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Improvement of the Low-Temperature Cracking and Shear Resistance of Semi-Flexible Mixture Modified by Polymers

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Abstract: Semi-flexible mixture, as a rigid and flexible pavement material, has good rutting resistance and water stability, but its low-temperature cracking and shear resistance are poor. This paper studies and characterizes the low-temperature cracking resistance and shear resistance of semi-flexible mixtures modified by redispersible emulsion powder and epoxy resin. The performance of matrix asphalt mixture and cement grouting material with different polymer contents were investigated. The flexural and shear performance of polymer-modified semi-flexible mixtures were measured based on low-temperature bending test and direct shear test. The results indicate that the addition of polymers, especially epoxy resin, can significantly improve the failure strain, flexural strength, stiffness modulus and shear strength of semi-flexible mixture, thus enhancing its low-temperature cracking and shear resistance.

1. Introduction

Semi-flexible pavement refers to a pavement that combines the advantages of cement concrete pavement and asphalt concrete pavement by filling cementitious grouting material into large pore matrix asphalt mixture. Its high-temperature stability and water stability are generally better than ordinary asphalt concrete pavement, and its fatigue resistance and low-temperature crack resistance are also greatly improved than ordinary cement concrete pavement [1-4]. The matrix asphalt mixture and cement grouting material, as the main compositions of semi-flexible pavement materials, have great differences in mechanical properties. Under the action of load, the inhomogeneous deformation will occur, resulting in pavement cracking [5-8]. In addition, the shrinkage of cement material itself is the most important factor that results cracks in semi-flexible pavement [9-11]. Therefore, the improvement of the crack resistance of semi-flexible mixture has become a key problem to be solved urgently in promoting its application [12-13].

In recent years, China has strengthened the research on semi-flexible pavement materials, and some cities have paved semi-flexible pavement test sections, such as Quanzhou, Nanjing, Suzhou, etc. These test sections have proved that road performance of the semi-flexible material was excellent [14]. At present, the research on semi-flexible pavement materials mainly focuses on the mix design of matrix asphalt mixture and high-performance cement grouting material [15-16]. In general, the volume method is used for the gradation design of matrix asphalt mixture, and the optimal asphalt-stone ratio is determined by drainage and scattering tests. Combining Marshall stability and flow value, the matrix asphalt mixture with large air void and strength can be obtained [17-19]. Additionally, the orthogonal test method is commonly used for cement grouting material design and the fluidity of cement grouting material is determined by the grouting test. By studying the effect of additives such as early strength agent and polymer modifier on the shrinkage of cement, the cement grouting material with good applicability is obtained [20-22]. The cracking mechanism of semi-flexible pavement material can be analysed through numerical simulation and laboratory tests. The peak stress, interface bonding strength, cohesion and fracture energy are selected to evaluate the bonding property of materials constituting the semi-flexible mixture [23-24]. In order to solve the problem of cracking of semi-flexible mixture, a lot of methods can be adopted, such as the addition of polymer in cement grouting material, the control of matrix asphalt mixture porosity and the improvement of asphalt viscoelasticity [25]. However, the effectiveness of these methods has not been thoroughly demonstrated by studies and trials.

In order to solve the problem of insufficient crack resistance of grouting semi-flexible material, this paper investigated the mix design of matrix asphalt mixture and the performance of cement grouting material with different polymer contents. The low-temperature cracking resistance and shear resistance of semi-flexible mixtures modified by redispersible emulsion powder and epoxy resin were studied and characterized based on laboratory test. The aim of this study is to improve the low temperature cracking resistance and shear resistance of semi-flexible mixture through the experimental study of polymer modification. These research findings can provide guidance on and a reference for the optimization and engineering applications of semi-flexible mixture.

2. Raw Materials and Test Methods

2.1. Raw Materials

2.1.1. Asphalt and Aggregates

SBS-modified asphalt, basalt aggregate, and limestone mineral filler were used in the experiments, and their properties are listed in Table 1-3.

Table 1: The properties of SBS-modified asphalt.

Indexes		Results
Penetration (25°C, 100g, 5s, 0.1mm)		53
Ductility (5°C, 5cm/min, cm)		31
Softening point (global method, °C)		82.5
Elastic recovery (25°C, %)		94.5
Solubility (%)		99.1
Flashpoint (%)		255
RTFOT residue	Mass change (%)	0.1
	Penetration ratio (25°C, %)	80
	Residual ductility (5°C, cm)	15

Table 2: The properties of aggregate.

