.1.2. MMA Type Waterproof Adhesive Layer. MMA waterproof system is composed of three materials: acrylic primer, methyl methacrylate waterproof film, and acrylic resin binder. MMA resin waterproof material has strong puncture resistance and chloride ion penetration resistance, good bonding performance, and high temperature

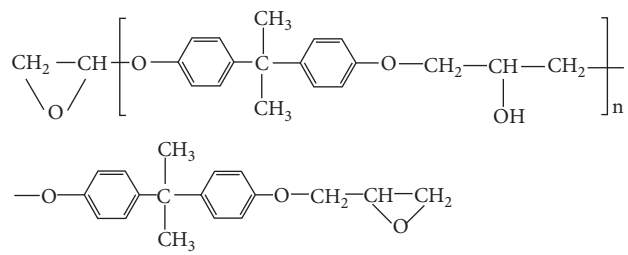

Figure 1: Molecular structure formula of bisphenol A epoxy resin, where "n" is the average degree of polymerization, the number of repeating structural units in the molecule.

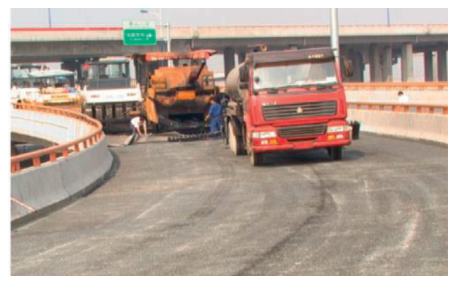

Figure 2: Application of epoxy resin in bridge deck [23].

performance, especially excellent flexibility, which can well adapt to the structural characteristics of orthotropic steel plate. It is widely used in pouring asphalt mixture pavement system [24]. The structural formula of MMA is shown in Figure 3.

MMA waterproof material has many years of application history in the United Kingdom and other countries, and the service life has exceeded 50 years. The application of MMA in bridge deck pavement is shown in Figure 4. It was used late in China. The Hong Kong Tsing Ma Bridge which was opened to traffic in 1997 adopted this waterproof material. Wuxi S342 began to apply this material on the main span in 2006 and then it was successively applied on several bridges such as Chongqing Caiyuanba Bridge, Guizhou Beipanjiang Bridge, Nanchang Hongdu Bridge, and Hero Bridge. The Hong Kong-Zhuhai-Macao Bridge, which was completed and opened to traffic in 2018, also adopted an MMA waterproof adhesive layer, which has a good application effect. Due to the unique advantages and excellent application effect of MMA waterproof material, it has been more and more used in the field of bridge deck pavement.

3.1.3. Other Types of Waterproof Adhesive Layer. In addition to the above two commonly used resin type waterproof adhesive materials, resin type waterproof adhesive materials also include polyurethane waterproof adhesive materials and waterborne epoxy waterproof adhesive materials.

(1) Polyurethane waterproof adhesive materials: polyurethane waterproof adhesive materials are divided into single-component and two-component. One-component polyurethane waterproof adhesive material is developed by polymerization

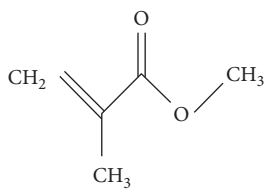

Figure 3: Molecular structure formula of methyl methacrylate.

Figure 4: Application of MMA waterproof adhesive layer on bridge deck [24].

reaction with isocyanate and polyether polyol as the main raw materials, with a variety of additives and fillers. The two-component polyurethane waterproof bonding material is composed of components A and B. Generally, component A is a polyurethane prepolymer, and component B is a curing agent. Polyurethane waterproof adhesive layer material has no toxic effect on the environment and belongs to environmentally friendly building construction materials. It has good waterproof and anticorrosion properties, and the coating layer has excellent properties such as high tensile strength, high bonding strength, aging resistance, and flexibility and has strong adaptability to matrix deformation. In addition, since there are rigid segments in the polyurethane molecular chain, polyurethane materials also have better wear resistance and higher mechanical strength. The structural formula of polyurethane is shown in Figure 5.

(2) Waterborne epoxy waterproof adhesive materials: Waterborne epoxy resin is a stable system that is dispersed in water by preparing traditional epoxy resin through physical or chemical methods. It does not contain volatile organic solvents, green environmental protection, excellent mechanical properties of the coating, strong adhesion with concrete substrate, and excellent water resistance. Although waterborne epoxy resin waterproof adhesive material is rarely used in the waterproof adhesive layer of bridge deck pavement, it has a wide application prospect [25, 26]. The molecular structure formula of waterborne epoxy resin prepared by the reaction of toluene diisocyanate, bisphenol A epoxy resin, and dihydroxymethyl propionic acid is shown in Figure 6 [27].

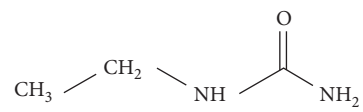

Figure 5: Molecular structural formula of polyurethane.

3.2. Technical Requirements for Resin Type Waterproof Adhesive Layer. The requirements for the waterproof adhesive layer of bridge deck pavement can be simply summarized as impermeable within the design life and can bond the bridge deck and pavement as a whole to jointly resist the action of vehicle load. The specific requirements are as follows:

(1) Impermeability: the main function of the bridge deck waterproof adhesive layer is to ensure that the external rainwater penetrates into the bridge deck through the pavement during the service life of the bridge, which requires that the waterproof bonding layer should have good impermeability and integrity to ensure that water will not enter the bridge deck through the damaged or missing parts of the waterproof bonding layer.

(2) Good bonding performance: as the structural layer of bonding bridge deck and pavement, the waterproof adhesive layer must not only have impermeability but also have good bonding performance, connect the bridge deck and pavement as a whole, bear force together, coordinate deformation, and maintain good integrity under the action of driving load [23].

(3) Temperature stability: during the construction of the upper asphalt layer, the high temperature of the asphalt mixture is easy to damage the waterproof adhesive layer material and reduce the waterproof performance. Moreover, the resin type waterproof bonding layer material is easy to become sticky and soft in high temperature weather, which will also lead to the decline of bonding waterproof performance. Therefore, the waterproof bonding layer material is required to have a certain high temperature stability. At low temperature, the brittleness of the material increases, which will lead to fracture during shrinkage and water seepage of the waterproof layer. Therefore, the waterproof bonding material is required to have a certain low temperature flexibility.

