Investigation of the Properties of Epoxy Resin-Modified Asphalt Mixtures for Application to Orthotropic Bridge Decks

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ABSTRACT: Compared with the general pavement, the steel bridge deck pavement endure much larger deform and higher temperature. Epoxy asphalts were used to prepare modified asphalt concrete for steel bridge deck paving. The effects of epoxy resin contents on the fatigue life and creep properties of epoxy asphalt mixture were investigated in this study. The fatigue properties of epoxy asphalt mixtures were studied by the indirect tension fatigue test at different stress. A static creep test with a loading and recovery period was conducted on the asphalt mixture. The results showed that the fatigue life and recovery elasticity of asphalt mixtures with epoxy resins was large, which indicated that the fatigue property could be improved by epoxy resin. Compared with control asphalt, epoxy asphalt showed better resistance to deformation and recovery performance. Epoxy resin has caused a dramatic ascent in the creep stiffness modulus of asphalt mixture. And Burgers model can describe the creep performance of epoxy asphalt. Based on the obtained results, epoxy asphalt mixtures had decrease in permanent deformation and increase in fatigue life. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 2310–2316, 2011

Key words: epoxy asphalt; fatigue; creep; permanent deformation

INTRODUCTION

Asphalt is an important construction material in paving industry. Nowadays, asphalt concrete pavements have to sustain increasingly large loads. When these loads are combined with adverse environmental conditions, the failures (such as the low temperature cracking, fatigue cracking, and the permanent deformation) lead to the rapid deterioration of road structures.[1] To improve the engineering properties of asphalt, it is frequently blended with various modifiers. The modification of asphalt by polymers produces a new material, which sometimes has very different mechanical properties from the conventional asphalt.[2]

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Orthotropic steel decks have been widely applied to long span bridges because its light weight contributes to reduce dead load. Compared with the general pavement, the steel bridge deck pavement endure larger deform and higher temperature. Conventional plastomeric or elastomers polymers-modified asphalt cannot change the thermoplastic nature of asphalt, which means that asphalt mixture flow easily at high temperature.[3,4] To resolve this problem, asphalt binders and epoxy resin are used in combination for resolving the afore-mentioned problems. Epoxy asphalt is prepared by mixing an epoxy resin and an asphalt material with curing agent.

Generally, polymer-modified asphalt is a material with strong viscoelastic behavior. As such, it requires new methods and new parameters for its characterization.[5] The creep experiment is one of the basic tests for the study of mechanical properties of materials. During creep, the stress is kept constant and the strain varies. The relevant material function in creep is the compliance function.[6] It is believed that this test and parameter are important for the estimation of the permanent deformation in asphalt pavements. In addition, the fatigue resistance of asphalt mixture is the ability to withstand repeated stress/strain without fracture. Generally speaking, low asphalt content, high air void mixtures are prone to show low fatigue life, and high asphalt content mixtures tent to permanent deformation first.

Epoxy asphalt has been successfully prepared in previous investigation.[7,8] However, the effects of epoxy resin on the pavement engineering performances are significant, and the mechanism is complex. In this study, the epoxy asphalt mixture was prepared and the effects of the epoxy resin content on the creep and fatigue properties of epoxy asphalt mixture were assessed.

EXPERIMENTAL

Raw materials

The 60/80 pen grade asphalt was used, and the physical properties of the asphalt and chemical composition are listed in Table I.

The styrene-butadiene-styrene (SBS) copolymer used, Grade 1301, was produced by the Yueyang Petrochemical Co., China. This was a linear-like SBS, containing 30 wt % styrenes, and the weight-average molecular weight of SBS is 120,000. The epoxy resin used was diglycidyl ether of bisphenol A and its epoxy value is 0.52 mol/100 g. It was made in Shanghai Xinhua Resin Co., Shanghai, China. Methyl tetrahydro phthalic anhydride curing agent was provided by Jiaxing Fine Chemical Co., Zhejiang province, China.

The dolerite aggregate was used for preparing epoxy asphalt mixture and the crushed limestone powders were applied as mineral powder (or filler). Table II exhibits the summary of the aggregate and mineral powder properties. The combined aggregate gradation curve is given in Figure 1.