Indexes		Results			
Aggregate size (mm)		10~20mm	5~10mm	3~5mm	0~3mm
Los Angeles wear value (%)		18.4	15.2	14.5	13.4
Flat elongated particles content (%)	>9.5mm	3.7	5.4	6.6	/
	<9.5mm	4.2	6.3	7.5	/
Crushing value (%)		14.2	13.6	/	/
Water absorption rate (%)		0.45	0.68	0.81	1.15
Apparent relative density (g/cm^3)		2.861	2.858	2.888	2.811

Table 3: The properties of mineral filler.

Indexes	Results
Hydrophilic coefficient	0.68
Moisture content (%)	0.1
Plasticity index (%)	2.8

2.1.2. Cement Grouting Material

Portland cement (P.O 42.5) is used and its properties is listed in Table 4. The fineness modulus of sand used in the experiment is 1.28. LDM7300P redispersible emulsion powder, produced by Jiangsu Subote New Material Co. Ltd. (Nanjing, China), and F0704 epoxy resin, obtained from Shenzhen Jitian Chemical Co. Ltd. (Shenzhen, China), are used as polymer modifiers, respectively. Their properties are shown in Table 5-6. The property of the curing agent for the test is also shown in Table 6.

Table 4: Physical properties of Portland cement.

Density (g/cm^3)	Specific surface area (m^2/kg)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)	
		Initial setting	Final setting	3d	28d	3d	28d
2.94	346	177	253	25.2	48.2	5.1	7.8

Table 5: The properties of LDM7300P redispersible emulsion powder.

Indexes	Results
Appearance	White powder
Volatile matter content (%)	0.8%
Apparent density (g/cm^3)	0.49

Table 6: Physical properties of epoxy resin and curing agent.

Type	Solid content (%)	Viscosity (mPa·s, 25°C)	Specific gravity (g cm^3)	pH	Epoxy content
Epoxy resin	50±3	<1000	1.01~1.08	2~7	400~800
Curing agent	44±2	>2000	1.00~1.08	8~11	200~320

2.2. Mixture Ratio Design

2.2.1. Design of Matrix Asphalt Mixture

The matrix asphalt mixture with large porosity is very important to the grouting rate and performance of semi-flexible mixture. In this paper, two matrix asphalt mixtures, named GOAC-13-II and GOAC-16-II were designed with reference to the semi-flexible asphalt pavement in Japan. The mixture graduations are shown in Table 7.

Table 7: The gradation of GOAC-13-II and GOAC-16-II (%).

Mixture type	10-20mm	5-10mm	3-5mm	0-3mm	Mineral powder	Oil-stone ratio
GOAC-13-II	13.5	68	9	8	1.5	3.4
GOAC-16-II	84	0	4	9	3	3.2

2.2.2. Design of Polymer-modified Cement Grouting Material

Two groups of polymer-modified cement grouting materials were designed with redispersible emulsion powder and epoxy resin, as shown in Table 8. The polymer content in each group was 0%, 5% 10%, 15% and 20%. The group A and group B represent redispersible emulsion powder modified cement grouting material and epoxy resin modified cement grouting material, respectively.

Table 8: Polymer-modified cement mortar mix ratio (kg/m^3).

No.	Cement	Sand	Water	Polymer
A1	1000	500	630	0
A2	1000	500	580	50
A3	1000	500	530	100
A4	1000	500	480	150
A5	1000	500	430	200
B1	1000	500	630	0
B2	1000	500	550	50
B3	1000	500	480	100
B4	1000	500	400	150
B5	1000	500	330	200

2.3. Specimen Preparation and Grouting Molding

The specimens for performance test of matrix asphalt mixture and polymer-modified cement grouting material were prepared in strict accordance with the specifications of JTG E20 and JTG 3420. The polymer-modified semi-flexible mixture specimens were prepared as follows:

• Before the preparation, the temperature of the matrix asphalt mixture specimen was monitored until it was below 20 ℃.

• The around and bottom of specimen was sealed with plastic wrap to prevent cement grouting material from flowing out during grouting.

