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EPOXY-RESIN ADHESIVE FOR SEAM FILLING AND POTHOLE REPAIR IN PAVEMENT MAINTENANCE

UPORABA VEZIVA NA OSNOVI EPOKSI SMOLE ZA ZAPOLNJEVANJE LUKENJ PRI VZDRŽEVANJU PLOČNIKOV

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Aiming at the problems of asphalt pavement crack sealing and pothole repair materials, an epoxy-resin adhesive with high forming strength, good toughness and room-temperature curing was prepared. In addition to being used as a road filling sealant, the adhesive can also be used for preparing a cold patching mixture for pits. The properties of the epoxy-resin adhesive, the construction performance and road performance of the pouring sealant and cold patch were studied. The results showed that the early strength of the epoxy-resin adhesive was fast and high, the curing volume shrinkage was small, the low-temperature characteristics and tensile properties were good, and the toughness was excellent. As a pouring sealant, the epoxy-resin adhesive had excellent low-temperature bending resistance. The cold patching mixture based on the adhesive exhibited strong cohesiveness, good low-temperature crack resistance, and excellent high-temperature stability and water stability. This adhesive expands the application of epoxy resin in repairing cracks and pits of asphalt pavements, and is of great significance in promoting the development of the asphalt pavement maintenance technology.

Keywords: pavement, epoxy resin, adhesive, construction

V članku je opisana priprava in lastnosti veziva na osnovi epoksidne smole za reševanje problema tesnenja razpok in krpanja lukenj na asfaltiranih pločnikih. Avtorji so pripravili vezivo z veliko trdnostjo, dobro žilavostjo po oblikovanju in utrjevanju pri sobni temperaturi, ki ni uporabno samo kot polnilno tesnilo temveč se lahko uporabi tudi kot hladna mešanica za krpanje jamic oziroma lukenj. Preučevali so lastnosti izdelane epoksidne smole in njeno odpornost na obremenitve. Rezultati so pokazali, da se epoksidna smola hitro strdi in že zelo hitro ima dobro trdnost ter tudi majhen skrček pri nizkih temperaturah. Izdelan material ima dobre natezne lastnosti in odlično žilavost ter kot polnilo odlično odpornost proti upogibanju pri nizkih temperaturah. Hladna mešanica za krpanje razpok in lukenj ima tudi močno kohezivnost, odlično visokotemperaturno stabilnost in vodoodpornost. Avtorji so poudarili, da razvito epoksidno vezivo širi uporabnost epoksi smol tudi na področje gradbeništva oziroma na področje razvoja tehnologije vzdrževanja asfaltiranih pločnikov.

Ključne besede: vzdrževanje pločnikov, epoksidna smola, vezivo, gradbeništvo

1 INTRODUCTION

Asphalt is a temperature-sensitive material, which is brittle in winter and soft in summer. Under long-term impacts of the traffic load and natural environment, rutting disease is prone to occur in summer, and cracks, looseness, pits, and other diseases are prone to occur in winter.[1–3] If these cracks and pits are not repaired in time, the disease will further expand under the combined effect of heavy traffic and water, affecting driving comfort and road service life,[4] and seriously endangering driving safety. Therefore, the challenges of how to quickly and efficiently seal cracks and repair pits have become a long-term concern of an increasing number of researchers.

As crack sealing materials, we mainly use hot asphalt sealants, normal temperature asphalt sealants[5,6] and chemical sealants.[7,8] Hot asphalt sealants are prone to bond failure at high temperatures[9,10] and brittle fracture at low temperatures.[11] The aging performance of room-temperature asphalt sealants is poor.[5,12] The chemical sealant has a stable performance and it still has good performance after aging.

Epoxy resin exhibits strong adhesion after curing and is widely used as an adhesive. Thermosetting epoxy resin has excellent chemical resistance and high bond strength.[13,14] The chemical crosslinking reaction product of a curing agent and epoxy resin shows good cohesion, which can significantly improve the high-temperature strength and deformation resistance of the adhesive.[15] There are many types of epoxy resins and curing agents. Through a reasonable material selection and formula design, polymer materials meeting the requirements of different conditions can be prepared.[16,17] Wang et al.[18] prepared super-viscosity epoxy grouting, and their results show that super-low-viscosity epoxy grouting materials can be used to repair microcracks in construction. Modesti et al.[19] found that an epoxy resin sealant can ef-

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fectively restore the overall mechanical properties of concrete. Liu et al.[20] prepared a new epoxy polymer-modified-asphalt cold patching mixture, and found that the cold patching mixture has a good repair effect in winter and rainy seasons. Pedram et al.[21] found that a mixture with a high epoxy-resin content exhibits excellent mechanical properties and durability. Therefore, epoxy resin is an ideal pavement-crack filling and pothole-repair material.