TABLE II
Properties of the Used Aggregate and Mineral Powder

Raw materials	Test properties		Test results
Aggregate	Coarse aggregate angularity (%)		100
	Fine aggregate angularity (%)		52
	Flat/elongated particles (%)		9.8
	Clay content (%)		0.3
	Coarse aggregate specific gravity (g/cm^3)		2.838
	Coarse aggregate absorption (%)		2.3
	Fine aggregate specific gravity (g/cm^3)		2.801
	Fine aggregate absorption (%)		4.3
	Sand equivalent (%)		65
	Combined aggregate specific gravity (g/cm^3)		2.825
	Combined aggregate apparent specific gravity (g/cm^3)		3.022
	Abrasion loss (%) (Los Angeles)		12.6
	Frost action (%) (with Na_2SO_4)		8.15
	Polishing value		0.60
Mineral powder	Specific gravity (g/cm^3)		2.727
	Major chemical compounds	CaO content (%)	52.3
		SiO_2 content (%)	1.68
	Percent passing (%)	0.3 mm	99.4
		0.15 mm	97.4
		0.075 mm	88.9

Preparation of asphalt mixture specimens

The Marshall method (ASTM D1559) was used for determining optimal asphalt content of epoxy asphalt mixtures. The mixture was mixed at 120°C, and the specimens (101.6 mm diameter and 63.5 ± 1.3 mm high) were prepared with 50 blows compacting energy per side at a temperature of 110°C. The Superpave gyratory compactor (EP-31111 model, America) was employed to prepare epoxy asphalt mixture specimens for creep tests and indirect tensile fatigue tests. Gyrate number is 100. Cores were taken from the compacted specimens. To obtain the required geometry, the obtained cores were carefully sawed and polished. Two identical specimens were tested and analyzed for creep tests or indirect tensile fatigue tests. The diameter and height of specimens for creep tests were 100 and 100 mm, and for indirect tension fatigue test were 100 and 63.5 mm, respectively. During specimen's preparation, epoxy asphalts were blended with aggregates for about 90 s prior to the addition of mineral filler. The air void contents for all specimens were controlled at 2.5% by the total volume of compacted asphalt concrete to increase the impermeability and fatigue performance of asphalt concrete.

TABLE I
Physical Properties of Asphalt

	Test properties	Measured values
Physical properties	Penetration (25°C, 0.1 mm)	77
	Softening point (°C)	45.9
	Ductility (15°C, cm)	118
	Ductility (5°C, cm)	13.4
	Viscosity (135°C, mPa s)	500
Chemical composition (wt %)	Saturates	23.24
	Aromatics	32.17
	Resins	33.86
	Asphaltenes	10.73

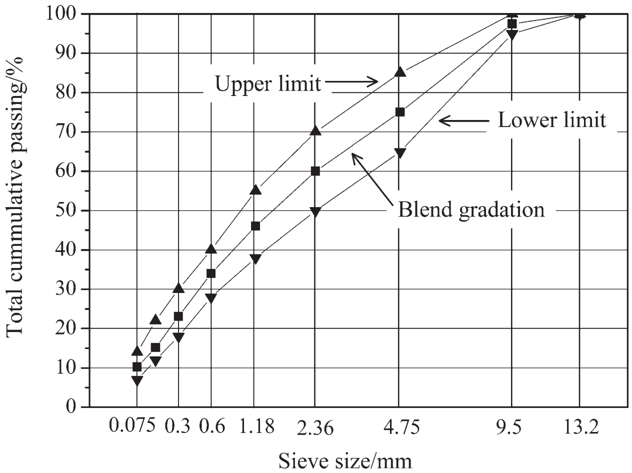

Figure 1 Combined aggregate gradation curve.

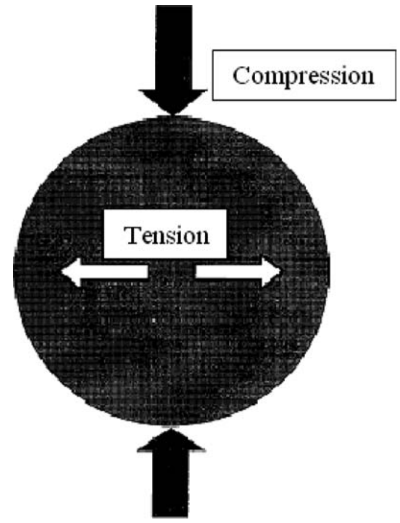

Figure 3 Indirect tension fatigue test of asphalt mixtures.

