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RESEARCH ON PAVEMENT PERFORMANCE OF WATERBORNE EPOXY RESIN-MODIFIED EMULSIFIED ASPHALT BINDERS AND POTHOLE REPAIR MATERIALS

RAZISKAVA KVALITETE PLOČNIKOV IN MATERIALOV ZA POPRAVILO LUKENJ NA CESTAH, IZDELANIH Z DODATKI ASFALTNIH VEZIV, EMULGIRANIMI Z EPOKSIDNIMI SMOLAMI NA VODNI OSNOVI

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Traditional emulsified asphalt pothole repair materials exhibit poor temperature sensitivity, low mechanical properties, and poor water stability. Two-component waterborne epoxy resin (WER) is composed of epoxy emulsion and a curing agent, and has remarkable mechanical properties, adhesion, durability, and environmental friendliness. Two-component waterborne epoxy resin (WER) was used to modify neat emulsified asphalt, enhancing its binder properties and improving the pavement performance of pothole repair materials. The influence of the WER modifier on the pavement performance of emulsified asphalt binder and its mixture was studied. The research showed that the WER emulsion and curing agents could polymerize and produce epoxy resin under emulsified asphalt as the dispersion medium. Fourier transform infrared spectra analysis indicated that the modification of the emulsified asphalt by WER was mainly physical. With an increase in the WER content, the mechanical properties and high-temperature deformation resistance of waterborne epoxy resin-modified emulsified asphalt (WEA) binder were significantly improved while ductility was decreased. The mechanical properties of the WEA mixture had an excellent linear correlation with the water-loss rate. When the WER content exceeded 15 %, the mechanical properties, water stability, high-temperature stability, and anti-stripping performance of the WEA mixture were significantly improved. When the WER content was less than 20 %, the modifier played a reinforcing role in the emulsified asphalt binder, and the low-temperature crack resistance of the WEA mixture gradually improved with the increase in the modifier content. After exceeding the critical content, the WEA mixture gradually exhibited brittleness and hardness, and its low-temperature performance decreased. In summary, it was recommended that the WER modifier content range be 15–20 % for the pothole repair material system.

Keywords: waterborne epoxy resin, emulsified asphalt, binders, mixtures, pothole repair materials

Tradicionalni emulgirani asfalti se uporabljajo za popravilo razpok ter lukenj na cestah in pločnikih. Le-ti so običajno temperaturno zelo občutljivi, imajo slabe mehanske lastnosti in slabo vodno odpornost oziroma stabilnost. Dvo-komponentna epoksidna smola na vodni osnovi (WER; angl.: two-component waterborne epoxy resin) pa je mešanica, sestavljena iz epoksidne emulzije in trdilca oz. sredstva za utrjevanje s pomočjo toplotne obdelave. WER ima odlične mehanske lastnosti, adhezijo ter stabilnost (trajnost) in je okolju prijazen material. Avtorji so v pričujoči raziskavi WER uporabili kot nadomestilo za brezhiben emulgiran asfalt.Tako naj bi bistveno izboljšali vezavo materialov uporabljenih za popravilo lukenj na cestah in pločnikih’ ter tako izboljšali njihovo kvaliteto (dobo trajanja). V tem članku avtorji opisujejo študijo vpliva lastnosti WER modifikatorja na emulgirano asfaltno vezivo za izboljšanje kvalitete pločnikov in njegovih mešanic. Raziskava je pokazala, da WER emulzija in trdilec lahko enostavno polimerizirata in tvorita epoksidno smolo kot sredstvo za nanašanje z disperzijo. Spektralna analiza FTIR (angl.: Fourier transform infrared spectra analysis) je pokazala, da je proces modifikacije emulgiranega asfalta z WER predvsem fizikalne narave. S povečano vsebnostjo WER so se mehanske lastnosti in odpornost proti visoko temperaturni deformaciji epoksidne smole na vodni osnovi modificiranega emulgiranega asfaltnega veziva (WEA) močno izboljšale. Izboljšala se je tudi njegova duktilnost. Mehanske lastnosti WEA mešanice so imele odlično linearno korelacijo (ujemanje) s hitrostjo izgube vode. Ko je vsebnost WER v WEA mešanici presegala 15 % so se vrednosti za mehanske lastnosti, vodno stabilnost, visoko-temperaturno stabilnost ter odpornost proti luščenju oziroma drobljenju (angl.: anti-stripping performance) močno izboljšale. Ko je bila vsebnost WER manjša kot 20 % je modifikator učinkoval kot ojačevalec v emulgiranem asfaltnem vezivu in nizko-temperaturna odpornost WEA mešanice proti nastanku razpok se je izboljševala postopoma z naraščajočo vsebnostjo modifikatorja. Ko pa je bila presežena kritična vrednost je WEA mešanica postopoma postajala vse bolj krhka in trda, zmanjšala se je tudi njena odpornost proti nastajanju razpok pri nizkih temperaturah. V zaključku avtorji priporočajo, da naj je vsebnost WER modifikatorja med 15 % in 20 % v materialih za popravilo lukenj oziroma razpok na cestah in pločnikih.

Ključne besede: epoksidna smola na vodni osnovi, emulgiran asfalt; veziva; mešanice, materiali za popravilo lukenj in razpok na cestah in pločnikih

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1 INTRODUCTION

By the end of 2023, China's road mileage had reached 5.4368 million kilometers, of which maintenance mileage accounted for over 99 %. During the service process of asphalt pavement, continuous aging of the asphalt binder and the erosion of moisture decrease its adhesion performance. Moreover, coupled with the combined effect of vehicle loads and environmental factors, asphalt pavement often suffers from potholes, affecting the pavement's service quality and leading to traffic accidents.[1–3] Pothole repair materials for asphalt pavement can be divided into hot-mix asphalt mixture and cold-mix asphalt mixture (cold-repair material).[4–7] However, due to the limited number of potholes and repair materials required for asphalt pavement, the production and transportation process of factory-mixed hot-asphalt mixture is more complicated, and it has significant limitations as a repair material. The preparation and construction of emulsified asphalt repair materials do not require extensive heating or temperature control and offer advantages such as a simple construction process and low energy consumption, which is more in line with the concept of green transportation development.[8–10] However, traditional emulsified-asphalt repair materials make it difficult to achieve the same level of hot-mix asphalt mixtures in terms of performance. Although the currently used polymer latex (such as styrene butadiene latex, and chloroprene latex) can improve various properties to a certain extent, emulsified-asphalt repair materials still need further improvement in mechanical properties, deformation resistance, water stability, and other aspects of pavement performance.