(4) Anticonstruction damage performance: after the waterproof layer is paved, the exposed waterproof layer shall withstand the rolling action of pedestrians. When paving the surface layer, the material transportation vehicles shall drive on the waterproof layer, and the road roller shall roll the surface layer. Therefore, the waterproof layer shall be able to withstand the puncture and damage of aggregates during construction.

In addition to the above general requirements, due to the vast territory of China, some regions have special engineering requirements for waterproof adhesive layer materials. For example, for the humid, hot, and rainy areas in

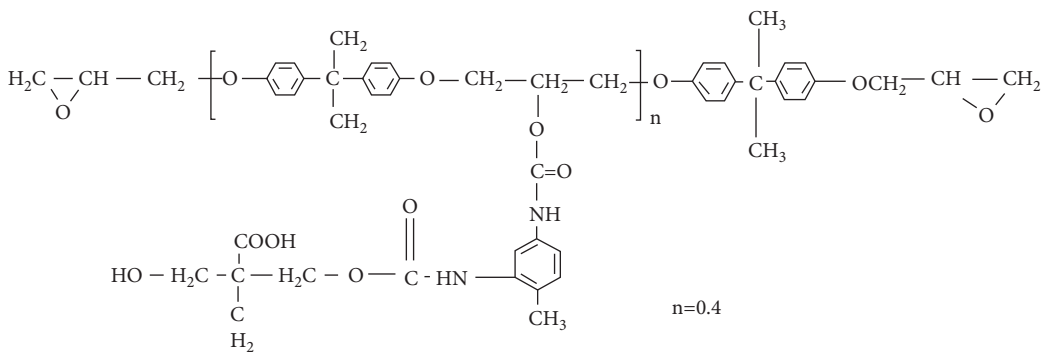

Figure 6: Molecular structural formula of waterborne epoxy resin [27].

southern China, the service life of the waterproof adhesive layer of bridge deck pavement is greatly reduced under the influence of the climatic conditions of complex temperature change and abundant rain, which is easy to cause damage to the bridge pavement structure and affect the use safety of the bridge. Therefore, the requirements for the waterproof adhesive layer to resist high temperature deformation are more strict. For the cold areas in northern China, due to the obvious seasonal temperature change, the influence of freeze-thaw cycle and deicing salt is also serious, which requires that the waterproof adhesive layer material have not only good low temperature crack resistance but also good corrosion resistance and water damage resistance.

4. Comparative Evaluation of Relevant Standards

With the in-depth research on the waterproof adhesive layer materials of bridge deck pavement by researchers, relevant departments in China have also formulated a series of relevant specifications for resin waterproof adhesive materials. The National Development and Reform Commission issued "Waterproofing coatings for concrete bridge and road surface" (JC/T 975-2005) in 2005 [28]. The technical indicators requirements of polyurethane resin waterproof adhesive layer applied to concrete bridge deck are specified according to the indicators of tensile strength, elongation at break, bonding strength, and impermeability. The Ministry of Transport issued the "Technical guide for design and construction of bridge deck pavement of highway steel box girder" ([2006] No.274) in 2006 [29]. Technical indicators such as elongation at break, bonding performance, and low temperature flexibility specify the relevant technical requirements for reactive resin type waterproof adhesive layer materials used in steel bridge deck pavement. The General Administration of Quality Supervision, Inspection and Quarantine of China and Standardization Administration jointly issued "Polyurethane Waterproof Coatings" (GB/T 19250-2013) [30] in 2013. Compared with (JC/T 975-2005), this specification increases the requirements for the hardness, heat resistance, and other technical indicators of polyurethane waterproof adhesive layer materials. The Ministry of Transport of China issued the "Specifications for design and construction of pavement on highway steel deck bridge" (JTG/T 3364-02-2019) [31], which further made relevant regulations for the resin type waterproof adhesive layer used on steel bridge decks. The relevant specifications and performance evaluation indicators of resin type waterproof adhesive layer materials in China are compared and analyzed. The specifications and evaluation indicators are shown in Table 1.

Table 1 shows that, in the relevant specifications of China's resin type bridge deck pavement waterproof adhesive layer, each specification has clear requirements for the bonding performance and elongation at break of the waterproof adhesive layer material. Except for individual specifications, most specifications have clear requirements for the tensile strength, impermeability, and low temperature flexibility of resin type waterproof adhesive layer materials. It can be seen that bonding strength, elongation at break, tensile strength, impermeability, and low temperature flexibility are the main technical indicators for evaluating the performance of resin type waterproof adhesive layer materials.

There is a big disparity in the requirements for the bonding strength of resin waterproof adhesive layer materials in various specifications in China, mainly due to the different test methods adopted in various specifications. The test method adopted by JTG/T 3364-02-2019 and [2006] No. 274 is shown in Figure 7(a), which uses a universal material testing machine to test the pull-out strength between the waterproof adhesive layer and the steel plate. The test method adopted in GB/T 19250-2013 specification is shown in Figure 7(b). Stick the tensile upper fixture with the coating surface, and then install the test piece with the tensile upper fixture on the testing machine to test the bonding strength. The test method adopted in JC/T 975-2005 specification is shown in Figure 7(c). Stick the waterproof bonding layer material on the upper and lower sides of the test piece (one side is cement concrete and the other side is asphalt mixture), and then place it on the tensile testing machine for tensile strength test. Among the three test methods, the method shown in Figure 7(a) is the most commonly used.

Different Chinese specifications have different performance requirements for resin type waterproof adhesive

Table 1: Performance evaluation indicators and requirements of resin-based waterproof adhesive layer.