Performance tests

Indirect tensile fatigue tests were also performed by means of Universal Testing Machine (UTM-25, Australia). The loading pattern used was a haversine signal. During a complete repetition, the loading time was 0.1 s following by a rest period of 0.4 s. The fatigue tests conducted at the temperature of 15°C. Five stresses (0.369, 0.563, 0.749, 0.936, and 1.119 MPa) were involved. Five stress levels are 20, 30, 40, 50, and 60% of the indirect tensile strength of original asphalt mixture. The Apparatus of indirect tensile and the testing are shown in Figures 2 and 3. The indirect tensile strength of original asphalt mixture is 1.845 MPa. When the 50% strength is reduced, it is assumed that fatigue life has been reached and the test is ended.

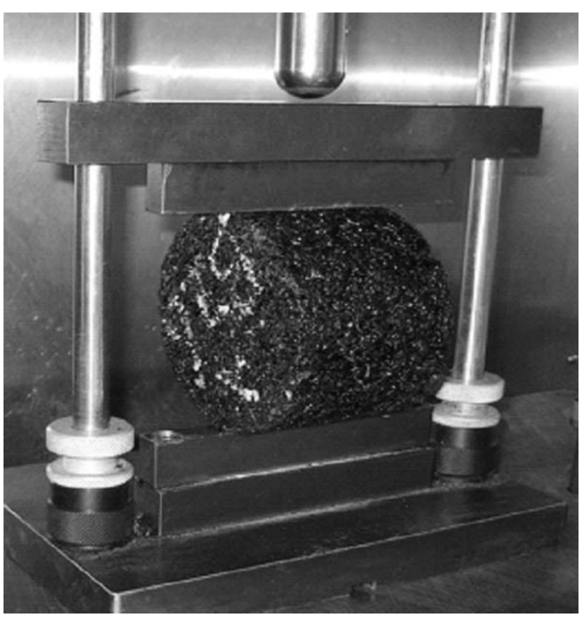

Figure 2 Apparatus of indirect tensile test.

The static creep tests were carried out using UTM 25 to apply axial stress to asphalt mixture specimens measuring the vertical deformation. The test consists of applying a static axial stress of 100 kPa on the upper part of a cylindrical specimen for a period of 3600 s and unloading time is 4500 s at a temperature of 20°C. The axial strain of the sample is recorded as a function of time.

RESULTS AND DISCUSSION

Conventional physical properties of epoxy asphalt mixture

The voids in mineral aggregate, voids filled with asphalt, air void are very important to asphalt mixtures, because these volumetric properties significantly affect asphalt mixture performances. Table III shows the conventional physical properties of epoxy asphalt mixture with different contents of epoxy resin. Marshall stability is defined as the maximum load carried by a compacted specimen tested at 60°C at a loading rate of 50 mm/min. This stability is generally a measure of the mass viscosity of the aggregate-asphalt cement mixture and is affected significantly by the angle of internal friction of the aggregate and the viscosity of the asphalt cement at 60°C. The Marshall stability of 10.8, 23.4, 32.2, and 53.9 kN was obtained for epoxy asphalt mixture with 0, 20, 35, and 50 wt %. It means that epoxy resin gives the contribution of the high temperature deformation resistance to the asphalt mixture.

Generally, Marshall stability and flow values are generally measured for information but not used for acceptance. It is not an effective index in predicting

TABLE III
Conventional Physical Properties of Epoxy Asphalt Mixture

Properties		Epoxy asphalt mixtures with different contents of epoxy resin			
		0 wt %	20 wt %	35 wt %	50 wt %
Voids in mineral aggregate (%)		13.7	13.7	13.9	13.8
Voids filled with asphalt (%)		83.9	83.2	84.9	84.1
Air void (%)		2.2	2.3	2.1	2.2
Marshall stability (kN)		10.8	23.4	32.2	53.9
Flow (0.1 mm)		48	39	23	16
Indirect tensile strength (MPa)		0.83	1.98	2.85	4.6
Loss of Marshall stability (%)		14.3	12.8	9.8	9.6
Loss of indirect tensile strength (%)		11.5	11.2	10.9	10.8
Rutting	Dynamic stability (cycles/mm)	718	10,264	27,391	30,216
	Maximum deflection (mm)	6.8	2.6	0.248	0.247

