Research on low-temperature crack resistance of toughened epoxy asphalt mixture

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Abstract: In order to overcome the problems of long test time and large error existing in traditional methods, a new test method for low temperature crack resistance of toughened epoxy asphalt mixture is designed in this paper. This method is mainly based on the results of low-temperature performance of epoxy asphalt mixture, combined with grey theory to analyse the correlation of epoxy asphalt content, different sieve pass rate and low-temperature performance index, so as to obtain the relationship between different influencing factors and the low-temperature crack resistance performance index of epoxy asphalt mixture, and obtain the test results according to the relationship analysis results. The experimental results show that the method has the advantages of short test time, low error and reliability, and can be further applied in practice.

Keywords: toughened; epoxy asphalt; mixture; low-temperature crack resistance; test.

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1 Introduction

So far, the number of various types of transportation has increased rapidly. Coupled with the continuous expansion of the demand for logistics transportation, the number of various large-scale vehicles, heavy-duty vehicles and overloaded vehicles continues to increase, resulting in the fact that the traditional asphalt concrete pavement has been a very serious challenge (Wang and Wang, 2017; Zhang, 2017). At present, the damage of asphalt pavement includes many types. Generally, the damage of highway mainly includes rutting, cracking and so on. In cold regions, asphalt pavement cracking is a very common phenomenon, especially in the northern part of China, because of the temperature changing from high to low, it is easy to cause the pavement structure layer cracking (Li et al., 2019a). In the initial stage, cracks do not have a great impact on the performance of the pavement, but with the long-term immersion of rain and snow water, and under the repeated action of a large number of vehicle loads, the strength of the pavement will obviously decrease. In addition, due to scouring and other external forces, the pavement cracks continue to widen, and the asphalt pavement on both sides of the cracks is broken, which accelerates the speed of pavement damage and reduces the pavement usability. Therefore, in the research of historical mixture, the low-temperature crack resistance test of toughened epoxy asphalt mixture has become a hot topic of current research.

In view of the above problems, a test method of low-temperature crack resistance of toughened epoxy asphalt mixture based on fractal theory is proposed in Li and Qin (2018). In this method, the fractal dimension of asphalt mixture base is calculated by fractal theory through testing the matrix asphalt mixture with voidage of 28% prepared by different mineral aggregate gradation combinations. According to the results of low temperature anti cracking test of asphalt mixture, the regression relationship between it and splitting strength, failure tensile strain and stiffness modulus is established, so as to realise the low temperature crack resistance test of asphalt mixture. Because of the time-consuming problem of this method, it is difficult to achieve the ideal application effect. In Zhang et al. (2016), a test method for low-temperature crack resistance of toughened epoxy asphalt mixture is designed based on grey entropy method. In this method, the critical bending tensile strain index of asphalt mixture is tested through the low temperature bending test of small beam, and the significance of influencing factors of low temperature cracking resistance of asphalt mixture, such as aggregate gradation, stone type, asphalt penetration, asphalt dosage, void ratio, sieve pass rate and mixing temperature, is analysed by using grey entropy method. The method has the problem of large test error, and the actual application effect is not good. Zhu et al. (2019) proposes a test method for low-temperature crack resistance of toughened epoxy asphalt mixture based on long-term natural aging. In view of the insufficient consideration of the aging degree of asphalt binder in the current ductility test, this method redesigns the test conditions of different aging degrees. By testing the ductility of asphalt with different aging degrees, the ductility changes of asphalt in different aging stages are obtained, and the test results are obtained. However, the method has the problems of large test error and long test time, and the actual application effect is not good.