Test items		JTG/T 3364-02-2019			[2006] No.274	GB/T 19250-2013	JC/T 975-2005
		Epoxy resin I	Epoxy resin II	Methyl methacrylate	Reactive resin	Polyurethane	Polyurethane
Solid content (%)		—	—	≥95.0	—	Single: 85.0 Double: 92.0	98.0
Tensile strength (23°C) (MPa)		≥1.0	≥3.0	≥12.0	—	≥6.0	≥2.45
Elongation at break (23°C) (%)		≥10	≥100	≥130	≥20①	≥450	≥450
Surface drying time (23°C) (h)		≤0.5	—	≤0.5	—	≤12	≤4
Hard work time (23°C) (h)		≤1.0	—	≤1.0	—	≤24	≤8
Impermeability		0.3 MPa, 24 h impermeable			—	0.3 MPa, 2 h impermeable	0.3 MPa, 30 min impermeable
Water absorption (%)		≤0.3	≤0.3	—	—	≤5.0	≥0.2
Bonding strength (MPa)		≥5.0	≥3.0	≥5.0	≥5.0	≥1.0	≥0.05
Shear strength (25°C) (MPa)		—	—	—	≥3.0	≥0.2 (50°C)	≥3.0
Low temperature flexibility (°C, no cracks)		—	—	−20	−20	−35	−40
Hardness (shore hardness D)		—	—	50–70	—	60	—
Impact resistance (1 kg, 50 cm)		—	—	No cracks	—	No cracks	—
Heat resistance (°C)		—	—	—	—	—	160°C without flowing and dripping
Tear strength (N/mm)		—	—	—	—	30	—
Aging at constant elongation	Heating aging	—	—	—	—	No crack and deformation	—
	Artificial climate aging	—	—	—	—	No crack and deformation	—
Heat treatment (80°C, 168 h)	Tensile strength retention rate (%)	—	—	—	—	80–150	80
	Elongation at break (%)	—	—	—	—	≥400	≥400
	Low temperature flexibility	—	—	—	—	−30°C, no cracks	−35°C, no cracks
	Heating expansion rate (%)	—	—	—	—	—	≤1.0
	Mass loss	—	—	—	—		≤1.0
Alkali treatment (0.1% $NaOH + Ca(OH)_2$, 168 h)	Tensile strength retention rate (%)	—	—	—	—	80–150	—
	Elongation at break (%)	—	—	—	—	≥400	—
	Low temperature flexibility	—	—	—	—	−30°C, no cracks	—
Acid treatment (2% H_2SO_4, 168 h)	Tensile strength retention rate (%)	—	—	—	—	80–150	—
	Elongation at break (%)	—	—	—	—	≥400	—
	Low temperature flexibility	—	—	—	—	−30°C, no cracks	—
Artificial climate aging (1000 h)	Tensile strength retention rate (%)	—	—	—	—	80–150	—
	Elongation at break (%)	—	—	—	—	≥400	—
	Low temperature flexibility	—	—	—	—	−30°C, no cracks	—
Salt treatment	Tensile strength retention rate (%)	—	—	—	—	—	80
	Elongation at break (%)	—	—	—	—	—	≥400
	Low temperature flexibility	—	—	—	—	—	−35°C, no cracks
	Mass increase	—	—	—	—	—	≤2.0
Impermeability after hot rolling							0.1 MPa, 30 min impermeable

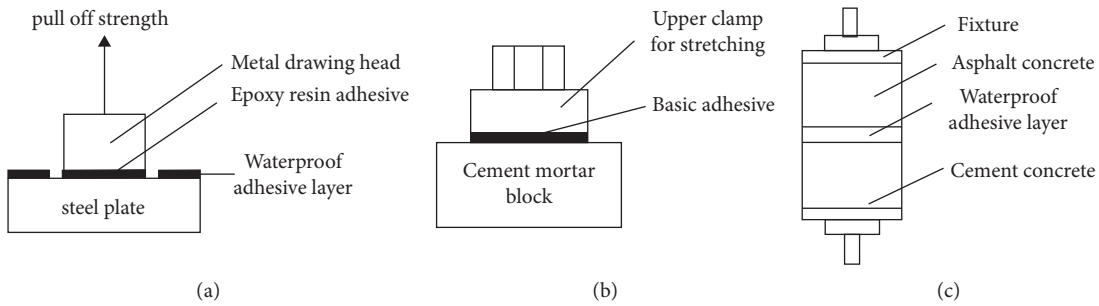

Figure 7: Test method of bonding strength between waterproof adhesive layer and steel plate.

layer. JTG/T 3364-02-2019 and [2006] No.274 lack requirements for the corrosion resistance of resin type waterproof adhesive layer materials, while the remaining specifications put forward specific requirements for corrosion resistance. For example, GB/T 19250-2013 stipulates that the tensile strength retention, elongation at break, and low temperature flexibility of the polyurethane waterproof adhesive layer after heat treatment, acid treatment, and alkali treatment are 80–150%, ≥400%, and no cracks at −30°C, respectively.

The reactive resin was not subdivided in [2006] No.274 issued by the Ministry of Transport in 2006, because there was little research on the resin type waterproof adhesive layer by researchers in China at that time, and the resin type waterproof adhesive layer used was mainly epoxy resin type waterproof adhesive layer. With the increasing application of MMA waterproof adhesive layer, JTG/T 3364-02-2019 further subdivides the reactive resin into epoxy resin adhesive and methyl methacrylate resin and increases the requirements for technical indicators such as tensile strength and impermeability. The epoxy resin was subdivided into type I and type II. Type I epoxy resin adhesive is mainly composed of epoxy resin and curing agent, which plays the role of preventing water erosion and bonding the lower layer. The upper layer can be constructed only after it is completely cured. Type II epoxy resin adhesive is also mainly composed of epoxy resin and curing agent, which plays the role of preventing water stop erosion and bonding between upper and lower layers. It can continue to react and bond after the construction of protective layer. At the same time, detailed regulations are made for the amount of different resin type waterproof adhesive layer materials, among which the amount of MMA is 2.5–3.5 kg/m^2, the amount of epoxy resin adhesive type I is 0.6–1.1 kg/m^2, and the amount of type II epoxy resin adhesive is 0.4–0.5 kg/m^2. This is because, with the rapid development of bridge construction in China and the intensification of heavy traffic, the resin waterproof adhesive layer has gradually become the main bridge deck waterproof adhesive material due to its good bonding performance. The relevant research and engineering application have increased, the requirements for the waterproof adhesive layer have gradually increased, and the relevant specifications of the waterproof adhesive layer have become more and more perfect.