the deflection of asphalt mixture. The wheel tracking test with a solid rubber-faced tire was used to provide the data of the permanent deformation (rut) evolution with the repetitions of loading. So the wheel tracking test was employed to evaluate the rutting resistance of epoxy asphalt mixture. The experiment condition were as follows: the square slab specimens are immersed in dry atmosphere at 60°C ± 0.5°C for 6 h and then a wheel pressure of 0.7 MPa, the wheel traveling distance of the wheel was 230 ± 10 mm at a speed of 42 ± 1 cycles/min, is load to test for 60 min by a special solid rubber tire. Rut deflections were measured per 20 s and dynamic stability was defined as eq. (1):

$$\mathrm{DS} = \frac{15N}{d_{60} - d_{45}} = \frac{42 \times 15}{d_{60} - d_{45}} \qquad (1)$$

where N is wheel traveling speed, generally, $N = 42$ cycles/min, d_{60} and d_{45} is the tracking depth at 45 and 60 min, respectively.

Dynamic stability and maximum deflection was obtained for epoxy asphalt mixtures with different content of epoxy resin. The results showed that asphalt mixture show high dynamic stability and antideflection when epoxy asphalt was used. Rutting phenomena indicated that the epoxy resin increase the elastic and stiffness of asphalt binder.

To investigate the effect of water on epoxy asphalt mixture, the loss of Marshall stability and the loss of indirect tensile strength was measured. The loss of indirect tensile strength and loss of Marshall stability are usually used to predict the stripping susceptibility of asphalt mixtures. The maximum values necessary to ensure good pavement performance and therefore 25 and 20% for the loss of Marshall stability and loss of indirect tensile strength are generally considered to be reasonable and acceptable maximum values. The results indicated that both the loss of Marshall stability and loss of indirect tensile strength are less than 11%, though related values are different. Therefore, the moisture susceptibility of asphalt mixture is improved significantly when epoxy asphalt binder is used to prepare asphalt mixture. It is attributed to epoxy resin increasing the adhesion between asphalt binders and aggregate, and cohesive of asphalt binder. Thus, epoxy asphalt mixture show high Marshall stability and indirect tensile strength. Water is not easy to destroy the adhesion between asphalt binder and aggregate at high temperature, and cohesion of asphalt binder. Thus, the moisture susceptibility of asphalt mixture is improved.

Fatigue properties

Indirect tensile fatigue test results of asphalt mixtures with different contents of epoxy resin at different stress corresponding to the fatigue life are shown in Figure 4. When compared with the control mixture (the epoxy resin contents is 0 wt %), the loading repetitions to failure N_f of epoxy asphalt mixture are

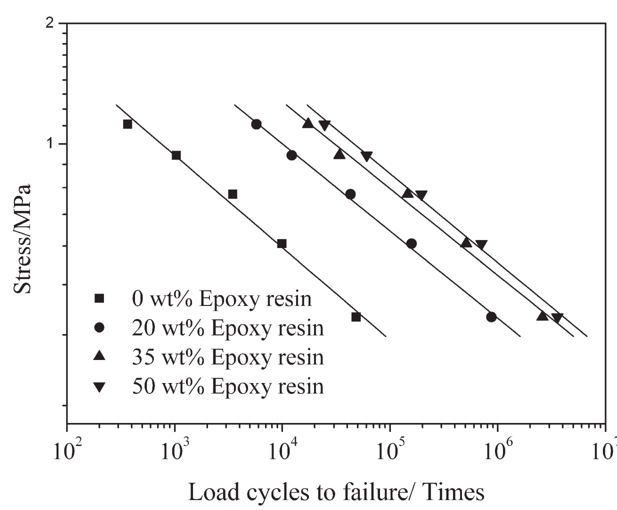

Figure 4 Fatigue life of epoxy asphalt mixtures.

TABLE IV
Fatigue Equation of Epoxy Asphalt Mixtures and Regression Coefficient

Epoxy resin contents/wt %	Fatigue equation	R^2
0	$N_f = 754(\sigma_0)^{-4.3312}$	0.9888
20	$N_f = 10{,}033(\sigma_0)^{-4.5849}$	0.9965
35	$N_f = 30{,}498(\sigma_0)^{-4.6127}$	0.9912
50	$N_f = 40{,}397(\sigma_0)^{-4.6486}$	0.9878