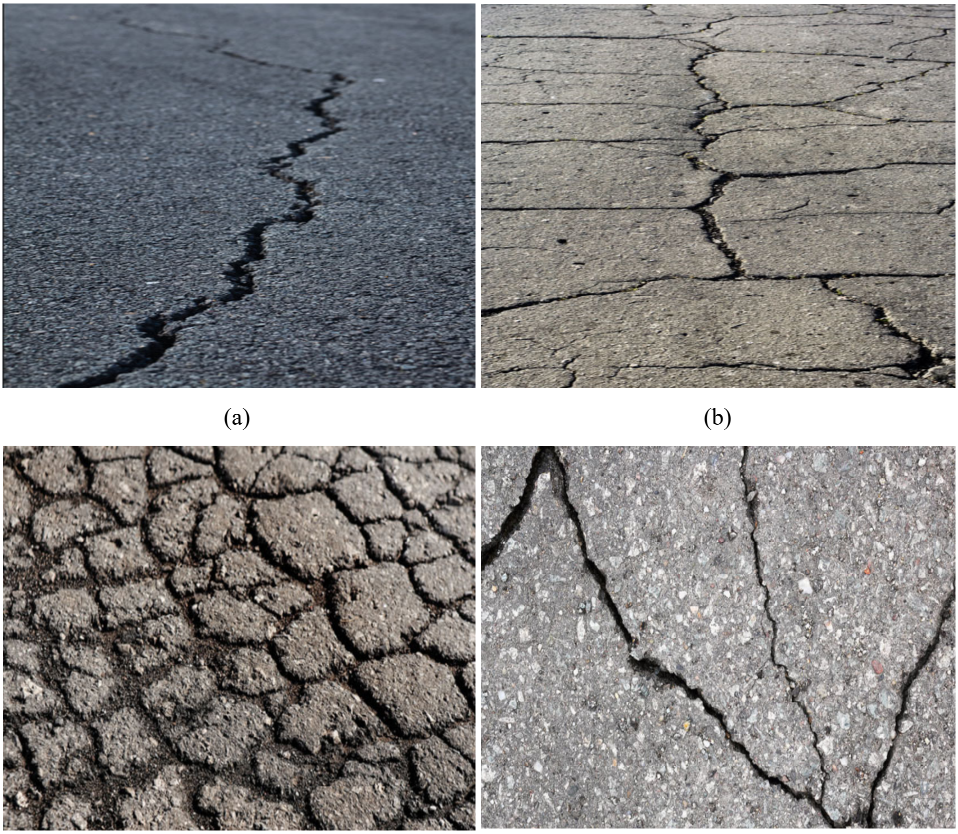
In order to solve the problem that the traditional method analysis is too one-sided and there is no clear definition of the relationship between the influencing factors of cracking resistance, the grey theory is used to analyse the correlation between epoxy asphalt content in epoxy asphalt mixture. Through the analysis of different screening pass rate and low-temperature performance index, it is concluded that different influence factors and low-temperature crack resistance of epoxy asphalt mixture.

2 Cracking principle of toughened epoxy asphalt mixture

Due to the different environment and climate conditions in different regions, the fracture severity is different in different regions. In order to fully understand the causes of transverse cracks, the investigation and analysis are carried out in different areas.

Figure 1 is used to show several common pavement cracks.

Figure 1 Crack situation of different asphalt pavement (see online version for colours)



(a) (b) (c) (d)

Based on the analysis of the causes of the cracks, the main types of fractures are shown in Figure 2.

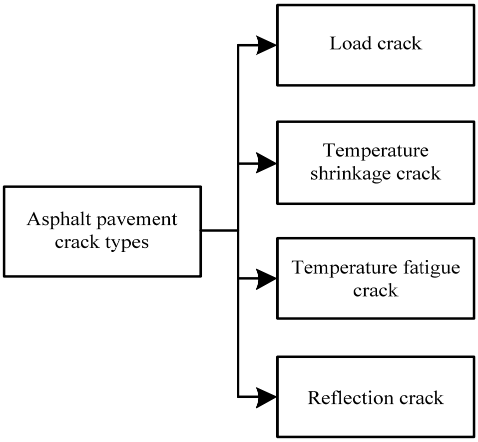


Figure 2 Classification of asphalt pavement cracks

1 Material properties:

- The special properties of asphalt temperature stiffness are the primary factor affecting the low temperature cracking of asphalt mixture. The low viscosity asphalt mixture will reduce its formation speed because of the decrease of temperature. In the low temperature environment, the stronger the deformation resistance of asphalt mixture is, the better the crack resistance is (Tao et al., 2017; Zhang and Zhou, 2016).
- Aggregate type and mixture.
- Asphalt content.
- Porosity.

The temperature stress test of asphalt mixture with different residual voids is carried out. The results show that the smaller the porosity is, the lower the failure temperature is, but there is no significant difference between them. When the pavement is damaged, the difference between the porosity and the temperature stress is large. At this time, the smaller the porosity is, the higher the temperature stress is (Cheng et al., 2018).

2 Environmental factors:

- Temperature.
- Cooling rate.
- Pavement aging.

The longer the pavement is used, the more likely it is to produce cracks due to temperature.