5. Working Performance of Resin Type Waterproof Adhesive Layer

5.1. Basic Performance. The waterproof adhesive layer is between the pavement layer and the bridge deck. It needs to have good impermeability to prevent water infiltration from eroding the bridge deck. At the same time, it also needs to have good tensile properties to adapt to the cooperative work with the bridge deck. During its service, it also needs to bear the influence of the external environment. In view of this, the research trends of tensile properties, impermeability, and environmental adaptability of resin waterproof adhesive layer materials in China are systematically investigated to provide theoretical support for their practical engineering application.

5.1.1. Tensile Properties. The research summary on the tensile properties of investigated epoxy resin and MMA waterproof adhesive layer materials in China is shown in Figure 8 [18, 19, 32–42].

Figure 8 shows that, in the research dynamics of the investigated resin type waterproof adhesive layer materials in China, the distribution of the tensile strength and elongation at break of the epoxy resin waterproof adhesive layer is relatively dispersed, and the data distribution range of the tensile strength of 50% is 5.6–15.93 MPa, with an average value of 11.22 MPa. The data distribution range of 50% elongation at break is 30.1–136%, with an average value of 108%. It can be seen from the distribution that the elongation at break corresponding to low tensile strength is higher, and that corresponding to high tensile strength is lower. When the tensile strength exceeds 10 MPa, the elongation at break remains at about 30%. The tensile strength distribution of MMA waterproof adhesive layer material is relatively concentrated, mainly in 12.39–13.21 MPa, with an average value of 12.71 MPa. The distribution of elongation at break is also relatively concentrated, mainly between 226% and 278%.

It can be seen that the tensile strength and elongation at break of the MMA waterproof adhesive layer material are better than the epoxy resin waterproof adhesive layer material, and the flexibility is better.

5.1.2. Environmental Adaptability. The research on the environmental adaptability of the waterproof adhesive layer in China is mainly low temperature resistance. The research

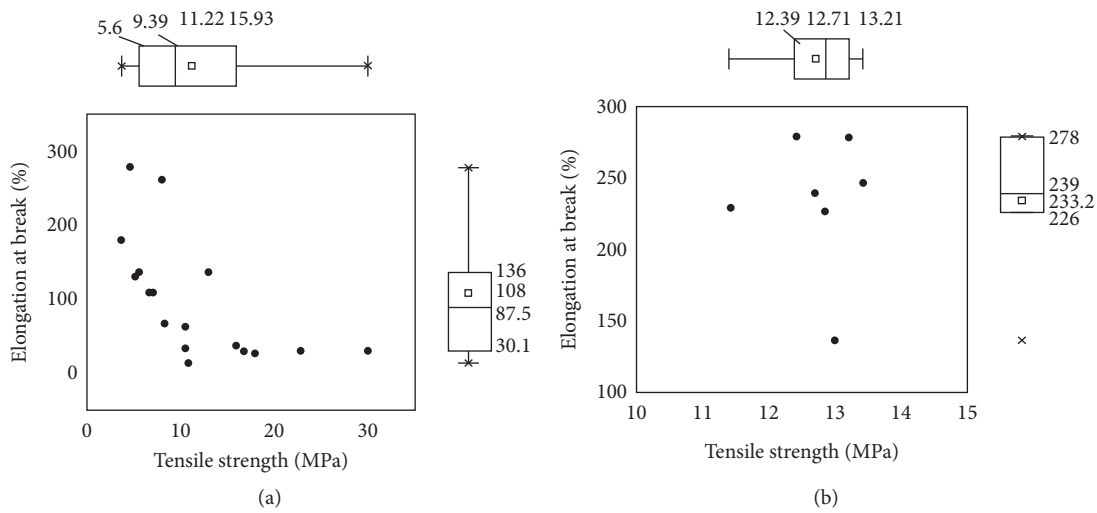

Figure 8: Tensile properties: (a) epoxy resin; (b) MMA.

dynamics of the investigated epoxy resin and MMA waterproof adhesive layer at low temperature are summarized in Figure 9 [18, 38–44].

Figure 9 shows that, among the low temperature performance research trends of the resin type waterproof adhesive layer investigated, the low temperature performance of the epoxy resin waterproof adhesive layer material is not outstanding in which the research trends of −20°C without crack meeting the specification requirements account for only 28.57%, and the maximum proportion of −10°C without crack is 42.86%. The overall low temperature performance of the MMA waterproof adhesive layer is better than that of the epoxy resin. The survey data of no cracks at −20°C that meet the requirements of the specification accounted for 87.5%, but there are still 12.5% of the survey data that do not meet the requirements of the specification.

In addition to low temperature resistance, individual researchers have also studied the acid, alkali, and salt corrosion resistance of the resin type waterproof adhesive layer. It is found that both epoxy resin waterproof adhesive layer materials and MMA waterproof adhesive layer materials have good acid, alkali, and salt corrosion resistance, and the corrosion resistance of the MMA waterproof adhesive layer is better than that of the epoxy resin waterproof adhesive layer materials [33].

5.1.3. Impermeability. Waterproofing is an important function of the waterproof adhesive layer of bridge deck pavement. Therefore, in the original state, the material must have good impermeability. Among the research trends investigated, scholars all use pavement water seepage meters to conduct impermeability tests to detect the impermeability of the resin type waterproof adhesive layer. The results show that the impermeability of the resin type waterproof adhesive layer is good, and it meets the requirements of 0.3 MPa and 24 h impermeability [18, 38–40, 45–47].

In conclusion, both epoxy resin and MMA waterproof adhesive layer materials have good tensile strength, acid, alkali, and salt corrosion resistance, and impermeability. The epoxy resin type waterproof adhesive layer material has poor flexibility, and the MMA type waterproof adhesive layer material has better flexibility, which meets the requirements of use. This is because the three-dimensional network structure formed by the epoxy resin after curing is compact and dense, and the crosslinking density is high, which makes its flexibility poor. The fracture surface of the epoxy resin waterproof adhesive material is shown in Figure 10. The cross section is relatively smooth and the fracture opening is sharp, indicating that its flexibility is poor and showing typical brittle fracture characteristics. At present, the commonly used methods to improve the flexibility of epoxy resin mainly include the use of thermoplastic, thermosetting resin to increase the flexibility and the addition of flexible chain segments, block polymers, and nanomaterials to improve the flexibility. Their addition effectively improves the shortcomings of high brittleness and high crosslinking density of epoxy resin.