increased remarkably. For example, the N_f at 0.369 MPa stress for three epoxy asphalt mixtures are 18 times (20 wt % epoxy resin contents), 54 times (35 wt % epoxy resin contents), 74 times (50 wt % epoxy resin contents) of the corresponding N_f of the control mixture, respectively. It indicates that the fatigue property of asphalt mixtures can be improved with the addition of epoxy resin. The reason maybe that the concentrated stress produced by fatigue loading can be absorbed and dispersed by epoxy resins and the development of micro-cracks can be delayed, which result in the postpone of damages for asphalt mixtures. Otherwise, at low stress levels, elastic strain acts on dominant action in the fatigue process. The elastic strain recovered after unloading. The plastic deformation becomes dominant action with stress level increasing. Epoxy resin can increase the elasticity of asphalt. Thus, it is obvious that the fatigue property of asphalt mixture is enhanced significantly at lower stress levels. The fatigue property of asphalt mixture can be depicted by the fatigue equation as eq. (2):

$$N_f = K(\sigma_0)^{-n} \tag{2}$$

where N_f is the fatigue life; σ is the applied stress; K, n are material constants.

TABLE V
Composition of Creep Deformation of Asphalt Mixture

Mixture	ε /10^{-6}	$\varepsilon_e + \varepsilon_{de}/10^{-6}$	$\varepsilon_v/10^{-6}$
Control	2342	595	1741
EP 20 wt %	954	167	787
EP 35 wt %	618	270	348
EP 50 wt %	491	212	279

Table IV gives the regression constants of asphalt mixtures with and without epoxy resin. It can be observed that the values of K and n are increased when epoxy resins are added, which result in an increase in cycle numbers to failure for asphalt mixtures, especially at lower stress levels. Moreover, it can be seen that the fatigue life increase with the epoxy resin contents increasing. Furthermore, the fatigue properties of epoxy asphalt were predicted by fatigue equation. To meet different requirement, the epoxy asphalt was prepared by mixing different content of epoxy resin.

Creep properties

Figure 5 displays the results of comparison between the strain of control asphalt mixture and epoxy asphalt mixtures at 20°C temperature and 100 kPa stress level. Deformation resistance of epoxy asphalt mixture is more than control asphalt mixture as seen in Figure 5. The amount of strain in epoxy asphalt mixture is lesser than control asphalt mixture's. This behavior can be attributed to the epoxy asphalt binder of these mixtures. Epoxy asphalt mixtures have same gradation as control asphalt mixture. The mechanical properties of epoxy asphalt mixtures mostly rely on the properties of binder and the contact of stone to stone. Epoxy asphalt binder show more cohesive and adhesive than original asphalt

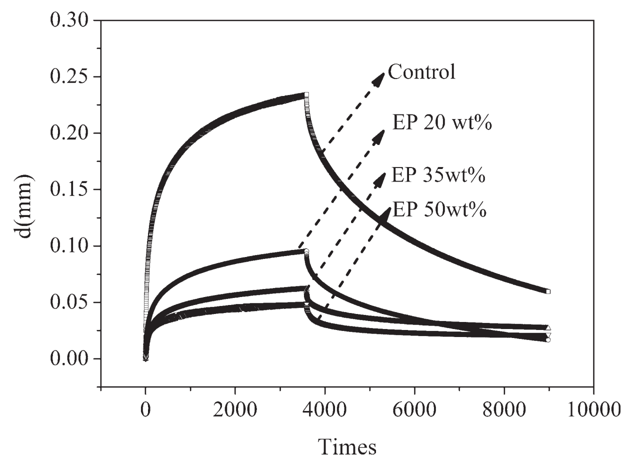

Figure 5 Creep curves for asphalt mixture with different epoxy resin.

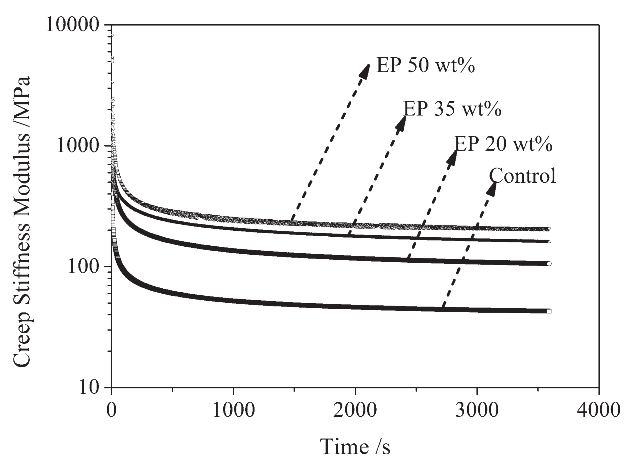

Figure 6 Development of creep stiffness modulus for epoxy asphalt mixtures.