Waterborne epoxy resin (WER) is a thermosetting polymer material composed of WER emulsion and a waterborne curing agent, and it has excellent mechanical properties, adhesion, durability, and environmental friendliness. WER has good flowability at room temperature using water as the dispersing medium. Due to its excellent performance, WER is widely used in industries such as construction, healthcare, coatings, adhesives, etc.[11–14] The use of WER as a modifier to prepare waterborne-epoxy-resin-modified emulsified asphalt (WEA) has also become a research hotspot in the road maintenance industry.[15] The current research on applying WER to road maintenance by scholars mainly includes two aspects: the WEA binder and WEA mixture. Shi et al.[16] prepared a self-emulsifying WER emulsion by chemically grafting acrylic monomer. It was found that when the grafting temperature was 110 °C, the reaction time was 2 h, and the amount of acrylic monomer was 30 %, the WER emulsion had the best centrifugal stability. The WER modifier had good compatibility with emulsified asphalt and could significantly improve the adhesion performance of emulsified asphalt when the dosage reached 40 %. Xu et al.[17] used waterborne polyurethane (WPU) to modify WEA, thus improving its low-temperature crack-resistance performance. It was found that WPU can significantly improve the long-term creep behavior of composite emulsified asphalt. At a WPU content of 10 %, the relaxation rate of composite emulsified asphalt increased by 1.93 times, and the elongation at break and toughness increased by 300 % and 171 %, respectively. Yang et al.[18] prepared non-ionic WER using the phase inversion method and added it to modified emulsified asphalt. They found that the WER modification process of emulsified asphalt was mainly a physical modification, and the WER modifier could significantly improve the adhesion performance, mechanical properties, and high-temperature stability of emulsified asphalt. He et al.[19] studied the effect of the WER modifier on the performance of emulsified asphalt binders. The results showed that WER could significantly improve emulsified asphalt's mechanical properties and high-temperature elastic recovery performance. Infrared spectroscopy analysis revealed that the modification process was a physical modification. In summary, WER can significantly improve the high-temperature stability, adhesion, and mechanical properties of emulsified asphalt binders. The performance improvement of the WEA binder is related to the dosage of the WER modifier.

In addition, researchers further analyzed the impact of WER on the performance of emulsified asphalt-curing materials. Liu et al.[20] studied the effect of WER on the micro-surfacing mixture performance of emulsified asphalt and found that WER can significantly improve the anti-rutting performance, water stability, and durability of micro-surfacing mixtures. The WEA binder was a high-performance micro-surfacing binder. Han et al.[21,22] applied WER as a binder to micro-surfacing mixtures and found that when the WER modifier content exceeded 12 %, the wear resistance, shear strength, and tensile strength of the mixture were significantly improved. Xu et al.[23] studied the application of WEA mixture for pothole repair and found that the water stability and high-temperature stability of the mixture continuously improved with an increase in the WER modifier content, which also proved the feasibility of preparing pothole repair materials with the WEA binder. Currently, research on waterborne-epoxy-resin-modified emulsified asphalt mainly focuses on the performance of binders and their application in preventive maintenance, such as micro-surfacing. There is limited research on the WEA mixture for repairing potholes in asphalt pavement. A systematic study on the influence of WER on the performance of emulsified-asphalt binder and its repair materials is required.

This work was based on the performance requirements for pothole repair materials for asphalt pavement and we studied the influence of WER modifier on the macroscopic and microscopic properties of emulsified-asphalt binder and its mixture, providing a reference for the preparation and performance evaluation of emulsified-asphalt pothole-repair materials.

Table 1: Basic properties of emulsified asphalt

Demulsification speed	Angler viscosity$_{25}$	Solid content (%)	Penetration (25 °C, 0.1 mm)	Ductility (15 °C, cm)	Softening point (°C)	Storage stability (%)
slow setting	8	58.6	82	=100	46.3	0.2

Table 2: Basic properties of WER emulsion

Appearance	Solid content (%)	Epoxy value	pH	Average particle size (μm)
milky white fluid	50	0.23	7.5	2.0

Table 3: Basic properties of the curing agent

Appearance	Solid content (%)	Active hydrogen equivalent	pH	Specific gravity
light yellow uniform fluid	50.2	210	8.9	1.04

2 EXPERIMENTAL PART

2.1 Raw materials

The emulsified asphalt used in this research was a cationic slow-cracking type provided by Shanghai Wanzhao Fine Chemical Co., Ltd. Its basic properties are shown in **Table 1**. The WER modifier was composed of WER emulsion and a water-soluble curing agent, which were prepared in the laboratory. The WER emulsion was non-ionic, and the water-soluble curing agent was a modified amine curing agent.[18] Their basic properties are shown in **Tables 2** and **3**. The mineral aggregates used in this paper were composed of three grades of aggregates and mineral powder: 0–5 mm, 5–10 mm, and 10–15 mm, all of which were made of limestone. AC-13 was used as the repair material gradation, as shown in **Figure 1**.

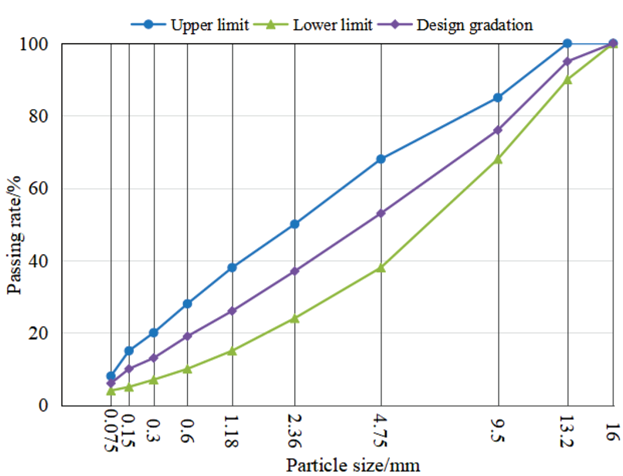

Figure 1: AC-13 gradation

2.2 Preparation

2.2. Preparation of the WEA binder

First, the WER emulsion and curing agent were weighed in accordance with the mass ratio of the $m_{WER\ emulsion}$: $m_{curing\ agent}$ = 2:1 and manually stirred until they were uniform. Secondly, we weighed a certain amount of emulsified asphalt in a beaker and added the above WER modifier to the emulsified asphalt in proportions of (5, 10, 15, 20, and 25) % (calculated as the ratio of WER emulsion and curing agent to the total system mass). We turned on mechanical stirring, adjusting the speed to 300–500 min^{-1}. It was stirred for 5 min to obtain the WEA mixture. Finally, the WEA mixture was put into the corresponding test mold and cured at room temperature for 15 d. After the water-based epoxy resin was cured and most of the moisture evaporated, it was placed in an 80 °C oven for 12 h to obtain the WEA binder. In addition, the WEA binder with a 0 % modifier content was still prepared with the evaporation-residue method for the relevant specimens.