5.2. Bonding Performance. Bonding performance between the waterproof adhesive layer and the bridge deck is an important technical indicator for evaluating the road performance of resin type waterproof adhesive layers. Researchers often use the pull-out strength and shear strength of the pull-out test and shear test to characterize its bonding performance and individually use the tensile shear test to test the bonding strength. In order to make the analysis results representative, it mainly focuses on the comparative analysis of the bonding performance between the pull-out test and the shear test. Based on this, the research trends of the pull-out strength and shear strength of the resin type waterproof adhesive layer in China are combined systematically, and the influence of the material type on the bonding performance of the waterproof adhesive layer is explored. The pull-out test

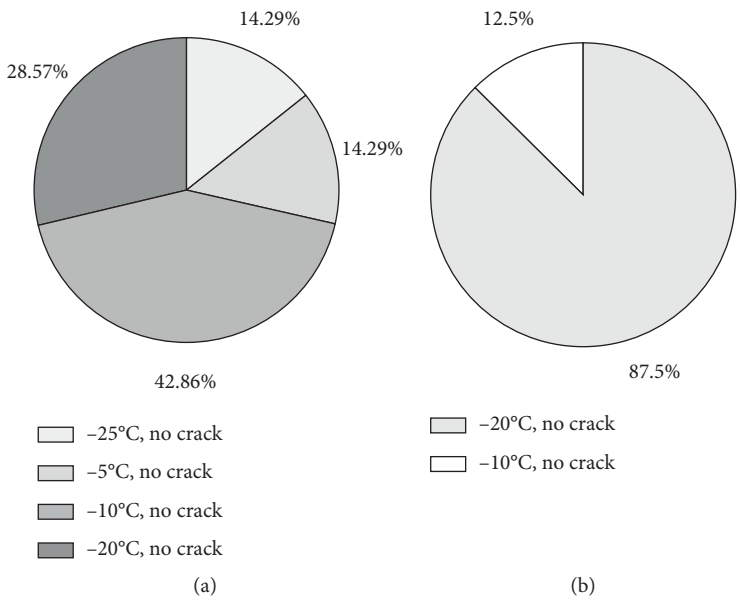

Figure 9: Low temperature properties: (a) epoxy resin; (b) MMA.

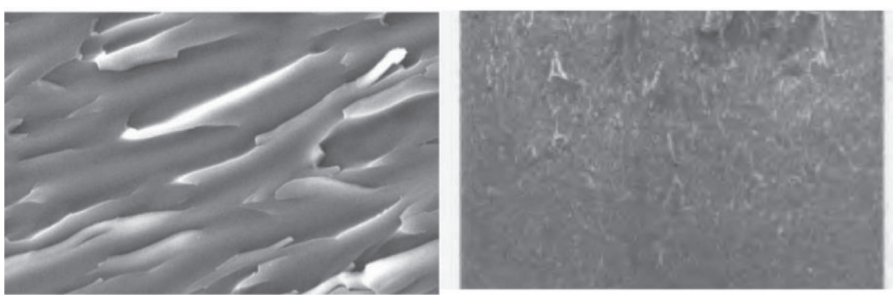

Figure 10: Microstructure of epoxy resin fracture surface [47, 48].

adopts the method of testing the pull-out strength with the drawing head shown in Figure 7(a).

5.2.1. Bonding Performance of Epoxy Resin Waterproof Adhesive Layer. The pull-out strength and shear strength of epoxy resin type waterproof adhesive layer in China are summarized in Figure 11 [18, 32–46, 49–53].

Figure 11 shows that the $Q1$ value of pull-out strength of epoxy resin type waterproof adhesive layer material at 25°C is 2.72 MPa, the $Q2$ value is 4.37 MPa, the $Q3$ value is 5.88 MPa, and the average value is 4.59 MPa. The Iqr value is 3.16 MPa. $Q1$ is the smaller quartile value of the box diagram, $Q2$ is the median value, $Q3$ is the larger quartile value, and Iqr is the 50% data distribution range, which is $Q3–Q1$. According to the Iqr value, 50% of the data in this group are between 2.72 and 5.88 MPa. The Iqr value shows that the data are relatively scattered. The $Q1$ value of pull-out strength at 60°C is 0.33 MPa, $Q3$ is 2.19 MPa, and the average value is 1.77 MPa, and the Iqr value is 1.86 MPa. It can be seen from the Iqr value that this set of data is also relatively scattered, with 50% of the data being between 0.33 and 2.19 MPa. It can be seen from the average pull-out strength at 25°C and 60°C that when the temperature increases, the pull-out strength of epoxy resin waterproof adhesive layer decreases significantly, with a decrease of about 61.4%.

The shear strength $Q1$ value of epoxy resin waterproof adhesive layer material at 25°C is 3.43 MPa, $Q3$ value is 4.99 MPa, the average value is 4.01 MPa, and the interquartile range (Iqr) value is 1.56 MPa. According to the values of $Q1$ and $Q3$, 50% of the data in this group are between 3.43 and 4.99 MPa. The Iqr value shows that the data is scattered, but its mean value is closer to the median, and the distribution is more symmetrical. When the temperature rises to 60°C, the shear strength $Q1$ value of the epoxy resin waterproof adhesive layer material is 0.74 MPa, the $Q3$ value is 1.32 MPa, the average value is 0.92 MPa, and the Iqr value is 0.58 MPa. It can be seen from its Iqr value that the data distribution is relatively concentrated. Same as the pull-out strength, when the temperature increases, the shear strength of the epoxy resin waterproof adhesive layer material is also significantly reduced, from 4.01 MPa to 0.92 MPa, a decrease of about 77.1%. The shear strength and pull-out strength data at 25°C and 60°C of epoxy resin waterproof adhesive layer are dispersed to a certain extent, because, in addition to temperature, humidity, roughness of