In this paper, an epoxy-resin adhesive with high strength, good toughness and normal temperature curing was developed. The adhesive can not only be used as a road filling sealant but can also be used to prepare a cold patching mixture for pits. The properties of the adhesive were examined with viscosity and curing degree tests, and the bonding performance of the sealant repair structure was studied with a low-temperature beam bending test. The construction and road performance of the cold patch were studied using construction workability, high-temperature rutting, low-temperature bending and freeze-thaw splitting tests.

2 EXPERIMENTAL PART

2.1 Materials

2.1.1 Epoxy-resin adhesive

In this paper, bisphenol A type E-44 epoxy resin was selected as the epoxy-resin material. DMP-3-800LC poly mercaptan was selected as the curing agent. Active diluent butanediol diglycidyl was selected as the diluent. Polyurethane prepolymer was selected as the toughening agent. Tertiary amine accelerator DMP30 was selected as the accelerator. The epoxy-resin adhesive was mixed at normal temperature. The mass proportions of (E-44 epoxy resin : curing agent : diluent : toughening agent : accelerator) were (100 : 55 : 50 : 20 : 3).

2.1.2 Aggregate and filler

The coarse aggregate used in the test was limestone gravel, the fine aggregate was manufactured sand, and the filler was limestone powder without agglomerations, clean and dry after grinding. The aggregates and mineral powder all met the requirements of JTG F40-2004.

2.1.3 Mineral gradation

This study was based on the AC-10 grading design; the grading curve is shown in **Figure 1**.

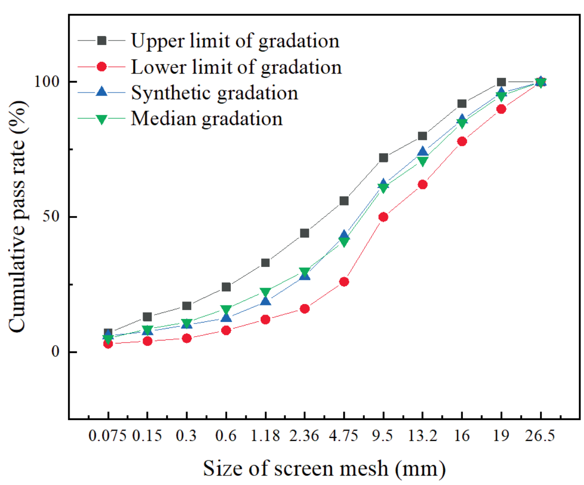

Figure 1: Mineral gradation curves

2.2 Methods

2.2.1 Mixing process of the cold patching mixture

The main preparation steps were as follows. Firstly, the adhesive was prepared in the above proportions. Then the coarse aggregate was placed in a mixing pot and mixed with the prepared adhesive at room temperature for 180 s so that the binder fully covered the aggregate surface. Finally, the fine aggregate was poured into the mixing pot and stirred for 300 s to obtain an epoxy-resin cold patching mixture for trench repair. The content of the adhesive was 2 %. Their stirring was done at 360 min^{-1} and the temperature was 25 °C.

2.2.2 Viscosity test

The viscosity-test reference standard was T 2794-2013. The equipment included a dV-II + Pro rotary viscometer produced by Brook Company from the United States, and the test temperature was 25 °C.

2.2.3 Curing degree and curing volume shrinkage test

The extraction method (T 2576-2016) was used to determine the curing degree of the adhesive. For the curing volume shrinkage test, we first used a disposable syringe to slowly and evenly inject the adhesive into a 5 mL small glass measuring cylinder. After curing at 25 °C for 7 d, the adhesive was placed in a 60 °C oven for 1 h. When it was cooled to room temperature, volume V of the adhesive cured in the measuring cylinder was recorded. The curing-shrinkage formula is shown in Equation (1).

$$\phi = \frac{5 - V}{5 \times 100\%} \tag{1}$$

2.2.4 Glass transition temperature test

A 200 F3 differential scanning calorimeter produced by Niche Company from Germany was used in the experiment. Firstly, the furnace temperature was raised to 60 °C at the rate was 10 °C/min. Then, the furnace temperature was cooled from 60 °C to –60 °C at the same rate for 3 min. Finally, the furnace temperature was raised from –60 °C to 60 °C at the rate of 10 °C/min. The sample weight was about 5–10 mg. The inflection point of the curve data during the second heating process was selected as the glass transition temperature T_g.