3 Geometric dimension of pavement structure:

- Pavement width.
- Pavement thickness.
- Friction coefficient.

- Construction cracks.

  When the asphalt layer with low stiffness is rolled by steel bars at high temperature, it is easy to cause transverse cracks on the pavement (Shi, 2017; Li et al., 2019b).

To sum up, the cracking mechanism of toughened epoxy asphalt mixture is analysed, and the correlation between epoxy asphalt content and different mesh passing rate and low-temperature performance index is studied, which lays a solid foundation for further analysis of flow transformation performance of toughened epoxy asphalt.

3 Analysis of rheological properties of toughened epoxy asphalt

Dynamic test is not only the main method to study the modulus and fatigue characteristics of toughened asphalt materials, but also the most basic means of elasticity research. Dynamic shear flow is mainly used to measure the complex shear modulus $\gamma_{\max}$ and phase angle (δ) of asphalt to characterise the viscosity and elastic properties of asphalt (Zhang et al., 2018; Zhang and Liu, 2018). In general, the specific calculation formula of complex shear modulus is as follows:

$$G* = \frac{\tau_{\max}}{\gamma_{\max}} \tag{1}$$

The maximum shear stress is expressed by $\tau_{\max}$ and the maximum shear strain is expressed by $\gamma_{\max}$.

According to the CP rule of elasticity-viscoelasticity, the following relations can be obtained.

$$\sigma(t) = G*(\omega)\gamma(t) \tag{2}$$

where the shear modulus $G * (\omega)$ can be expressed as follows:

$$G*(\omega) = i\omega\int_0^\infty \varphi(\xi)\exp(-i\omega\xi)d\xi \tag{3}$$

where i is the elastic coefficient, φ is the viscosity coefficient of asphalt, and ξ is the asphalt mass fraction.

In general, there are the following relations:

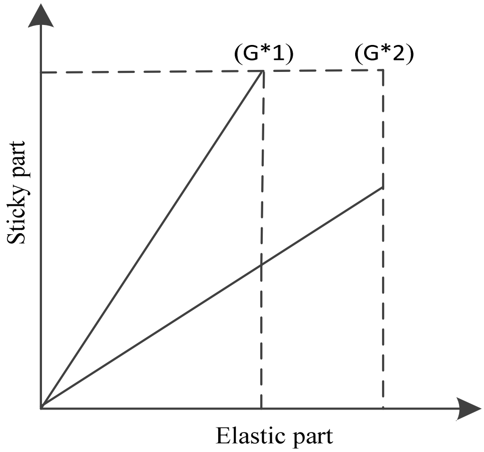
$$G*(\omega) = G'*(w)iG'*(\omega) \tag{4}$$

$$\left|G*(\omega)\right| = \sqrt{\left[G*(\omega)\right]^2 + \left[G'*(\omega)\right]^2} \tag{5}$$

In the above formula, $G' * (\omega)$ represents the shear storage modulus (Liu et al., 2019a), and also represents the energy stored during the internal deformation of asphalt material, that is, the dynamic stiffness, also the elastic part of asphalt.

The composition of the composite shear model is shown in Figure 3.

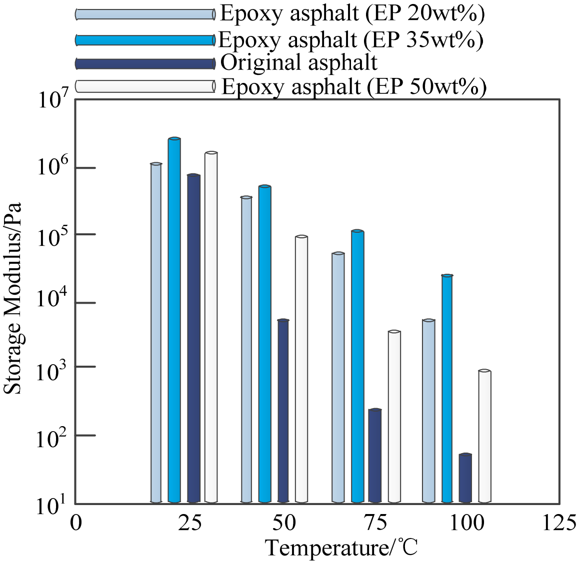
Figure 3 Composition structure of composite shear modulus



Asphalt is a typical viscous material. When epoxy resin is added to asphalt, the original structure of asphalt will be changed, and its change law and elastic form will also change obviously (Li et al., 2019c; Xue et al., 2016). After curing, the stiffness of epoxy resin increases obviously, which is closer to elastomer. Because epoxy resin is a thermosetting material, compared with traditional asphalt material, the influence of temperature on its fluidity is obviously smaller.