2.3 Preparation of WEA mixtures

The preparation of the WEA mixture used in this study includes the following steps: (1) In accordance with $m_{WER\ emulsion}$: $m_{curing\ agent}$ = 2:1, the WER emulsion and curing agent were mixed evenly to obtain the WER modifier; (2) Through the internal blending method (i.e., the proportion of WER modifier in the system), different WER modifiers were added to emulsified asphalt and mixed evenly for use; (3) Dried and cooled aggregates were poured into a mixing pot in accordance with the ratio and mixed evenly. The external water was adjusted according to a total water consumption of 5 %. The optimal binder content of 9 % was added to the WEA mixture and mixed for 90 seconds; (4) A specific quality WEA mixture was poured into the mold to prepare Marshall specimens and rutting specimens. Among them, Marshall specimens were compacted on both sides 50 times; (5) Each specimen was placed in an 80 °C oven for 32 h to cure, after which the Marshall specimen underwent a second double-sided compaction of 25 blows on each side. The specimens were cooled at room temperature for at least 12 h before demolding and, finally, WEA pothole repair materials with waterborne epoxy resin contents of (0, 5, 10, 15, 20 and 25) % were obtained.

2.3 Methods

2.4.1 Chemical structure

An ALPHA II Fourier transform infrared spectrometer produced by Bruker was used to analyze the chemical structure of the WEA binder with different modifier contents. The Fourier transform infrared spectrometer performed 60 scans within 4000 cm^{-1} to 600 cm^{-1} to obtain infrared spectral data.

2.4.2 Mechanical properties

An ETM204C universal testing machine produced by Shenzhen Wance Instrument was used to analyze the mechanical strength of the WEA binder. According to Section 2.2, the WEA mixture was prepared using different processes and coated in the middle of the pull-off mold with a 0.2 g/cm^2 coating. The pull-off test mold consisted of drill core samples from the AC-13 hot-asphalt mixture and steel molds bonded together (diameter Φ = 50 mm), as shown in **Figure 2**. The stretching rate was controlled at 2.0 mm/min, and the testing temperature was room temperature. The maximum destructive strength was recorded. Each WEA binder contained five parallel specimens, and the average value was used to determine the pull-off strength.

2.4.3. Three main index tests

Considering that WER forms a network structure in emulsified asphalt after solidification, and that the traditional method of evaporating residue from emulsified asphalt destroys the original WER structure, the test results cannot reflect the actual performance of the WEA binder. Therefore, this investigation adopted a layered pouring method to prepare penetration, softening points, and ductility samples. Firstly, a WEA mixture with 5–25 % content was prepared according to method A. The WEA mixture was placed into the corresponding mold in three stages at room temperature, with a pouring interval of 15 d. Then, samples were placed in an 80 °C oven for 12 h. In addition, the binder with a 0 % modifier content was still prepared using the evaporation residue method. Finally, the WEA binder's penetration, softening point, and ductility were tested in accordance with the *Test Specification for Asphalt and Asphalt Mixtures in Highway Engineering* (JTG E20-2011).

2.4.4 High-temperature stability

Referring to the ASTM D7175 specification, a DHR-2 dynamic shear rheometer (a 25-mm parallel plate) produced by the TA company was used to test the rheological properties of the WEA binder. The temperature scanning mode was used to test the rheological properties of the WEA binder with different modifier contents in a temperature range of 52–82 °C. The temperature interval was 6 °C. The strain value was 0.1 %, and the angular frequency was 10 rad/s. The high-temperature stability of the WEA binder was evaluated.

2.5 WEA mixture properties test

In accordance with the *Test Specification for Asphalt and Asphalt Mixtures in Highway Engineering* (JTG E20-2011), the mechanical properties, water stability, high-temperature deformation resistance, low-temperature crack resistance, and anti-stripping performance of the WEA mixture were tested to evaluate various aspects of pavement performance of pothole repair materials comprehensively.

This research studied the microstructure and macroscopic properties of the WEA binder and its mixtures with different modifier contents. The flowchart is shown in **Figure 2**.