2.2.5 Tensile strength and elongation at break test

A tensile specimen was prepared according to the test method of T 2567-2008. After curing at 25 °C for 7 d, the prepared dumbbell-shaped tensile sealant specimen was placed in an oven at 60 °C for 1 h and then tested with the CMT5105 universal test. The test temperature was –10 °C and the tensile rate was 10 mm/min.

2.2.6 High-temperature rutting test

According to the rutting test method of T 0719-2011, a rutting plate specimen was formed, and its dimensions were (300 × 300 × 50) mm. The specimen was cured in a 25 °C environment box for 28 d. The test temperature was 60 °C, the wheel pressure was 0.7 MPa; the rutting deformation data were recorded for 45 min and 60 min.

2.2.7 Low-temperature beam bending test

According to the test specification of the T 0715-2011 low-temperature bending-test method, a rutting plate specimen was formed and kept in the 25 °C environment box for 28 d. After that, the rut plate was cut into a prism beam specimen, with dimensions of (250 ×30 × 35) mm; it was placed in a freezing solution with a constant temperature of –The test temperature was –10 °C and the loading rate was 50 mm/min.

2.2.8 Marshall immersion test

According to the test specification of the T 0709-2011 Marshall immersion stability test, the epoxy-resin adhesive cold patching mixture was double sidedly compacted 75 times to form Marshall specimens with a diameter of 101.6 mm and height of 63.5 mm. The specimens were cured in the 25 °C environment box for 28 d. After curing, the bulk density and porosity parameters of the Marshall specimens were tested, and the Marshall stability was tested after two groups of specimens were placed in a flume with a constant temperature of 60 °C for 30 min and 48 h.

2.2.9 Freeze-thaw splitting test

According to the test procedure of the T 0729-2011 freeze-thaw splitting test, the specimens were cured in the 25 °C environment box for 28 d. After curing, the first group of specimens was kept at room temperature; the second group of specimens was placed in a plastic bag after vacuum saturation, and 10 mL of water was added to the specimens; then the bag was placed into a refrigerator at a constant temperature of –18 °C for 16 h. After taking out the specimens, they were removed from the plastic bag and placed into a water tank with a constant temperature of 60 °C. After a dwell time of 24 h, the specimens were taken out and both groups of specimens were placed in a water tank with a constant temperature of 25 °C for 2 h. The splitting rate was 50 mm/min.

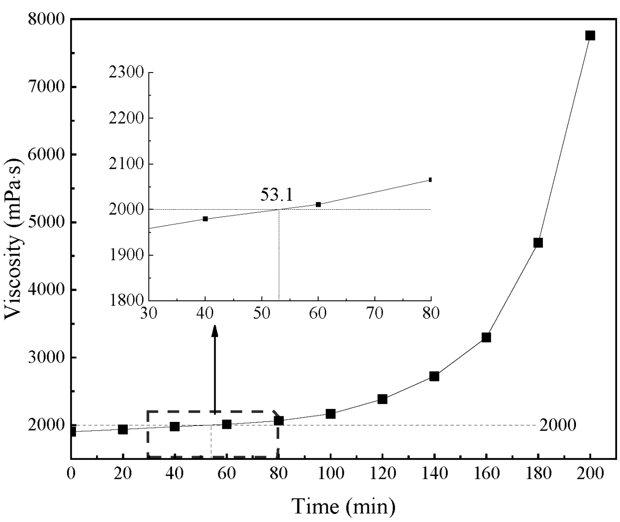

Figure 2: Change in the adhesive viscosity with time

3 RESULTS AND DISCUSSION

3.1 Epoxy resin adhesive properties

3.1.1 Viscosity

According to the requirements of T 1041-2007, the operation time of a sealant should be more than 30 min. In the actual construction process, the permeability of the adhesive was closely related to the viscosity. The viscosity was in a reasonable range of 1000–2000 mPa·s, which did not affect the permeability of the cracks. Therefore, the period from the initial adhesive viscosity to 2000 mPa·s was defined as the operable time in this paper. Considering that the adhesive was produced at room temperature, the viscosity test temperature was 25 °C; the viscosity of the adhesive changed as shown in **Figure 2**.