The dynamic shear rheometer test is carried out for different content of epoxy asphalt and original asphalt (Gao et al., 2017). The specific experimental results are shown in Figure 4.

Figure 4 Relationship between temperature and storage modulus (see online version for colours)



It can be seen from Figure 4 that the storage modulus will decrease with the increase of temperature, which is due to the gradual softening of asphalt and the decrease of its stiffness under high temperature environment. Moreover, the storage modulus increases with the increase of epoxy resin content, and the relationship between them is mainly positive proportion.

The relationship between temperature and loss modulus is shown in Figure 5.

Figure 5 Relationship between temperature and loss modulus (see online version for colours)

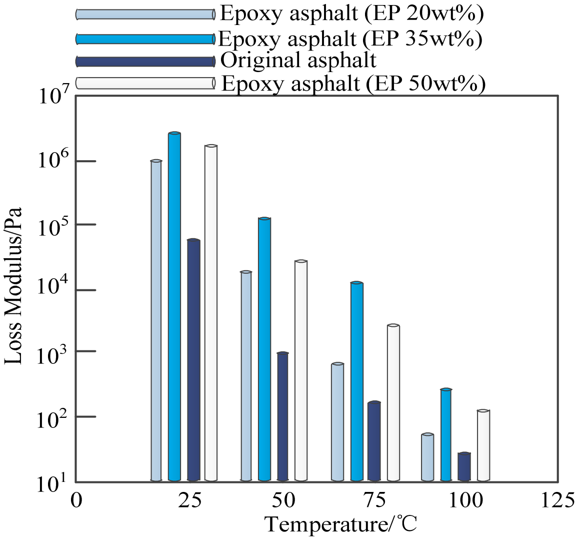
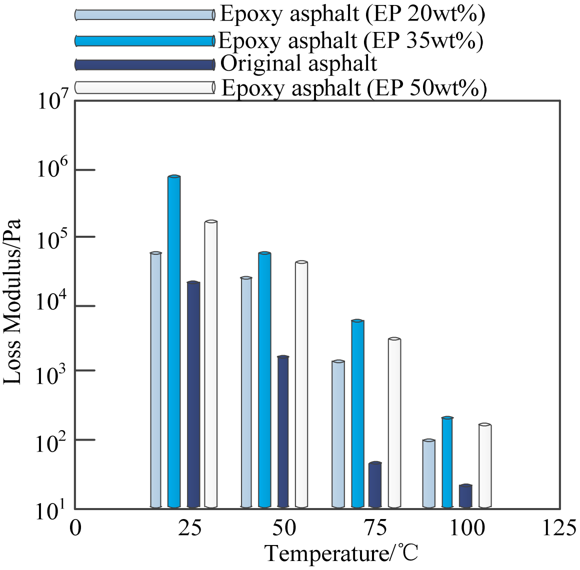


Figure 6 Relationship between temperature and rutting factor (see online version for colours)



It can be seen from Figure 5 that the loss modulus of asphalt decreases with the increase of temperature, and there is an inverse proportional relationship between them.

The following research focuses on the permanent deformation resistance of epoxy asphalt. The specific experimental results are shown in Figure 6.

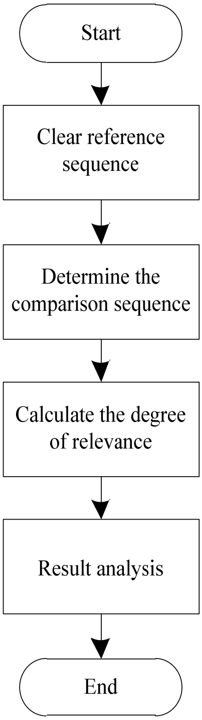
Analysis of the data in Figure 6 shows that epoxy resin can improve the high temperature grade of asphalt (Cui et al., 2018; Shu et al., 2018) and effectively improve the resistance to permanent deformation.

Through the above process, the relationship between different influencing factors and crack resistance performance indexes is obtained, which provides a solid guarantee for obtaining more accurate test results.