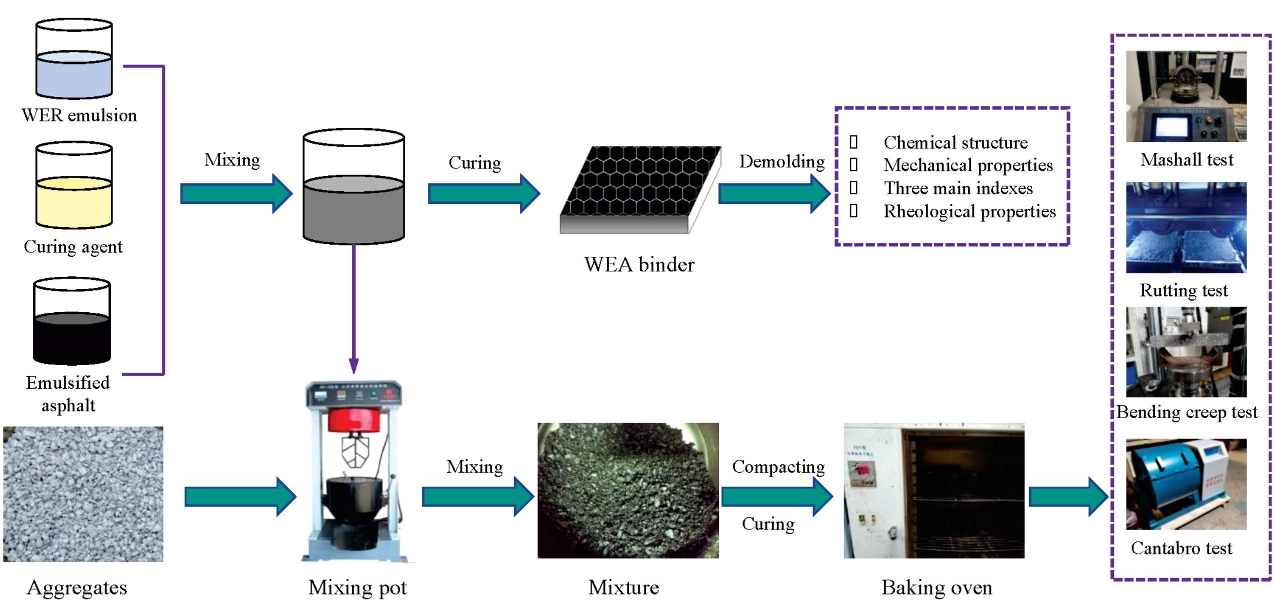

Figure 2: Flow chart

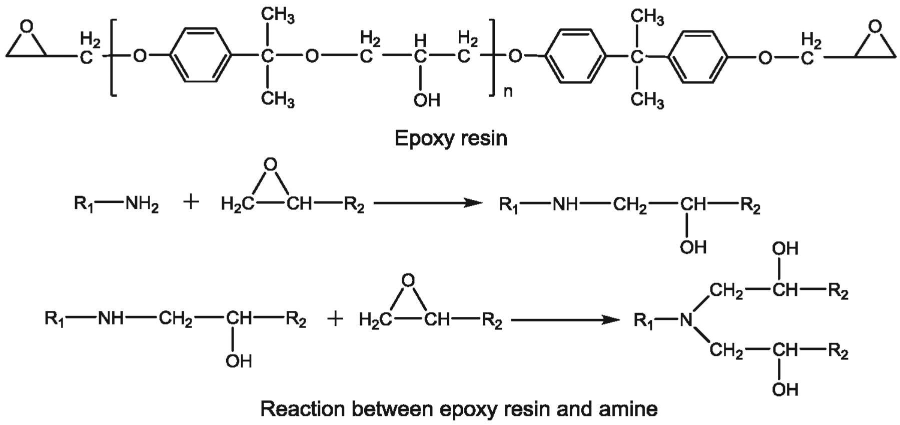

Figure 3: Reaction process of WER emulsion and curing agent

3 RESULTS AND DISCUSSION

3.1 WEA binder properties

3.1.1 Chemical structure

After the WER modifier is added to emulsified asphalt, the WER emulsion and curing agent polymerize in the emulsified asphalt as the dispersion medium, and the modifier gradually polymerizes from small molecules to large molecules. Finally, a continuous network structure is formed in emulsified asphalt. Fourier transform infrared spectroscopy was used to analyze the chemical structure of the emulsified-asphalt residue, cured WER modifier, and WEA binder. The results are shown in **Figures 3** and **4**, and **Table 4**.

Table 4: Main infrared absorption peaks

Peaks/cm^{-1}	Functional groups
3400, 3346	Stretching vibrations of -OH and -NH
2851-2963	Symmetric and antisymmetric stretching vibrations of C-H bonds in alkyl groups
1739	Stretching vibration of C=O
1607, 1597, 1508	Stretching vibration of benzene ring skeleton
1456	In-plane stretching vibration of C-H
1376	Symmetric angular vibration of $-CH_3$
1034-1298	In-plane stretching vibrations of C-O bonds at different positions
721-874	Out-of-plane rocking vibration of C–H on the benzene ring

The primary raw material of WER emulsion in this research is bisphenol A epoxy resin, which reacts with an amine curing agent to form a hydroxyl compound and cross-linking structure. The reaction process is shown in **Figure 3**. **Figure 4a** shows that the emulsified asphalt residue is still mainly composed of hydrocarbon compounds, and the infrared spectra mainly include absorption peaks of alkyl and aromatic hydrocarbons. In addition, the absorption peak of emulsified asphalt residue also includes some peaks of other derivatives, such as a strong absorption peak near 3400 cm^{-1}, attributed to the stretching vibration of N-H. The in-plane stretching vibration peaks of C-O correspond to 1087 cm^{-1} and 1038 cm^{-1}. This is because the emulsified asphalt used in

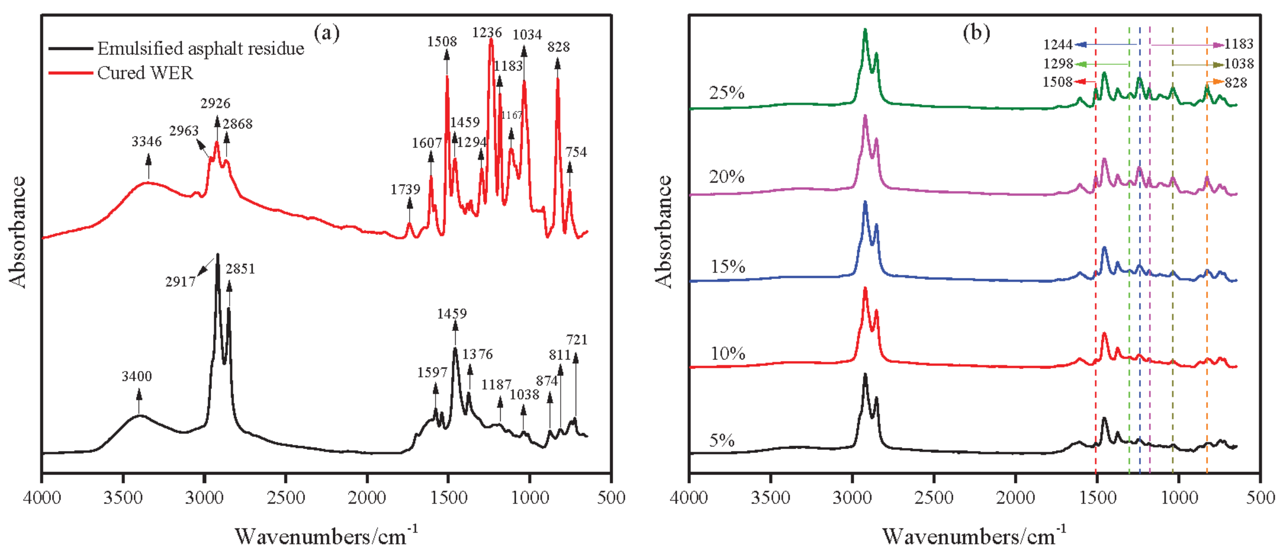

Figure 4: Infrared spectra: a) emulsified asphalt and cured WER, b) WEA binders

this study was an amine cationic emulsifier, and these peaks were characteristic of the emulsifier. It can also be seen From **Figure 4a** that the cured WER modifier has a strong absorption peak at 3346 cm^{-1}, attributed to the chemical reaction between the epoxy group and the amine group, generating a large amount of hydroxyl compounds. The cured WER modifier's infrared absorption peak is consistent with the results from **Figure 3**. It can also be seen from the cured WER infrared spectra that there is basically no epoxy-group absorption peak at around 910 cm^{-1}, indicating that the group has completely reacted. From **Figure 4b**, it can be seen that with the increase in the WER modifier content, the absorption peaks of the WER binder are significantly enhanced at 1508 cm^{-1}, 1298 cm^{-1}, 1244 cm^{-1}, 1183 cm^{-1}, 1038 cm^{-1}, and 828 cm^{-1}. These are absorption peaks of epoxy resin, also proving that the WER emulsion and curing agent can react in emulsified asphalt to form epoxy resin. It can also be seen from **Figure 4b** that the infrared absorption peak of the WEA binder is the superposition of the emulsified-asphalt residue and cured WER modifier, and no new absorption peak appears. Therefore, the modification of emulsified asphalt by WER was mainly a physical modification.