Figure 2 shows that the initial viscosity of the adhesive is not more than 2000 mPa·s as it remains in a reasonable range of 1000–2000 mPa·s, indicating that the adhesive has good perfusion for asphalt pavement cracks. The viscosity of the adhesive increases with the curing time, and the viscosity increases rapidly after about 2 h, indicating that the adhesive can reach the gel state earlier and form the initial strength in the construction process. In addition, the viscosity of the adhesive exceeds 2000 mPa·s at 53.1 min, meeting the requirement of the operating time exceeding 30 min, so the adhesive has good pour viscosity.

3.1.2 Curing degree and curing volume shrinkage

In this part, the curing degree and curing volume shrinkage of the adhesive were tested at 25 °C. The test samples were tensile specimens formed by curing. The test results are shown in **Table 1**.

Table 1: Test results for the curing degree and volume shrinkage of the adhesive

Degree of cure (%)	Volume shrinkage (%)
95.19	1.6

When the curing degree is greater than 95 %, it can be considered that the epoxy resin is completely cured, indicating that the adhesive has been completely cured and the cured product has good aging resistance and long-term performance. The volume shrinkage of the adhesive was within 2 %, indicating that the internal stress generated by the adhesive in the curing process was small, having little effect on the tensile properties and adhesion properties of the cured adhesive.

3.1.3 Glass transition temperature

When using the low-temperature evaluation method of polymer materials, glass transition temperature T_g is also commonly used to characterize the low-temperature performance of materials. Amorphous polymer materials undergo three different states: from low temperature to high temperature, from the glass state to the glass-rubber state, and then to the rubber state. When an adhesive is below the glass transition temperature, it is prone to brittle fracture under load. The glass transition temperature of our adhesive was tested with differential scanning calorimetry (DSC) to evaluate the low-temperature characteristics of the adhesive.

The test result shows that the glass transition temperature of the adhesive was –18.1 °C, meeting the requirements of the rubber state at low temperatures in winter.

3.1.4 Tensility

An adhesive must have a certain tensile strength to sustain the expansion and shrinkage trend of cracks with temperature changes. Due to a decrease in the nighttime temperature or sudden drop in the temperature, the adhesive may also be subjected to the tensile stress caused by crack expansion. Therefore, the test curing temperature was 25 °C, and the measurement temperature was –10 °C. The tensile properties of the adhesive were tested during the molding process at room temperature. The results are shown in **Figure 3**.

As shown in **Figure 3**, at the beginning of curing, the growth rate of the tensile strength of the adhesive was very obvious. Especially, the growth rate was the fastest in the first three days, reaching 3.69 MPa on the 3rd day. After 15 d of curing, the tensile strength increased slowly, reaching 5.83 MPa on the 28th day, and the overall tensile strength was large. At the beginning of the reaction, the elongation at the break of the adhesive gradually increased with the extension of the reaction time; basically, within 1–2 days, the elongation at break reached a maximum of 133.12 %. As the reaction continued, the elongation at break decreased gradually with the extension of the curing time, having a good negative correlation with the tensile strength. However, the overall elongation at break was higher than 121 %, exhibiting an excellent tensile deformation ability. In summary, the adhesive has good tensile properties.