4 Low-temperature crack resistance test of toughened epoxy asphalt mixture

According to the relationship between different factors and crack resistance index, the test was carried out. In practical problems, there are many factors that affect the test indexes. In the system with a large number of factors, the specific development trend of the system is determined through the joint action of factors. The following focuses on the analysis and research combined with grey theory. The grey correlation analysis method mainly uses the similarity degree of sequence curve geometry to judge whether there is correlation between different factors (Xu et al., 2018). At the same time, in mathematics, the similarity is measured by grey correlation degree.

Figure 7 Operation flow chart of grey correlation analysis



Because of the characteristics of small amount of calculation and high precision, grey relational analysis has been widely used in practice. The specific operation process is shown in Figure 7.

1 clear reference sequence

2 different parameter sequences are compared (Liu et al., 2019b; Li et al., 2016)

3 the grey correlation degree is calculated

4 results analysis.

On the basis of the above, the following experimental test mainly selects seven factors, and each factor selects three levels for orthogonal experiment. The values of different factors and levels are shown in Table 1.

Table 1 Factors and horizontal combinations

Level number	*Factor number*	*a*	*b*	*c*	*d*	*e*	*f*
	Binder type	*Oil stone ratio*	*Types of stone*	*Aging*	*Fibre parameters*	*Types of mineral powder*	*Stirring temperature*
01	Zhonghai	4.95%	Limestone	Not aged	0%	Silica fume	170°C
02	Modified Zhonghai	4.65%	Granite	Short-term	3%	Limestone	175°C
03	Zhonghai + Durofiex	5.25%	Basalt	Long-term	5%	Calcium carbonate	180°C

Table 2 Calculation results of average value of experimental data index

Experiment serial number	*Bending tensile strength of joist/MPa*	*Flexural tensile strain of joist*	*Flexural tensile modulus of joist/MPa*	*0°C splitting strength/ MPa*	*–10°C splitting strength/ MPa*	*–20°C splitting strength/ MPa*
01	12.87	2,260.76	5,346.18	3.24	4.39	4.01
02	11.63	2,815.11	3,910.06	3.53	3.85	4.73
03	12.77	2,743.88	4,285.63	3.21	4.11	5.03
04	15.61	2,717.37	5,410.32	3.37	4.92	4.12
05	11.61	3,123.78	3,406.09	3.23	4.65	5.36
06	15.70	3,270.48	4,602.33	3.25	4.79	4.13
07	13.25	3,287.32	3,736.46	3.55	4.81	3.75
08	10.78	2,411.10	4,156.10	3.21	4.00	3.57
09	14.53	5,191.32	5,191.32	3.37	4.49	4.94
10	12.65	2,267.04	5,190.47	3.64	4.71	4.81
11	13.36	2,657.81	4,791.52	3.04	4.55	3.87
12	12.07	2,637.60	4,338.70	3.07	4.18	4.14
13	13.36	2,619.10	4,906.60	3.44	4.77	5.01
14	15.46	3,566.49	4,077.18	3.74	4.43	4.49
15	16.27	3,578.99	3,578.99	3.57	4.45	4.21

In order to obtain more ideal experimental results, it is necessary to analyse and process the experimental results. The experiment can be divided into two different forms:

1 visual method

2 method of variance analysis.

It is very simple and convenient to analyse a single index or factor. In the process of practical application, it is mainly used to measure the specific number of experimental results (Du et al., 2017; Zheng et al., 2018). Based on the above experimental data, 15 groups of experimental tests were carried out. The splitting tensile strength and flexural tensile failure modulus of different samples are tested, which lays a solid foundation for further data analysis. Tables 2 and 3 are the calculation results of the average values of the above experimental data.