TABLE VI
Parameters for Revised Burgers Model

Mixture	E_1 (/10^4 MPa)	E_2 (/MPa)	η_2 (/MPa s)	A (/Pa s)	B (/10^{-2})	*Error* (/%)
Control	1.142	183	0.2493	1.033	1.442	4.128
EP 20 wt %	3.102	192	0.2521	1.955	1.187	4.367
EP 35 wt %	4.110	193	0.2597	3.148	1.133	3.291
EP 50 wt %	5.969	195	0.2683	0.005	1.636	2.980

binder. Therefore, epoxy asphalt mixture show more resistance to deformation than control asphalt mixture.

Table V showed the composition of creep deformation of asphalt mixture containing different contents of epoxy resin. The total deformation and permanent deformation of epoxy asphalt mixture is lesser than control asphalt mixture's. The total deformation for control asphalt mixture is 2342 and three epoxy asphalt mixture are 954 (20 wt % epoxy resin contents), 618 (35 wt % epoxy resin contents), and 491 (50 wt % epoxy resin contents), respectively. Epoxy asphalt mixture showed more recoverable deformation than control asphalt mixture. These attributed to epoxy resin increasing the elastic and stiffness of asphalt binder.

Figure 6 showed that the development of creep stiffness modulus for asphalt mixtures with different contents of epoxy resin. Creep stiffness modulus trends, have shown a climb down. In control asphalt mixture, the rate of reduction is more than epoxy asphalt mixtures. Epoxy resin has caused a dramatic ascent in the creep stiffness modulus of asphalt mixtures so that epoxy asphalt mixture endured a larger of stress. After a sharp drop in early stages of loading, the creep stiffness modulus has roughly reached a plateau of 60, 108, 112 and 118 MPa for asphalt mixture with the epoxy resins of 0, 20, 35 and 50 wt %, respectively.

Revised Burgers model was used for fitting the creep curves of asphalt mixture and estimating their resistance deformation. The Revised Burgers model can be depicted by the equation as eqs. (3) and (4):

$$\varepsilon(t) = \sigma_0\left[1/E_1 + (1 - e^{-Bt})/AB + (1 - e^{-t\tau})/E_2\right] \quad (3)$$

$$\varepsilon(t) = \sigma_0\left[(1 - e^{-Bt_0})/AB + (1 - e^{-t_0\tau})e^{-(t-t_0)\tau}/E_2\right] \quad (4)$$

where σ_0 is applying stress, t and t_0 is time of start loading and total loading, E_1, $E_{2,}$ $\eta_{1,}$ and η_2 are constants, $\tau = E_2/\eta_2$. E_1 is elastic component coefficient, E_2 is delayed elasticity coefficient, η_1 is viscosity coefficient, η_2 delay viscosity coefficient.

The obtained mathematical functions for loading stage of tested samples are shown in Table VI. The results indicated that the E_1, E_2, and η_2 increased with the epoxy resin contents increasing. The elasticity of asphalt binder increased remarkably for E_1 increased. The E_1 and η_2 increased meaning that the antirutting of asphalt mixture was improved. Thus, the epoxy resin increased the elasticity and delay viscosity of asphalt binder, so that the resistance deformation of asphalt mixture was improved. Otherwise, from the fatigue test and creep test data, it indicated that the fatigue life is large when elastic strain acts on dominant action in the fatigue test process because the elastic strain recovered after unloading. Epoxy resin can increase the elasticity of asphalt. Thus, the fatigue life and the recovery elasticity of asphalt mixture are enhanced significantly.

CONCLUSIONS

Based on the study of the properties of asphalt mixtures with different contents of epoxy resin, the following conclusions can be obtained:

1. Compared with the control asphalt mixture (the epoxy resin contents is 0 wt %), Epoxy resin can increase remarkably the loading repetitions to failure (N_f) of epoxy asphalt mixture. And the more epoxy resin, the more fatigue life when epoxy resin contents lower than 50 wt %.
2. Epoxy asphalt binder show more cohesive and adhesive than original asphalt binder. Therefore, epoxy asphalt mixture show more resistance to deformation than control asphalt mixture.
3. Epoxy resin has caused a dramatic ascent in the creep stiffness modulus of asphalt mixtures so that epoxy asphalt mixture endured a larger of stress. Burgers model can describe the creep performance of epoxy asphalt. Based on the obtained results, epoxy asphalt mixtures had decrease in permanent deformation and increase in fatigue life.

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