3.1.2 Mechanical properties

The adhesion performance between the emulsified asphalt binder and aggregate directly affects the mechanical properties of the pothole repair materials. In order to better simulate the adhesion performance between the WEA binder and aggregate, this study used drill core samples from the hot-asphalt mixture as the bonding surface of the WEA binder, and the pull-off test results are shown in **Figure 5**.

With the increase in the modifier content, the mechanical properties of WEA binder gradually improve. Without modification, the mechanical strength of the 0 % WEA binder (emulsified-asphalt residue) is relatively low, with a pull-off strength of 0.11 MPa. The pull-off strength of the WEA binder with (5, 10, 15, 20, and 25) % modifier content is (0.23, 0.35, 0.62, 0.83, and 0.95) MPa, respectively, showing increases by (109, 218, 464, 655, and 764) % compared to the 0 % modifier content. From the growth rate curve, it can be seen that when the modifier content is below 15 %, the mechanical strength improvement of the binder is not significant. When the content of the modifier is 15 % or more, the pull-off strength of the binder increases rapidly. The reason is that with a low modifier content, WER exists as a dispersed phase in emulsified asphalt, having a relatively small impact on the mechanical properties of the binder.[24] When the modifier content exceeds a critical value, WER can form a continuous network structure in emulsified asphalt, and the modifiers' contribution to the entire system's mechanical properties is significantly improved. The pull-off strength of the WEA binder is also significantly enhanced.[25]

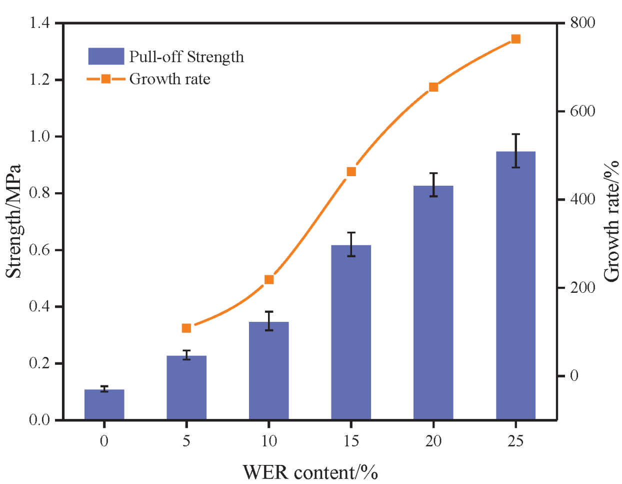

Figure 5: Pull-off test results

3.1.3 Three main indexes

Penetration, ductility, and softening point are three main indexes commonly used to test asphalt materials' consistency, malleability, and high-temperature performance. During this study, we tested the three main indexes of WEA binders, and the results are shown in **Table 5**.

Table 5: Three main indexes of WEA binders

Properties	WER content/%					
	0	5	10	15	20	25
Penetration (25 °C, 0.1 mm)	82	39	26	9	5	3
Ductility (25 °C, cm)	≥100	18.2	6.3	1.7	-	-
Softening point (°C)	46.3	68	>100	>100	>100	>100

With the increase in the WER content, the penetration and ductility of the WEA binder significantly decrease. After the modifier content exceeds 15 %, the penetration value is less than 1 mm. This is because WER gradually forms a dense and high-strength continuous network structure, improving the WEA binder's hardness. Moreover, after the modifier content exceeds 15 %, the ductility of the WEA binder is almost completely lost, and the sample exhibits brittle fracture during the stretching process. The reason is that asphalt gradually transforms from a continuous phase to a discontinuous phase, which hinders the slip between asphalt molecules. With the modifier content increase, the WEA binder's softening point significantly increases. When the modifier content exceeds 10 %, the temperature of the softening point is greater than 100 °C. WEA binder gradually changes from thermoplastic to thermosetting, and its high-temperature performance becomes excellent.

3.1.3 High-temperature stability

In summer, the surface temperature of asphalt pavement often exceeds 65 °C, and the asphalt material will