• The treated matrix asphalt mixture specimen was placed on the shaking table and the frequency of the shaking table was set as 50 Hz.

• The cement grouting material was slowly and evenly grouted from the top of the specimen.

• When the cement grouting material on the surface of the specimen was saturated, the grouting was stopped and the excess grouting material on the specimen surface should be scraped away.

• The entire grouting process should be completed within 1 hour.

2.4. Molding Experiment Methods

The drainage loss, scattering loss, percent air voids, percent connected air voids, and Marshall stability of matrix asphalt mixture were tested according to the specifications of JTG E20 and JT/T 1238. The fluidity, compressive strength, and flexural strength of cement grouting material were tested based on JTG 3420. The low-temperature bending test and direct shear test were conducted on polymer-modified semi-flexible mixture to evaluate its crack resistance according to JTG E20. The temperature for low-temperature bending test was selected as -10 ℃. Before the direct shear test, the specimens were placed in a constant temperature water bath at 20 ℃ and 60 ℃ for 6 h.

3. Results and Discussion

3.1. Matrix Asphalt Mixture

The drainage loss, scattering loss, percent air voids, percent connected air voids, and Marshall stability of matrix asphalt mixture are shown in Table 9. It can be found that the drainage loss, scattering loss, percent air voids, percent connected air voids, and Marshall stability of GOAC-13-II and GOAC-16-II matrix asphalt mixtures are meet the specification requirements, indicating that the selected GOAC-13-II and GOAC-16-II matrix asphalt mixtures can be used to prepare semi-flexible mixtures.

Table 9: Technical requirements and laboratory test results of base asphalt mixture.

Indexes	Percent air voids (%)	Percent connected air voids (%)	Marshall stability (kN)	Drainage loss (%)	Scattering loss (%)
GOAC-13-II	22.47	21.17	4.15	0.24	14.7
GOAC-16-II	24.34	22.81	4.43	0.18	14.5
Requirements	20-30	≥16	≥3.0	<0.3	≤15

3.2. Cement Grouting Material

The fluidity test results are shown in Figure 1. The fluidity is an important index that affects the injection of the cement grouting material. Generally, the fluidity of cement grouting material is required to be 10-14 s. In the study, the fluidity of cement grouting material can be effectively controlled by adjusting the water content in the mix ratio. The fluidity of the two polymer-modified cement grouting materials is about 12s, which can satisfy the basic performance requirement.

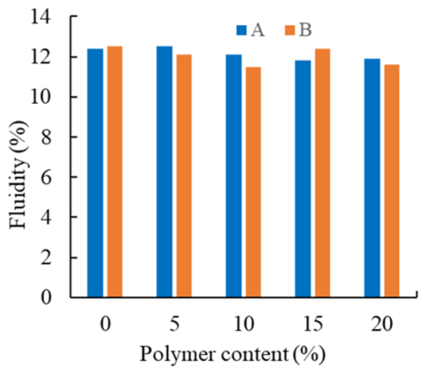

Figure 1: The fluidity of polymer-modified cement grouting materials.

The flexural strength results of cement grouting materials modified by redispersible emulsion powder and epoxy resin are shown in Figure 2. It can be found that, with the increase of the polymers content, the flexural strengths of 7d and 28d for two kinds of polymer-modified cement grouting materials gradually increase. When the content of polymer is 15%, the 7d and 28d flexural strengths of two kinds of polymer-modified cement grouting materials reach the maximum. The flexural strengths of redispersible emulsion powder modified grouting material are 6.8 MPa and 11.6 MPa, respectively. And the flexural strengths of epoxy resin modified grouting material are 8.2 MPa and 12.5 MPa, respectively.

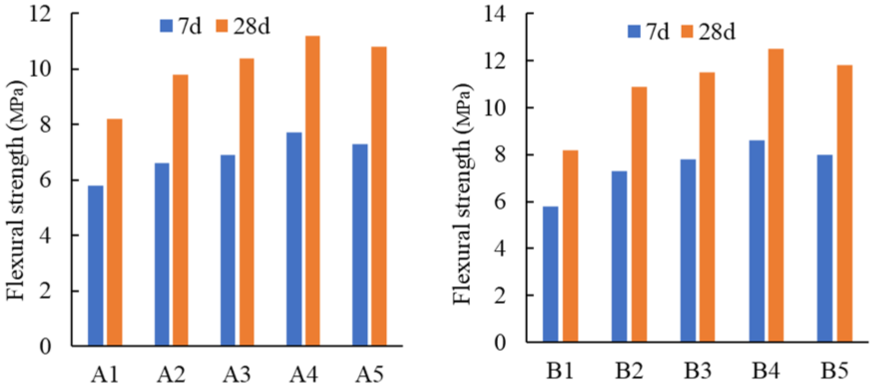

Figure 2: The flexural strength of polymer-modified cement grouting materials.