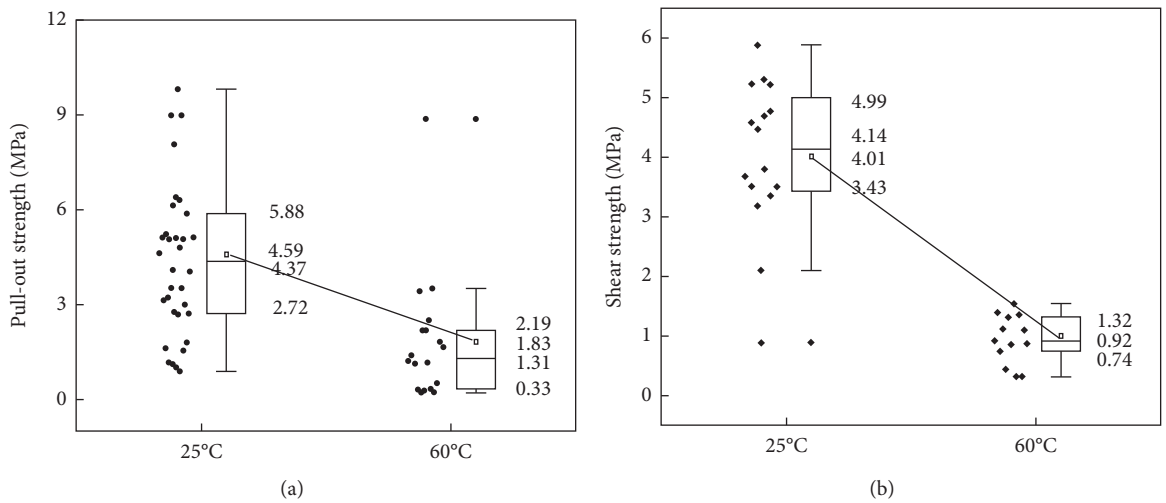

Figure 11: Bonding properties of epoxy resin waterproof adhesive layer: (a) pull-out strength; (b) shear strength.

bridge deck, thickness of waterproof adhesive layer, and other factors will have a certain impact on the bonding performance of waterproof adhesive layer. However, it can still be seen from these data that temperature will have a great impact on the bonding performance of waterproof adhesive layer.

5.2.2. Bonding Performance of MMA Waterproof Adhesive Layer. The pull-out strength and shear strength of MMA waterproof adhesive layer in China are summarized in Figure 12 [40–46, 50–53].

Figure 12 shows that the tensile strength $Q1$ of the MMA waterproof adhesive layer material at 25°C is 2.21 MPa, the $Q3$ value is 4.00 MPa, the average value is 3.44 MPa, and the Iqr value is 1.79 MPa. According to the distance between $Q1$ and $Q3$, 50% of the data in this group are between 2.21 and 4.00 MPa, and the Iqr value shows that the overall data is relatively scattered. At 60°C, the tensile strength $Q1$ value is 0.35 MPa, $Q3$ value is 2.2 MPa, and the average value is 1.47 MPa. From the average pull-out strength of 25°C and 60°C, it can be seen that when the temperature increases, the pull-out strength of the MMA waterproof adhesive layer material decreases significantly, with a decrease about 57.3%.

The shear strength $Q1$ value of MMA waterproof adhesive layer material at 25°C is 2.01 MPa, $Q3$ value is 3.07 MPa, the average value is 2.46 MPa, and Iqr value is 1.06 MPa. According to the Iqr value, the data are scattered. The $Q1$ value of MMA type waterproof adhesive layer material at 60°C is 0.71 MPa, the $Q3$ value is 0.25 MPa, the average value is 0.43 MPa, and the Iqr value is 0.46 MPa. According to the distance between $Q1$ and $Q3$, the 50% data distribution range of MMA waterproof adhesive layer material is 0.25–0.71 MPa. Compared with the temperature at 25°C, the shear strength of the MMA adhesive layer material at 60°C is significantly reduced by about 82.5%. Like the epoxy resin waterproof adhesive layer, the bonding performance of MMA waterproof adhesive layer also shows great discreteness due to the influence of multiple factors, but it can still be seen from these data that temperature has a great influence on the bonding performance of waterproof adhesive layer.

5.3. Comparison of Bonding Performance. The pull-out strength and shear strength of different types of China's resin type waterproof adhesive layer materials at 25°C and 60°C are compared and analyzed, as shown in Figures 13-14.

Figure 13 shows that, comparing the data distribution range and average value of 50% pull-out strength of two types of resin type waterproof adhesive layer materials at 25°C, it can be seen that the pull-out strength of epoxy resin waterproof adhesive layer materials is much higher than that of MMA. However, it can be seen from the Iqr values of the two kinds of waterproof adhesive layers that the data dispersibility of the epoxy resin waterproof adhesive layer material is also much greater than that of the MMA waterproof adhesive layer material.

When the temperature increased to 60°C, the pull-out strength of the two types waterproof adhesive layer materials decreased significantly. Among them, the drop of the epoxy resin type waterproof adhesive layer material was greater than that of the MMA type. At 60°C, the 50% data distribution ranges of the tensile strength of epoxy resin and MMA waterproof adhesive layer materials are basically the same, about 0.35–2.2 MPa. On the other hand, from the average value of epoxy resin and MMA waterproof adhesive layer, the tensile strength of epoxy resin waterproof adhesive layer material at 60°C is slightly better than that of MMA.

Figure 14 shows that, according to the data distribution range of the 50% shear strength of the two waterproof adhesive layer materials at 25°C, the shear strength of the epoxy resin waterproof adhesive layer is much higher than that of the MMA. By comparing the shear strength Iqr values of the two types of resin type waterproof adhesive layer materials at 25°C, it can be seen that the shear strength data of the epoxy resin waterproof adhesive layer has a larger dispersion and the MMA is smaller. However, even if the