Table 3 Calculation of experimental data index

Experiment serial number	*0°C splitting strain*	*–10°C splitting strain*	*–20°C splitting strain*	*0°C splitting modulus/ MPa*	*–10°C splitting modulus/ MPa*	*–20°C splitting modulus/ MPa*
01	4,894.18	4,826.10	1,828.41	829.09	1,255.59	2,896.39
02	4,594.78	4,564.49	1,051.02	928.21	1,071.60	5,868.71
03	3,961.25	4,715.94	4,554.40	940.44	1,153.92	1,535.16
04	3,999.11	5,160.17	3,453.91	993.26	1,307.22	1,523.42
05	3,385.76	4,521.58	3,552.35	1,096.48	1,391.30	2,039.87
06	5,356.08	6,634.22	3,900.67	759.85	983.98	1,481.66
07	4,869.90	4,746.23	1,424.57	920.15	1,341.49	3,329.92
08	4,461.01	4,251.51	939.96	840.37	1,251.20	4,846.17
09	3,272.18	5,795.27	3,615.45	1,246.70	1,063.05	1,844.05
10	4,370.14	3,474.10	3,393.33	1,078.58	1,820.18	1,887.30
11	4,620.02	4,493.82	1,878.90	776.58	1,359.76	2,710.88
12	4,594.78	4,635.17	1,666.89	1,026.37	1,192.17	3,625.91
13	4,281.80	4,483.72	1,586.11	937.22	1,327.16	4,450.24
14	4,877.48	4,958.25	1,525.54	665.65	1,154.52	3,849.93
15	5,021.35	4,211.13	2,000.06	812.70	1,323.69	2,329.49

Tables 4 and 5 show the coefficient of variation under different experimental intensities and the coefficient of variation of strain data in different experiments.

Analysis of the experimental data in Tables 4 and 5 shows that the coefficient of variation of splitting strength is obviously smaller, while that of joist bending is obviously larger. The maximum value of coefficient of variation is at 20°C.

In the following, the bending tensile strain of the joist is set as the inspection index, and the grey correlation method is used to analyse the influencing factors. The original data of the joist are shown in Table 6 (Li et al., 2019d).

Table 4 Variation coefficient of strength index

Experiment serial number	*Coefficient of variation of strength index/%*			
	0℃ splitting	*–10℃ splitting*	*–20℃ splitting*	*Joist bending*
01	7.55	6.62	5.83	7.30
02	7.24	18.47	10.49	12.45
03	9.83	9.49	4.73	20.43
04	7.19	3.36	5.03	7.34
05	8.47	6.10	8.04	7.42
06	9.77	8.20	5.83	10.87
07	9.44	5.18	11.73	5.51
08	4.96	10.83	23.87	3.97
09	6.40	5.81	4.02	7.86
10	6.24	4.48	14.47	13.91
11	5.54	10.23	7.52	9.23
12	4.04	10.64	6.01	11.69
13	4.13	6.87	3.82	8.43
14	7.80	10.15	6.18	12.58
15	10.52	6.84	11.60	16.52
Mean value	7.275	8.218	8.611	10.367

Table 5 Variation coefficient of strain index

Experiment serial number	*Variation coefficient of strain index/%*			
	0℃ splitting	*–10℃ splitting*	*–20℃ splitting*	*Joist bending*
01	8.62	9.85	20.02	19.17
02	10.71	8.09	24.94	18.63
03	15.26	11.64	25.57	17.96
04	9.80	4.45	26.86	11.89
05	9.73	7.16	3.35	16.59
06	6.82	6.55	10.55	16.87
07	6.84	6.80	11.63	5.64
08	3.80	4.93	13.38	12.60
09	8.42	13.03	15.41	4.52
10	9.30	18.83	28.91	10.64
11	11.94	19.18	35.95	9.01
12	12.93	11.18	16.67	20.38
13	19.08	6.11	26.40	19.44
14	7.31	6.34	21.42	13.20
15	5.99	2.45	16.82	12.38
Mean value	9.77	9.106	19.859	13.928

Table 6 Original data of joist

Content (%)	*Bending tensile strain*	*Oil stone ratio*	*0.075 mm*	*0.15 mm*	*0.30 mm*	*0.60 mm*	*1.20 mm*	*2.38 mm*	*4.80 mm*
1	2,784	5.16	2.4	3.5	7.0	11.7	11.7	15.2	30.4
2	2,901	5.31	2.1	4.01	12.15	7.6	7.6	13.3	34.2
3	3,075	5.46	3.6	4.71	6.14	14.6	14.8	13.0	24.9
4	2,995	5.71	4.2	3.01	10.11	9.7	10.7	12.5	29.7
5	2,963	5.76	4.8	3.71	5.12	6.8	6.8	11.8	43.9
6	2,842	5.01	2.1	4.31	10.16	13.7	13.7	10.5	27.9
7	2,721	6.06	2.7	4.91	4.12	9.8	9.6	9.8	41.8
8	3,047	6.31	3.4	3.31	9.13	5.8	5.7	8.4	46.8
9	3,149	6.34	3.9	3.91	3.11	12.7	12.9	7.6	39.0
10	3,036	6.61	4.5	3.51	8.14	7.9	8.7	6.4	41.6
Mean value	2,951.3	5.773	3.37	3.889	7.518	10.03	10.22	10.85	36.02

The correlation degree, strength range, strain range and modulus range of different influencing factors are determined by Table 7.