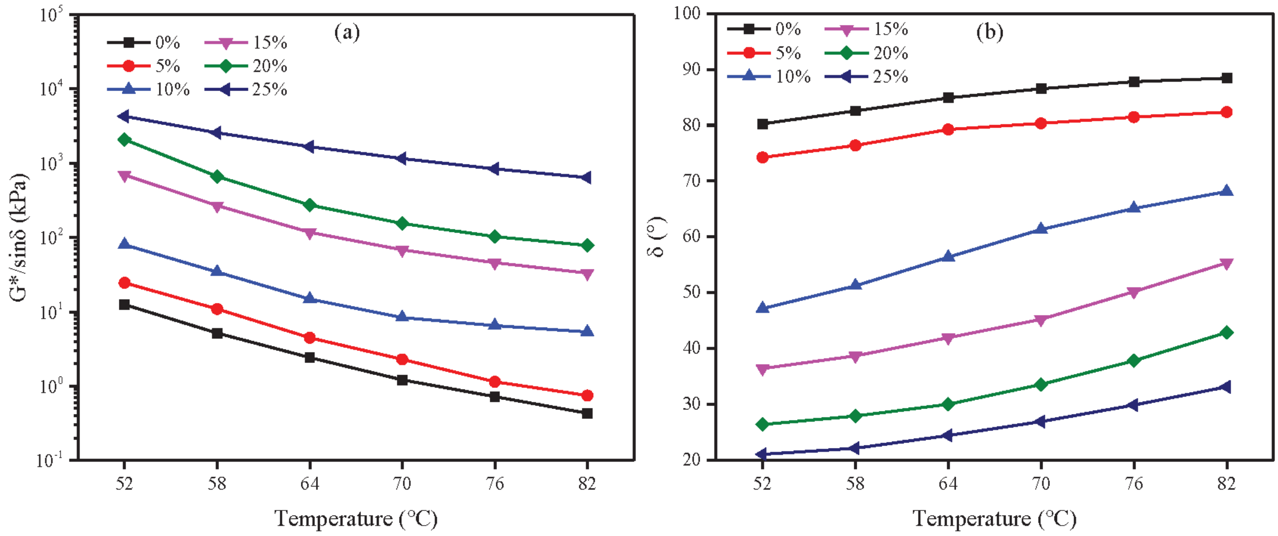

Figure 6: High-temperature stability: (a) rutting factor, (b) phase angle

gradually change from an elastic state to a flowing state, resulting in a significant decrease in its deformation resistance. High-temperature stability is also one of the main factors affecting the long-term performance of emulsified-asphalt repair materials. The temperature sweep mode of the dynamic shear rheometer was used to analyze the temperature dependence of the WEA binder with 0–25 % modifier contents to evaluate its high-temperature deformation resistance. The angular frequency was 10 rad/s, with a temperature range of 52–88 °C (a temperature interval of 6 °C) and a strain of 0.1 %. The experimental results are shown in **Figure 6**.

It can be seen from **Figure 6a** that the rutting factors (G^*/sin δ) of the six WEA binders gradually decrease with an increase in the temperature. At the same temperature, the higher the amount of the modifier added, the greater is the rutting factor of the binder and the better is its deformation resistance. At a low modifier content, WER can only be distributed as a dispersed phase in emulsified asphalt, and its modification effect on emulsified asphalt is poor. The binder reflects the characteristics of asphalt materials.[26] For example, the rutting factor curves for the 5-% and 0-% WEA binders are relatively close, and the rutting factor increase is insignificant. As the content of the modifier further increases, the WER in the binder gradually transforms from a dispersed phase to a continuous phase, which can form a continuous skeleton structure in emulsified asphalt. The WEA binder gradually exhibits the high elasticity of epoxy resin materials, and its deformation resistance is significantly improved at high temperatures.[27] For example, when the modified content exceeds 15 %, the rutting factor of the binder increases by two orders of magnitude compared to that of 0 %. The same result can also be obtained from **Figure 6b**. When the modifier content is less than 5 %, the phase angle of the WEA binder exceeds 70°, exhibiting the characteristics of a viscous material. WER has a poor modification effect on

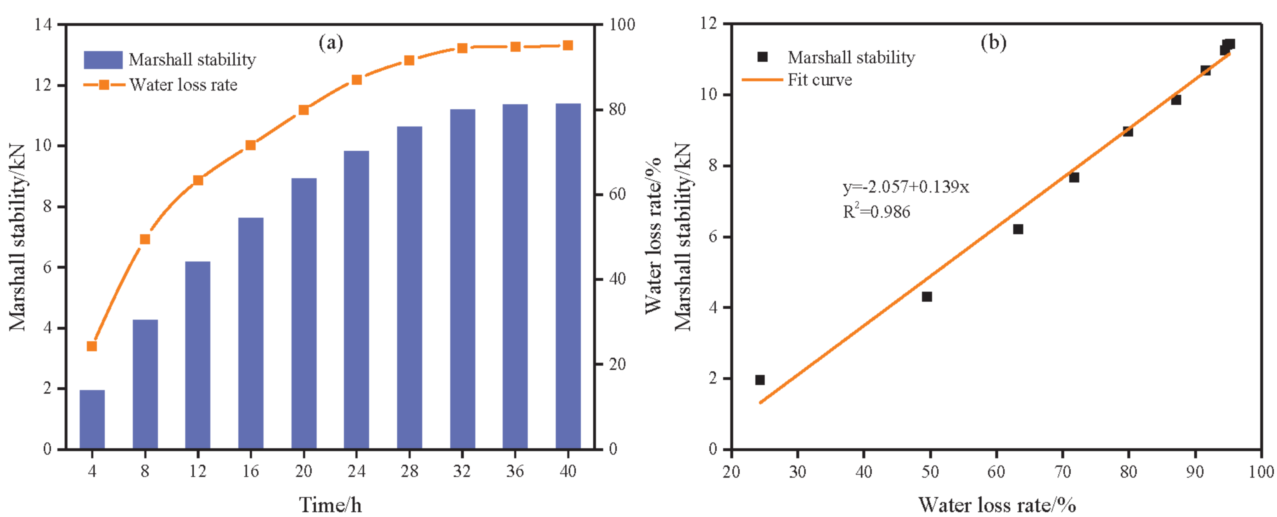

Figure 7: Variation in the mechanical properties of the WEA mixture with the water loss rate

emulsified asphalt. However, with the increase in the modifier content, the amplitude of the phase angle change in the binder decreases, and the high-temperature resistance stability improves.

3.2 WEA mixture properties

3.2.1 Growth law of mechanical properties

In the early stage of emulsified asphalt mixture construction, as the emulsified asphalt breaks, the asphalt particles coagulate, and they can only exhibit bearing capacity after the moisture has evaporated to a certain extent. Pothole repair materials for asphalt pavement, being surface materials, directly interact with vehicle loads and must have specific mechanical properties to maintain their overall stability during service.[12] In our study, we considered the WEA mixture with a 20 % modifier content as the research object and we analyzed the relationship between the water loss rate and Marshall stability of WEA repair materials. The curing temperature was 80 °C. The results are shown in **Figure 7**.

It can be seen from **Figure 7a** that, as the curing time increases, the water loss rate of the WEA mixture first gradually increases and then remains stable. After 32 h, the water loss rate is 94.5 %, remaining unchanged. Generally, the moisture in emulsified asphalt mixtures cannot wholly evaporate, partly because some of the moisture interacts with the polar components in the asphalt. On the other hand, water can also interact with mineral aggregates and disperse in the crystal structure of the aggregates in the form of bound water. **Figure 7a** shows that the change in the mechanical properties of the WEA mixture follows the same trend as the change in the water loss rate. After 32 h, the WEA mixture's Marshall stability remains unchanged. From **Figure 7b**, it can be seen that there is a significant linear positive correlation between the Marshall stability of the WEA mixture and the water loss rate. The higher the water loss rate, the greater is the Marshall stability. The reason is that the formation of the mechanical strength of emulsified asphalt mixture is divided into two stages: During the first stage, the binder undergoes emulsion breaking, and small asphalt particles gather to form large asphalt particles that adhere to the surface of the aggregate, while water is also separated from the emulsified asphalt; During the second stage, water gradually evaporates under the influence of external environment (temperature and wind), and large asphalt particles coalesce and form a whole. Aggregates are bonded together by asphalt, ultimately forming the mechanical strength of the mixture.[28,29] Therefore, the water loss rate directly affects the mechanical properties of the WEA binder.