The compressive strength results of cement grouting materials modified by redispersible emulsion powder and epoxy resin are shown in Figure 3. It can be concluded that the compressive strengths of 7d and 28d for two kinds of polymer-modified cement grouting materials gradually decrease with the increasing polymers content. When the polymers content is 20%, the 7d and 28d compressive strengths of redispersible emulsion powder and epoxy resin modified cement grouting materials decrease about 21% and 15%, respectively.

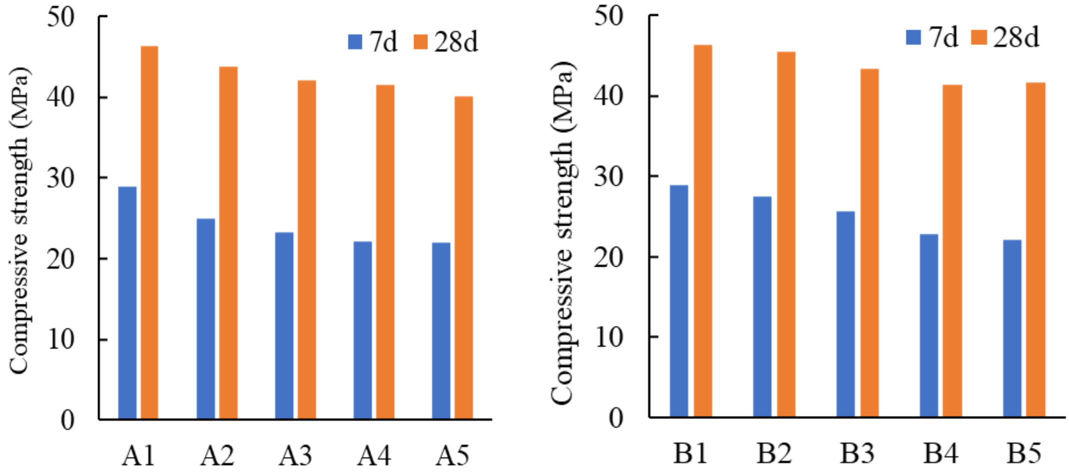

Figure 3: The compressive strength of polymer-modified cement grouting materials.

3.3. Polymer-modified Semi-Flexible Mixture

3.3.1. Low-temperature Cracking Resistance

In consideration of the properties of polymer-modified cement grouting materials, the groups of A4 and B4 are used as grouting materials to prepared the polymer-modified semi-flexible mixture based on the matrix asphalt mixtures of GOAC-13-II and GOAC-16-II. The low-temperature cracking resistance results are shown in Tables 10 and 11.

It can be found that the flexural tensile strength and failure strain of the redispersible emulsion powder and epoxy resin modified GOAC-13-II and GOAC-16-II are higher than that of the plain cement mortar modified GOAC-13-II and GOAC-16-II, and the stiffness moduli of the redispersible emulsion powder and epoxy resin modified GOAC-13-II and GOAC-16-II are lower than that of the plain cement mortar modified GOAC-13-II and GOAC-16-II, which indicates that the low-temperature cracking resistance of polymer-modified semi-flexible mixtures are improved by the addition of redispersible emulsion powder and epoxy resin.

In term of the low-temperature cracking resistance of the polymer-modified semi-flexible mixtures, epoxy resin modified GOAC-13-II and GOAC-16-II exhibits higher flexural tensile strength, higher failure strain, and lower stiffness modulus, which indicates that the low-temperature cracking resistance of epoxy resin modified semi-flexible mixtures are better than that of redispersible emulsion powder modified semi-flexible mixtures. When the polymer is the same, GOAC-13-II semi-flexible mixtures have higher flexural tensile strength and failure strain than that of GOAC-16-II semi-flexible mixtures, but the stiffness modulus of GOAC-16-II semi-flexible mixtures are better than that of GOAC-13-II semi-flexible mixtures. They all have good low-temperature cracking resistance and the type of semi-flexible mixture can be selected based on the engineering condition.