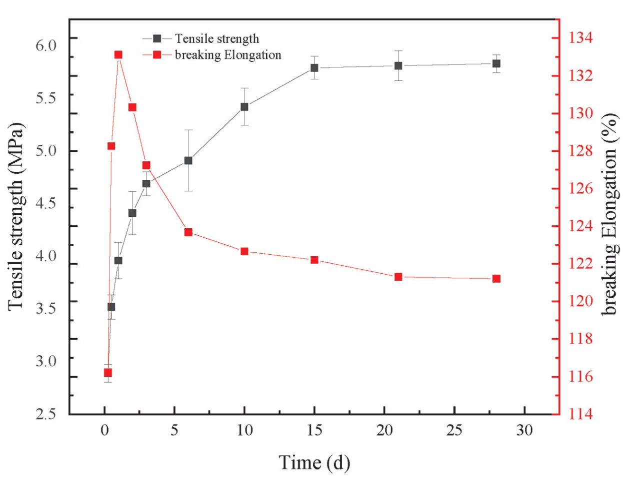

Figure 3: Formation of the adhesive tensile strength

3.2 Bending bonding properties of the adhesive for filling seams

In order to study the flexural-tensile adhesion performance of the adhesive and the crack wall-filling repair structure, an AC-13 graded asphalt mixture was used to prepare beam specimens for a low-temperature bending test. After bending fracture, the beam was separated from a 5-mm spacing, sealed with the adhesive on three sides, and poured with the adhesive on the unsealed surface. After molding at 25 °C for 7 d, it was placed in a 60 °C oven for 1 h. The repaired beams were tested under low-temperature bending. The results are shown in **Table 2**.

Table 2: Results for the flexural strength

Strength index	Specimen types	Value
Flexural-tensile strength (MPa)	Undamaged specimen	10.36
Bending bond strength (MPa)	Damage repair specimen	8.63
Bending tensile-strength ratio (%)	83.3	

It can be seen from **Table 2** that the flexural-tensile bond strength of the beam repaired with the adhesive recovered 83.3 % of the flexural-tensile bond strength of the undamaged specimen; its recovery degree is high, indicating that the low-temperature flexural-tensile resistance of the adhesive and the crack wall-filling repair structure is strong.

3.3 Cold patching mixture performance of the epoxy-resin adhesive

3.3.1 Cohesiveness

Following the JTG F40-2004 rolling sieve cohesion test method, 800 g of a cold patching mixture, uniformly mixed at room temperature, was put into a Marshall test model and placed into a (0, 10, 20 and 30) °C environment box for 4 h, respectively. After taking it out, both sides were compacted five times and demolded. After that the specimen was put into a standard sieve, stood up and rolled back 20 times. The damage rate of the specimen was determined. The test results are shown in **Table 3**.

Table 3: Rolling sieve test results

	Temperature (°C)			
	0	10	20	30
Failure rate (%)	6.53	4.79	5.43	4.52
Normative value (%)	≤40			

It can be seen from **Table 3** that the damage rate of the specimen at each temperature is less than 10 %, which is much lower than the standard value. It can be seen that the cold patching mixture has good cohesiveness, and particles can be bonded to each other as a whole through the adhesive without falling off.

3.3.2 Construction workability

In this study, an improved empirical method was used to evaluate the workability of the epoxy-based cold patching mixture. The test used temperatures of (0, 10, 20 and 30) °C to study the construction workability of the cold filling mixture at different temperatures. 500 g of the cold patch mixture of was weighed and mixed evenly at room temperature. The mixture was loaded into plastic bags and placed in environmental boxes at (0, 10, 20 and 30) °C for 4 h. After 4-h storage at each temperature, the cold patching mixture could be kneaded into clusters; the higher the temperature, the better was the clustering effect, indicating that the cold patch had good compactness. The agglomerated mixture could be easily patted and dispersed by beating it with a wooden stick; basically, it had no large aggregate and good porosity. The lower the temperature after the mixture was agglomerated, the better it could be dispersed into blocks in a short time without any external force. The block mixture could be patted and dispersed. The test shows that when the temperature is low, the porosity of the cold patching mixture is better; when the temperature is high, the compressibility of the cold patching mixture is better.

3.4 Road performance of the cold patching mixture

3.4.1 High-temperature stability

The pavement temperature is high in summer, and the asphalt pavement is deformed under the repeated actions of temperature and load. If deformation continues to accumulate, it will cause rutting, congestion and other diseases, affecting the traffic safety and reducing the comfort and road service performance. Therefore, it was necessary to test the high-temperature stability of the cold patching mixture. The test results are shown in **Table 4**.

Table 4: Rutting test results for the pavement cold patch mixture

45-min deflection (mm)	60-min deflection (mm)	Dynamic stability (times/mm)	Specification requirement (times/mm)	
			Common asphalt mixture	Modified SMA mixture
0.209	0.223	83200	1000	3000

It can be seen from **Table 4** that the dynamic stability of the cold patching mixture reaches 83200 times/mm, which is much higher than the requirement for the dynamic stability of the modified SMA mixture, which is not less than 3000 times/mm as specified in the Technical Specification for Highway Asphalt Pavement Construction (JTG F40-2004). Therefore, the high-temperature stability of the epoxy-resin cold patching mixture is good.