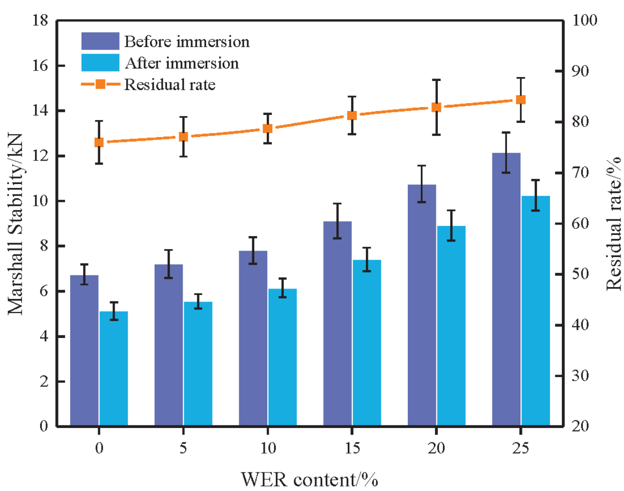

Figure 8: Water stability of WEA mixtures

3.2.2 Water stability

The repair material for asphalt pavement potholes must have good water stability to prevent new potholes from forming at the original potholes due to environmental and load factors. This study used the immersion Marshall test to test the water stability of the WEA mixtures with different modifier contents, and the results are shown in **Figure 8**.

As the WER content increases, the water stability of the WER mixture gradually improves. The Marshall stability values of the WEA mixtures with (0, 5, 10, 15, 20, and 25) % modifier content after immersion are (5.13, 5.56, 6.15, 7.41, 8.92, and 10.25) kN, respectively. Their residual stability is (76, 77.1, 78.7, 81.3, 82.9, and 84.4) %. The combined effects of emulsifiers and asphalt properties mainly influence the water stability of emulsified-asphalt cold-repair materials. Due to certain emulsifiers in the residue of emulsified asphalt, the emulsified asphalt mixture interacts closely with water during immersion. The hot water bath accelerates the dissolution of some emulsifiers in water, promoting the adherence of micro-pores in the binder to the aggregate surface. Under hot-water conditions, water directly penetrates the asphalt aggregate interface.[30,31] The spontaneous thermodynamic process of water entering the adhesive interface further transforms the original asphalt-aggregate interface into an asphalt-water and aggregate-water interface. At the macro level, it manifests as asphalt peeling off the surface of the aggregate, causing water damage to the mixture. This is also the main reason for traditional emulsified asphalt mixtures' lower water stability than that of hot-mix asphalt mixtures. From **Figure 8**, it can be seen that WER can improve the water stability of the WEA mixture. The reason is that the WER modifier is a polar material that can generate stronger adsorption with charged ions on the surface of aggregates. It is more difficult for water to penetrate the interface layer, thereby improving the adhesion between asphalt and aggregates.

3.2.3 High-temperature deformation resistance

Pothole repair materials for asphalt pavement should have excellent deformation resistance. Especially under high-temperature conditions, it is necessary to ensure that they do not produce more significant deformation under load to maintain the smoothness of the road sur-

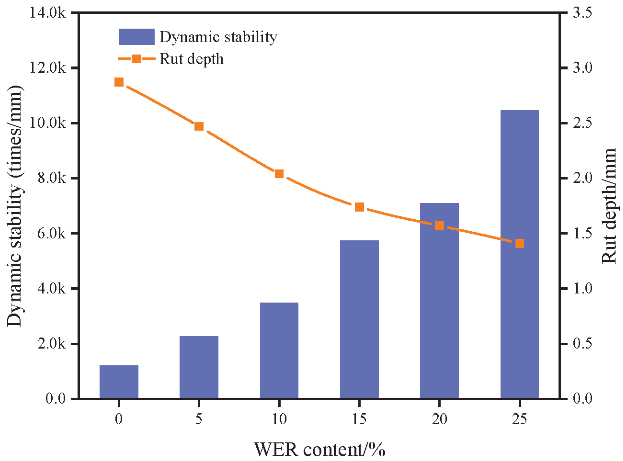

Figure 9: High-temperature deformation resistance of WEA mixtures

face. This study evaluated the high-temperature stability of WEA mixture with different modifier contents with rutting tests. The results are shown in **Figure 9**.

Generally, the high-temperature deformation resistance of emulsified asphalt mixtures is related to the aggregate gradation and binder. The binder is the main influencing factor when the gradation is consistent. **Figure 9** shows that the high-temperature stability of WEA mixtures is significantly improved with an increase in the waterborne epoxy-resin content. The dynamic stability of the WEA mixture with (0, 5, 10, 15, 20, and 25) % modifier contents is (1246, 2315, 3521, 5781, 7129, and 10495) times/mm, respectively. The 60-minute rut depth is (2.87, 2.47, 2.04, 1.74, 1.57, and 1.41) mm, respectively. The high-temperature deformation resistance of the WEA mixture with the 0-% modifier content is poor and cannot meet the performance requirements for asphalt pavement. With the addition of the WER modifier, the dynamic stability of the WEA mixture significantly increases, especially when the content exceeds 10 %. For example, the dynamic stability of the WEA mixture with the 15-% modifier content is about 5 times that of the mixture with the 0-% modifier content, reaching the performance level of the hot-mix asphalt mixture.[18,19] The reason is that the WER modifier can form a specific strength and continuous spatial network structure in emulsified asphalt when its content is 15 % or higher. It can resist the load under high-temperature conditions without significant deformation, significantly improving the high-temperature stability of the mixture.

3.2.4 Low-temperature crack resistance

Emulsified-asphalt pothole-repair materials undergo significant temperature changes during service and should also exhibit a certain level of low-temperature crack resistance.[32–34] This research evaluated the low-temperature stability of WEA mixtures with different modifier contents through low-temperature bending tests. Due to the lower mechanical strength of the mixture with the 0-% and 5-% content, they are prone to breakage during cutting. We only studied the low-temperature performance (–10 °C) of the mixtures with 10–25 % dosages, as shown in **Figure 10**.