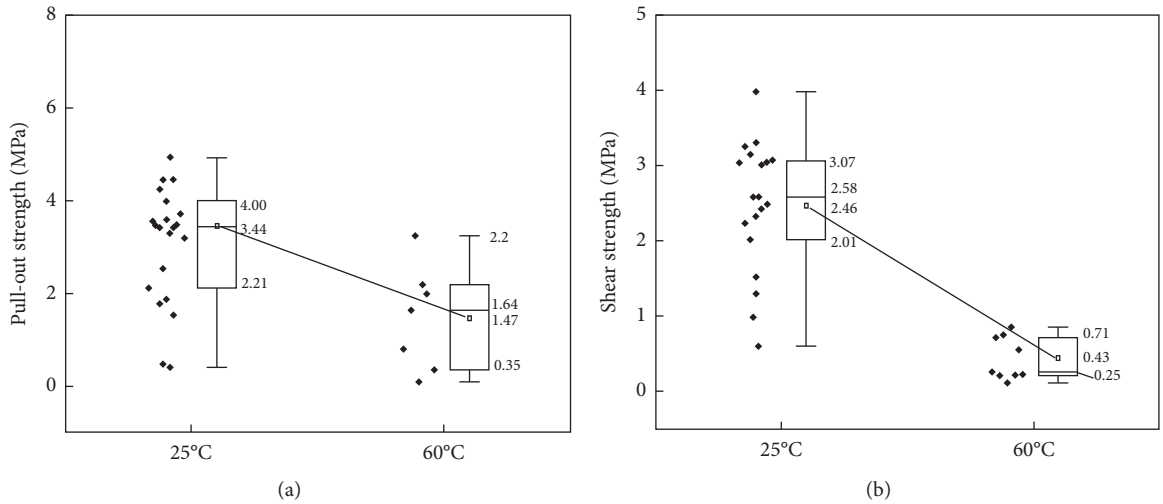

Figure 12: Bonding properties of MMA waterproof adhesive layer: (a) pull-out strength; (b) shear strength.

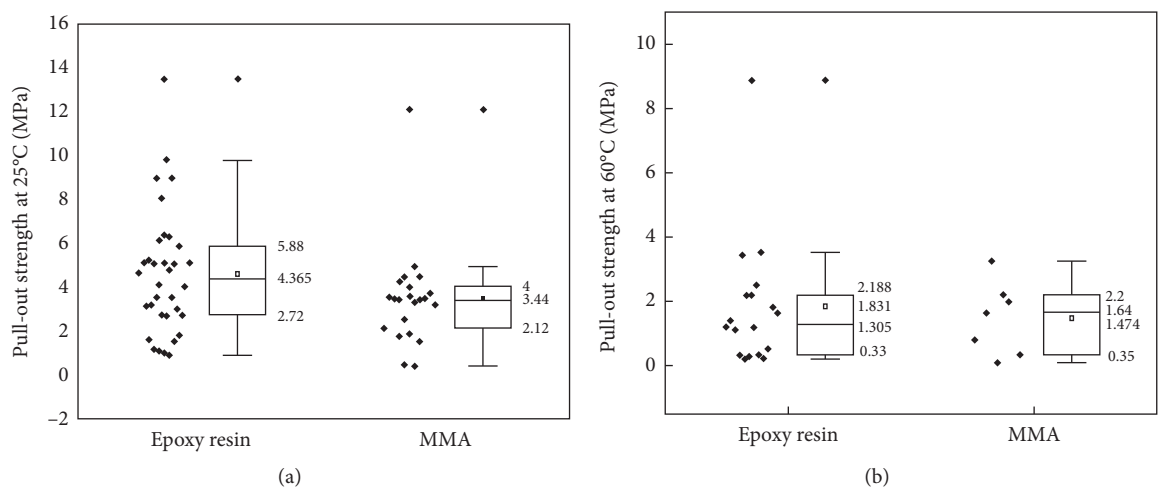

Figure 13: Pull-out strength comparison of resin waterproof adhesive layer: (a) pull-out strength at 25°C; (b) pull-out strength at 60°C.

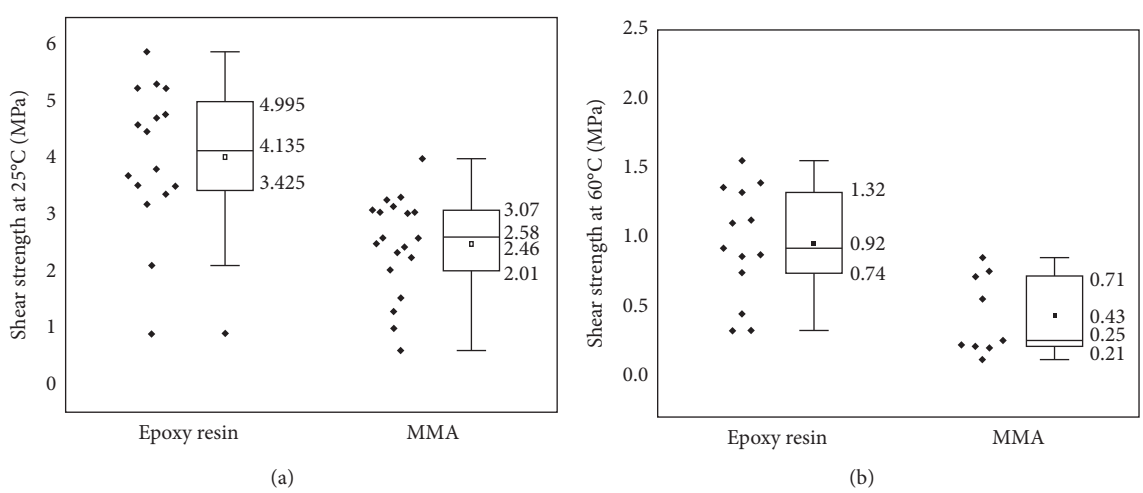

Figure 14: Shear strength comparison of resin-based waterproof adhesive layer: (a) shear strength at 25°C; (b) shear strength at 60°C.

Table 2: Key performance indicators recommendation of resin waterproof adhesive layer.

Test items	Pull-out strength (MPa)	Shear strength (MPa)	Tensile strength (MPa)	Elongation at break (%)	Low temperature flexibility	Impermeability
Technical requirement	≥5.0	≥3.0	≥6.0	≥100	−20°C, No crack	0.3 MPa, 24 h impermeable
Test method	JTG/T 3364-02-2019			GB/T 16777-2008		

epoxy resin waterproof adhesive layer has a large data dispersion, the box is significantly higher than the MMA, and the overall effect is still better than the MMA, showing good shear resistance.

When the temperature rises to 60°C, the shear strength of the two waterproof adhesive layers also decreases significantly, which is the same as the pull-out strength; among them, the decrease of MMA waterproof adhesive layer is greater than that of epoxy resin. At 60°C, from the average value and the 50% data distribution range of the two resin type waterproof adhesive layer materials, it can be seen that the shear resistance of the epoxy resin type waterproof adhesive layer material is better than that of the MMA. By comparing the Iqr values of the two types of resin type waterproof adhesive layer materials, it can be seen that the data dispersion of epoxy resin waterproof adhesive layer materials is greater than that of MMA. However, the box of epoxy resin type waterproof adhesive layer material is significantly higher than that of MMA type, and even if its dispersion is larger, it still shows good high temperature shear resistance.