3.4.2 Low-temperature crack resistance

Transverse cracks of asphalt pavement are mostly caused by low-temperature cracking of asphalt. Therefore, pavement cold patching materials must have low-temperature crack resistance to ensure that a repaired pavement has a certain deformation resistance to avoid low-temperature shrinkage cracks. To study the low-temperature crack resistance of cold patching prepared with the epoxy-resin adhesive, a low-temperature bending test was used to evaluate its low-temperature performance provided by the bending tensile strength and bending tensile strain. The test results are shown in **Table 5**.

Table 5: Low-temperature bending test results

Failure load (kN)	Mid-span deflection (mm)	Flexural-tensile strength (MPa)	Flexural- tensile strain	Stiffness modulus (MPa)
2524	0.487	20.32	2876×10^{-6}	7598

It can be seen from **Table 5** that the bending strain was 2876×10^{-6}, meeting the requirements of the Technical Specification for Highway Asphalt Pavement Construction (JTG F40-2004), stipulating that the bending strain of an ordinary asphalt mixture in a cold winter region should not be less than 2600×10^{-6}. The above results indicate that the epoxy-resin pavement cold patching mixture is suitable for most regions.

3.4.3 Water stability of the cold water feed

The stability of the cold water feed was evaluated with the Marshall Immersion test and freeze-thaw splitting test. The results of the Marshall Immersion test are shown in **Table 6**, and the results of the freeze-thaw splitting test are shown in **Table 7**.

Table 6: Volume indicators and Marshall Immersion results

Bulk density (g/cm^3)	Percentage of void (%)	MS (kN)	MS_1 (kN)	MS_0 (%)	Normative value (%)
2.455	1.387	100.43	95.78	95.37	≥ 80

In **Table 6**, MS is the Marshall stability of the specimen immersed for 30 min, MS_1 is the Marshall stability of the specimen immersed for 48 h, and MS_0 is the residual stability of immersion.

It can be seen from **Table 6** that Marshall-stability values before and after the immersion are large, and the residual stability of the specimen immersed is more than 95 %, meeting the requirements of the Technical Specification for Highway Asphalt Pavement Construction (JTG F40-2004), stipulating that the residual stability of an ordinary asphalt mixture in a wet area should not be less than 80 %. The above results indicate that the cold patching mixture prepared with the adhesive has excellent water stability.

Table 7: Freeze-thaw splitting test results

R_{T1} (MPa)	R_{T2} (MPa)	TSR (%)	Specification requirement (%)
3.617	3.359	92.87	≥75

In **Table 7**, R_{T1} is the splitting strength of the first group of specimens, R_{T2} is the splitting strength of the second group of specimens, and TSR is the freeze-thaw splitting strength ratio.

Table 7 shows that the splitting strength ratio of the cold patch is above 90 %, and according to the Technical Specification for Highway Asphalt Pavement Construction (JTG F40-2004), the splitting strength ratio of an ordinary asphalt mixture in semi-arid areas should not be less than 75 %. It can be seen that the water stability of the pavement cold patching mixture used in this study is significantly higher than that of the ordinary asphalt mixture. In summary, the epoxy pavement cold patching mixture has high water stability.

4 CONCLUSIONS

In this paper, an epoxy-resin adhesive that can be used for pavement crack filling and pothole repair was prepared. The properties of the adhesive and cold patching mixture, and their road performance were studied using physical-property, construction-performance and road-performance tests. The main results are as follows:

1) With regard to viscosity, the epoxy-resin adhesive exhibits good perfusion, allowing fast early strength formation and high strength, small curing volume shrinkage, good low-temperature properties and tensile properties, and excellent toughness.

2) As a filling sealant, the epoxy-resin adhesive has excellent low-temperature flexural-tensile strength, and the flexural-tensile bond strength of the beam repaired with this adhesive is restored to 83.3 % of the strength of the undamaged specimen.

3) The epoxy-resin cold patching mixture shows good cohesiveness in the test temperature range, and it still has good porosity and compactness after 4-h storage at each temperature. The high temperature performance of the cold patching mixture is significantly higher than that of the asphalt mixture, and its dynamic stability reaches 83200 times/mm. The bending strain at –10 °C meets the requirements for the asphalt mixture in a severe cold region. The residual stability of the immersed specimen is 95.37 %, and the freeze-thaw splitting strength ratio is 92.87 %, showing good water stability.

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