With an increase in the waterborne epoxy-resin content, the flexural strength and maximum bending strain first increase and then decrease, reaching their maximum with the 20-% modifier content. The flexural strength of the WEA mixtures with modifier contents of (10, 15, 20, and 25) % is (5.81, 6.79, 7.62, and 6.82) MPa, respectively, and the maximum bending strain is (2488, 2734, 2861, and 2783) $\mu\varepsilon$. The main reason for the above results is that with the increase in the content of waterborne epoxy resin, it gradually forms a specific spatial network structure in emulsified asphalt, which can play a reinforcing role. Therefore, the flexural strength and bending strain gradually increase. When the content of waterborne epoxy resin increases to a critical value, it can form a denser network structure in emulsified asphalt, and the binder system gradually transforms from the performance of emulsified asphalt to that of epoxy resin, exhibiting brittleness and hardness. Therefore, the low-temperature crack resistance gradually de-

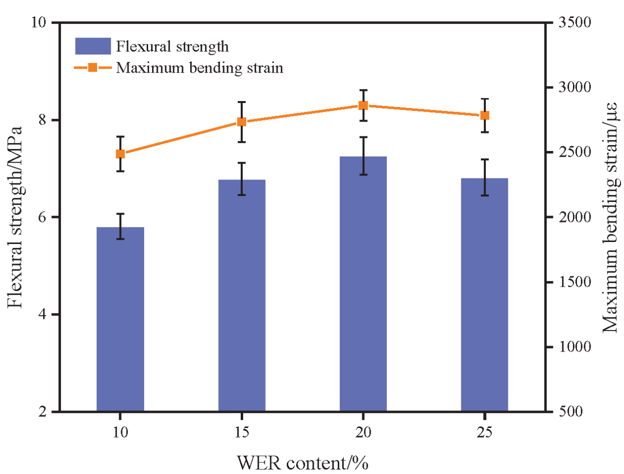

Figure 10: Low-temperature crack resistance of WEA mixtures

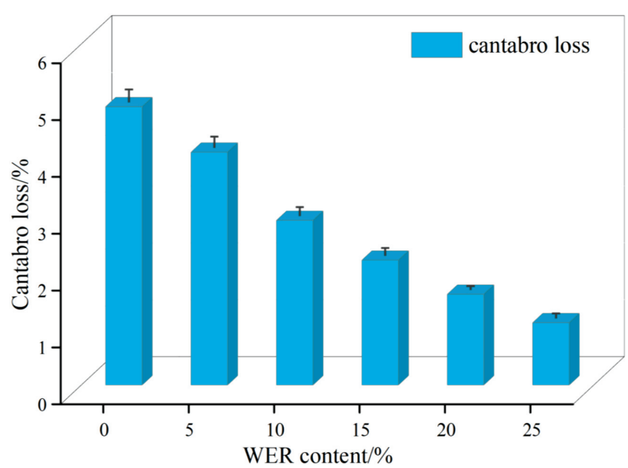

Figure 11: Anti-stripping performance of WEA mixtures

creases.[35] According to the aforementioned studies, the WEA content should be maintained between 15 % and 20 % to ensure good low-temperature performance.

3.2.5 Anti-stripping performance

Aggregate stripping has always been a common distress arising from the use of traditional emulsified-asphalt repair materials. The reason is that a road surface repaired with traditional cold-repair materials is slightly higher than the original road surface, and it will be more susceptible to the impact of vehicle tires. In addition, the insufficient adhesion of emulsified asphalt ultimately leads to stripping of the repair material.[36,37] The Cantabro test was used to analyze the anti-stripping performance of WEA mixtures with different modifier contents, and the results are shown in **Figure 11**.

With an increase in the WER content, the anti-stripping performance of WEA mixtures is significantly improved. The Cantabro loss rates of WEA mixtures with (0, 5, 10, 15, 20, and 25) % modifier contents are (4.9, 4.1, 2.9, 2.2, 1.6, and 1.1) %, respectively. When the modifier dosage is low, the improvement in the anti-stripping performance is not significant. For example, when the content is 5 %, the Cantabro loss is only reduced by 0.8 % compared to the 0-% content. With further increase in the WER content, the modifier gradually forms a continuous network structure in the emulsified asphalt, and the cohesion of the WER binder is significantly improved.

Polar materials exhibit an uneven charge distribution within molecules. In chemistry, polarity typically describes the formation of partial positive and negative charges caused by differences in the electronegativity within a molecule. As shown in **Figure 3**, the molecular structure of epoxy resin contains a large number of oxygen atoms with strong electronegativity, causing the electron cloud of carbon or hydrogen atoms with weak electronegativity to shift towards oxygen atoms. Ultimately, oxygen atoms become negatively charged, while carbon or hydrogen atoms become positively charged. Mineral aggregates are mostly composed of inorganic compounds with a certain charge on their surface. Therefore, the interaction force between polar materials and aggregate surfaces is stronger. Moreover, due to the strong polarity of WER, it has a strong adsorption effect on the surface of the aggregate, which can enhance the bonding strength of the binder and ultimately significantly improve the anti-stripping performance of the WER mixture[18,19]. Compared to the 0-% dosage, anti-stripping performance is improved by approximately 67 % and 78 % when the WER dosage is 20 % and 25 %, respectively. Therefore, waterborne epoxy resin can improve the anti-stripping performance of modified emulsified asphalt.

4 CONCLUSIONS AND FUTURE RESEARCH

(1) Infrared spectroscopy indicates that the modification mechanism of WER on emulsified asphalt is mainly physical. After the modifier content exceeded 15 %, the tensile strength and high-temperature deformation resistance of the binder were significantly improved, but the ductility decreased.

(2) As the curing time increased, the mechanical properties of the WEA mixture were gradually improved. There was a significant linear positive correlation between the Marshall stability and the water loss rate of WEA mixtures. After 32 h, the WEA mixture's Marshall stability remained unchanged.

(3) When the WER content exceeded 15 %, the mechanical properties, water stability, high-temperature stability, and anti-stripping performance of the WEA repair material were significantly improved.

(4) The bending creep test showed that when the WER content was less than 20 %, the low-temperature crack resistance of the WEA mixture improved with the modifier content. After exceeding this critical value, the low-temperature stability of the WEA mixture decreased.

Overall, WER modifiers can improve the mechanical properties, adhesion, and high-temperature stability of WEA binders and their mixtures. However, when the critical dosage is exceeded, the low-temperature performance is decreased. In further research, it is worth investigating how to improve the strength formation rate of WEA pit repair materials to meet the demand for rapid traffic reopening. The underlying reasons for the decline in the low-temperature performance of water-based epoxy resin-modified emulsified asphalt mixtures when the content of water-based epoxy resin exceeds a critical value need to be explored. The use of composite modification to enhance the low-temperature performance of WEA mixtures will also be studied.

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