Table 7 Analysis of influencing factors

Type	*Correlation degree*	*Strength range value/MPa*	*Strain range value/MPa*	*Modulus range/MPa*
Mixing temperature	0.9614	0.65	54	278
Types of mineral powder	0.8570	0.48	215	284
Fibre parameters	0.9063	1.23	395	587
Aging	0.8225	1.08	197	238
Types of stone	0.8631	1.39	98	325
Oilstones	0.8632	1.68	401	208
Types of asphalt	0.8737	2.57	553	752

Table 8 Influence range of different factors on failure tensile strain

Different types of factors	*The influence range of failure tensile strain at 0℃*	*The influence range of failure tensile strain at –10℃*	*The influence range of failure tensile strain at –20℃*
Mixing temperature	202	398	497
Types of mineral powder	289	213	401
Fibre parameters	158	587	396
Aging	1,125	852	1,702
Types of stone	278	200	765
Oilstones	265	867	801
Types of asphalt	52	621	512

Among them, the order of correlation degree is as follows: 01 > 03 > 08 > 07 > 06 > 05 > 02 > 04. Asphalt is the most influential factor on beam bending strength and bending strain. From the influence of various factors on the beam modulus, the asphalt type has a greater impact.

The influence range of different factors on the failure tensile strain is shown in Table 8.

According to the experimental data in Table 8, under the condition of 0°C failure tensile strain, the influence on the stone type is the largest; under the condition of –10°C failure tensile strain, the influence on oil aggregate ratio is the largest; under the condition of –20°C failure tensile strain, the influence on aging is the greatest.

The analysis results of influence of epoxy resin content on asphalt mixture performance are shown in Table 9.

Table 9 Influence of epoxy resin content on performance of epoxy asphalt mixture

Resin content/ %	*Oil stone ratio/ %*	*Design porosity of epoxy asphalt mixture/%*	*Void ratio of mineral aggregate/ %*	*Asphalt saturation/ %*	*Stable value/ KN*	*Flow value/ 0.1 mm*	*Splitting strength/ MPa*
0	6.5	5.0	15.2	81.5	12.9	44.2	1.01
	7.0	4.5	15.3	86.8	13.2	46.3	2.04
20	6.5	3.6	15.6	93.2	27.9	40.5	3.37
	7.0	3.3	15.7	95.4	27.8	41.8	3.31
35	6.5	3.5	15.8	94.9	35.8	37	3.94
	7.0	3.1	16.0	97.8	35.5	38.3	3.86
50	6.5	3.5	15.7	94.7	20.7	29.7	6.10
	7.0	3.2	15.9	96.9	21.2	30.5	5.94

Analysis of the experimental data in Table 9 shows that under the same epoxy resin content, when the asphalt aggregate ratio increases, the porosity of epoxy asphalt mixture shows a downward trend, while the porosity of mineral aggregate, asphalt saturation and flow value show a downward trend. In addition, when the content of epoxy resin increases significantly, the stability value and splitting strength increases.

5 Experimental test

5.1 Experimental scheme

In order to further test the application performance of this method, the overall experimental scheme is designed as follows:

1. Experimental environment: The hardware device is a 64 G SSD, 16 G cache and 8-core high-speed processor computer. SQL 2018 database and MATLAB software are set inside the computer to improve the experimental accuracy.
2. Experimental sample data: The splitting tensile strength and flexural tensile modulus of different samples of toughened epoxy asphalt mixture were measured and calculated repeatedly, and the most accurate data were used as the original experimental data.

3 Experimental methods: The method of Li and Qin (2018), method of Zhang et al. (2016), method of Zhu et al. (2019) and method designed in this paper are selected as experimental methods.