Table 10: The low-temperature cracking resistance results of GOAC-13-II semi-flexural mixture.

Type of grouting material for GOAC-13-II	Grouting fullness (%)	Flexural tensile strength (MPa)	Stiffness modulus (MPa)	Failure strain (με)
Plain cement mortar	96.5	8.89	4631	1719
Redispersible emulsion powder	97.1	10.66	3910	2441
Epoxy resin	96.7	10.94	3796	2580

Table 11: The low-temperature cracking resistance results of GOAC-16-II semi-flexural mixture.

Type of grouting material for GOAC-16-II	Grouting fullness (%)	Flexural tensile strength (MPa)	Stiffness modulus (MPa)	Failure strain (με)
Plain cement mortar	97.3	7.76	4305	1528
Redispersible emulsion powder	96.3	9.26	3866	2339
Epoxy resin	96.9	10.61	3605	2440

3.3.2. Shear Resistance

The shear performance results of different semi-flexible mixtures are shown in Tables 12 and 13. It can be concluded that the maximum shear forces at 20 ℃ and 60 ℃ of the redispersible emulsion powder and epoxy resin modified GOAC-13-II and GOAC-16-II are higher than that of the plain cement mortar modified GOAC-13-II and GOAC-16-II, indicating that the shear resistance of polymer-modified semi-flexible mixtures are improved by the addition of redispersible emulsion powder and epoxy resin.

In term of the shear resistance of the polymer-modified semi-flexible mixtures, epoxy resin modified GOAC-13-II and GOAC-16-II presents higher maximum shear forces at 20 ℃ and 60 ℃, which indicates that the shear resistance of epoxy resin modified semi-flexible mixtures are better than that of redispersible emulsion powder modified semi-flexible mixtures. When the polymer is the same, the maximum shear forces at 20 ℃ and 60 ℃ of GOAC-13-II semi-flexible mixtures are higher than that of GOAC-16-II semi-flexible mixtures, indicating that the shear resistance of GOAC-13-II semi-flexible mixtures are better than that of GOAC-16-II semi-flexible mixtures.

Table 12: The shear results of GOAC-13-II semi-flexural mixture.

Type of grouting material for GOAC-13-II	Grouting fullness (%)	Maximum shear force at 20℃ (kN)	Maximum shear force at 60℃ (kN)
Plain cement mortar	96.5	19.9	19.5
Redispersible emulsion powder	97.1	20.2	19.6
Epoxy resin	96.7	21.1	20.5

Table 13: The shear results of GOAC-16-II semi-flexural mixture.

Type of grouting material for GOAC-16-II	Grouting fullness (%)	Maximum shear force at 20℃ (kN)	Maximum shear force at 60℃ (kN)
Plain cement mortar	97.3	18.1	17.8
Redispersible emulsion powder	96.3	18.4	18.6
Epoxy resin	96.9	19.2	19.2

4. Conclusions

In this study, semi-flexible mixtures were prepared with redispersible emulsion powder and epoxy resin. The low-temperature cracking resistance and shear resistance of two kinds of polymers modified semi-flexible mixtures were evaluated. Based on the experimental results, the following conclusions can be drawn:

- The performance indexes of designed GOAC-13-II and GOAC-16-II meet the specification requirements and they can be used as the matrix asphalt mixture for the semi-flexible mixture.
- The addition of polymers can significantly improve the flexural strength of cement grouting materials, but can cause a slight loss of compressive strength. When the polymer content is 15%, the 28 d flexural strengths of redispersible emulsion powder and epoxy resin modified cement grouting materials are increased by 38% and 56%, respectively.
- Compared with the plain cement mortar semi-flexible mixture, the polymers modified semi-flexible mixtures perform better in terms of failure strain, flexural tensile strength, stiffness modulus and shear force, indicating that polymers modified semi-flexible mixtures have better low-temperature cracking resistance and shear resistance.
- The epoxy resin presents better than redispersible emulsion powder in improving the low-temperature cracking resistance and shear resistance of semi-flexible mixture.

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