In summary, the bonding performance of the epoxy resin waterproof adhesive layer is better than that of the MMA. This is because the inherent polar groups of epoxy resin waterproof bonding layer materials such as hydroxyl (–OH), ether bond (–O–), and some beneficial groups in curing agents and additives make a great contribution to the bonding performance. On the other hand, epoxy resin has the advantages of no by-product release, small shrinkage, and small system residual stress, which also contributes to the bonding performance of epoxy resin, so that epoxy resin has high bonding strength. When the temperature increases, the pull-out strength and shear strength of the two resin type waterproof adhesive layers are significantly reduced. This is because the increase of temperature affects the formation of material strength, resulting in the decrease of bonding strength. On the other hand, because the resin type material is a temperature-sensitive material, as the temperature increases, the material gradually softens and its bonding strength decreases. However, the two resin type waterproof adhesive layer materials still exhibit good bonding performance at high temperatures.

Comprehensively considering the relevant specification requirements and research dynamic investigation results of resin type waterproof adhesive layer in China, the key performance evaluation indicators requirements with better application effect are recommended for the epoxy resin type waterproof adhesive layer and MMA waterproof adhesive layer, and the specific indicators and test methods are shown in Table 2.

5.4. Study on Performance Based on Numerical Simulation. In addition to indoor tests to study the working performance of resin waterproof adhesive layer, many researchers in China have also established mechanical analysis models using different finite element programs to study the mechanical properties of waterproof adhesive layer.

Based on the established finite element model of bridge deck pavement system, Liu studied the influence of temperature and load on the shear stress of waterproof adhesive layer and obtained the maximum shear stress of waterproof adhesive layer under the most unfavorable conditions by calculating the shear stress of waterproof adhesive layer under the temperature-load coupling action [54]. Ding studied the influence of different waterproof adhesive layer material modulus on the maximum shear stress of the adhesive layer based on the established finite element model and believed that, under the same load, the smaller the waterproof adhesive layer material modulus is, the smaller the maximum shear stress of the bonding layer is and the less likely shear failure occurs [55]. Qian et al. used nonlinear finite element model to calculate the most unfavorable interlayer shear stress of waterproof adhesive layer under the action of stress field of the whole bridge, heavy load, and even load of sunshine temperature field. Based on the concept of contribution rate, they analyzed the contribution of stress field of the whole bridge, sunshine temperature field, and vehicle load to the interlayer shear stress of bonding layer, respectively [56]. Sun et al., based on the three-dimensional simulation model, found that, under the action of moving load, the maximum shear stress of waterproof adhesive layer appears directly below the wheel, and overload, horizontal force coefficient, vehicle speed, and other factors will affect the maximum shear stress of waterproof adhesive layer [57].

To sum up, researchers in China have conducted some research on the shear stress between waterproof adhesive layers based on finite element numerical simulation. These research results can not only provide mechanical indexes for indoor shear test or pull-out test but also provide theoretical reference for the study of bonding layer materials and adhesive layer structure. In the future, we should continue to carry out in-depth finite element numerical simulation research.

6. Conclusion and Outlook

This paper comprehensively investigated the relevant specifications and research trends of resin type waterproof adhesive layer materials in China, systematically combined the performance evaluation indicators and requirements of

relevant specifications, and defined the key performance evaluation indicators. The basic properties and bonding properties of resin waterproof adhesive layer materials are compared and evaluated. The main research conclusions are as follows:

(1) The resin type waterproof adhesive layer material types mainly include epoxy resin waterproof adhesive layer materials, MMA waterproof adhesive materials, polyurethane waterproof adhesive materials, and water-based epoxy resin waterproof adhesive materials. Among them, epoxy resin and MMA waterproof adhesive material are the most common.

(2) The resin type waterproof bonding layer shall have good impermeability, bonding performance, temperature stability, and construction damage resistance.

(3) Both epoxy resin and MMA waterproof adhesive layer materials have good tensile strength and impermeability, as well as acid, alkali, and salt corrosion resistance. MMA type waterproof adhesive layer material has better flexibility and meets the requirements of use. The flexibility of epoxy resin type waterproof adhesive layer is inferior to that of MMA waterproof adhesive layer.

(4) The bonding performance of epoxy resin waterproof adhesive layer is better than MMA. With the increase of temperature, the bonding strength of the two types of waterproof adhesive layers decreases significantly, but, at high temperature, the two types of resin waterproof adhesive layers have good bonding strength. At 60°C, the average bonding strengths of epoxy resin and MMA waterproof adhesive layers are 1.83 MPa and 1.47 MPa, respectively.

(5) The key performance evaluation indicators of the recommended resin type waterproof adhesive layer material are pull-out strength ≥5.0 MPa, shear strength ≥3.0 MPa, tensile strength ≥6.0 MPa, elongation at break ≥100.0%, low temperature flexibility of −20°C, no crack, and water impermeability of 0.3 MPa, 24 hours. The test method refers to China standards JTG/T 3364-02-2019 and GB/T 16777-2008.

From the perspective of future development trend, the future research direction of resin waterproof adhesive layer can focus on the following points:

(1) Although the resin waterproof adhesive layer material has excellent bonding performance, it has poor flexibility and is prone to cracking and other diseases under low temperature conditions. In the future, appropriate modified materials can be selected to modify it. On the basis of traditional flexibility modification, explore new methods and processes to increase flexibility and develop new multifunctional flexibility increasing agents.

(2) In the future, a set of performance evaluation methods for resin type waterproof adhesive layers suitable for different application scenarios should be established to achieve comprehensive performance evaluation and lay the foundation for future engineering applications.

(3) At present, China's research on the waterproof adhesive system of bridge deck pavement mainly focuses on the performance improvement but less on its durability. Therefore, in the future, we should conduct in-depth research on its durability, further solve the durability problem of the waterproof adhesive system of bridge deck pavement, and improve the service life and quality of bridge deck pavement.

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 there are no conflicts of interest regarding the publication of this paper.

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