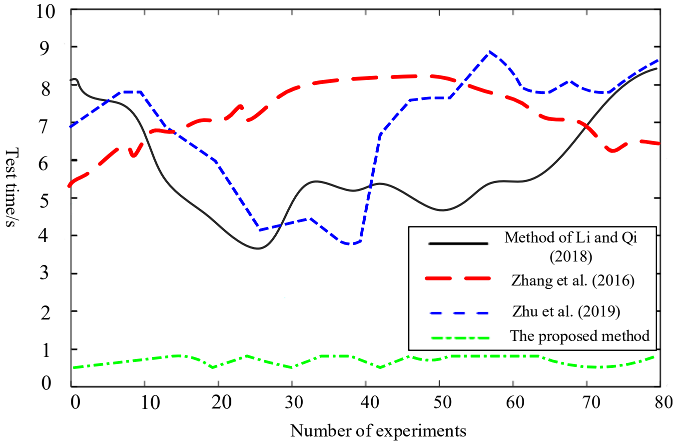
4 Experimental indexes: Firstly, the test time of different methods is compared, the shorter the test time is, the higher the test efficiency is; then the test error of four methods is compared, the lower the test error is, the higher the test accuracy is.

5.2 Experimental results

5.2.1 Test time

Based on the above experimental scheme, four methods are used to compare the test time, and the results are shown in Figure 8.

Figure 8 Test time (see online version for colours)



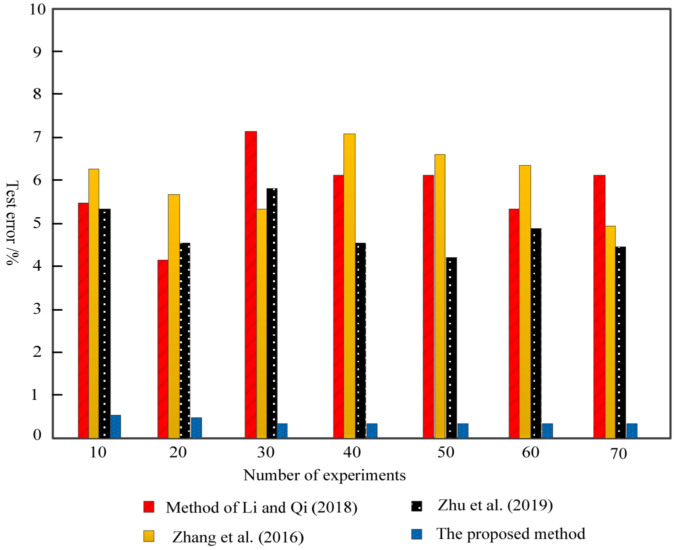
It can be seen from Figure 8 that the test time range of Li and Qin (2018) method is 3.4 s–8.4 s, that of Zhang et al. (2016) is 5.3 s–8.3 s, and that of Zhu et al. (2019) is 3.9 s–8.9 s, the test time of the research method is always less than 0.8 s, which is always lower than that of the literature comparison method, indicating that the method can quickly obtain the test results of low temperature crack resistance of toughened epoxy asphalt mixture.

5.2.2 Test error

On the basis of the above experiments, the test errors are compared, and the results are shown in Figure 9.

As can be seen from Figure 9, the test error range of Li and Qin (2018) method is 4.2%–7.3%, that of Zhang et al. (2016) is 5.4%–8.2%, and that of Zhu et al. (2019) is 4.3%–5.7%. Compared with the literature comparison method, the experimental error of the research method is always kept below 0.6%, indicating that the test results obtained by this method are more accurate. The reason is that the method is mainly based on the research results of low temperature performance of epoxy asphalt mixture, combined with grey theory to analyse the correlation between epoxy asphalt content, different screening pass rate and low temperature performance index, and analyse the relationship between different influencing factors and low temperature performance, so as to obtain more accurate test results.

Figure 9 Test error (see online version for colours)



6 Conclusions

This paper focuses on the low-temperature crack resistance test of toughened epoxy asphalt mixture, mainly according to the results of low-temperature performance of epoxy asphalt mixture, combined with grey theory, analyses the correlation between epoxy asphalt content, different sieve pass rate and low-temperature performance index, and clarifies the relationship between different influencing factors and anti cracking performance indexes, and according to the analysis results, the relationship between the two indexes is analysed. The results show that the compatibility between epoxy asphalt and asphalt is cross, and the stability and dispersion of epoxy asphalt are improved effectively by surfactant, and the amount of epoxy asphalt has the most significant effect on the low-temperature tensile strain of trabeculae. In the set range, the low-temperature bending tensile strain of the beam will increase with the increase of asphalt content. Through the orthogonal experimental analysis, the asphalt type has a very significant impact on the low temperature performance of the mixture. The experimental results show that the test time of the proposed method is always less than 0.8 s, the test error is always less than 0.6%, the test time is short and the error is low, so it can be widely used in practice.

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