

Experimental study on dynamic modulus of thermosetting epoxy asphalt mixture for steel deck pavement

Chen Leilei Qian Zhendong Luo Sang

(Intelligent Transportation System Research Center, Southeast University, Nanjing 210096, China)

Abstract: In order to study the dynamic performance of the thermosetting epoxy asphalt mixture (EAM), an experimental program on the dynamic modulus $|E^*|$ is conducted. First, $|E^*|$ of the EAM under different temperatures and frequencies are tested through the simple performance test (SPT), and the effects of temperatures and frequencies on the dynamic modulus of the EAM are analyzed. Secondly, the static modulus of the EAM and the dynamic modulus of other two ordinary mixtures are tested and compared to $|E^*|$ of the EAM. Finally the dynamic modulus master curve is constructed using the time-temperature superposition principle. The results show that the $|E^*|$ values increase with the increase in the test frequency while on the other hand, the $|E^*|$ values decrease with the increase in the test temperature. It also can be seen from the results that the dynamic modulus corresponding to the actual vehicle mode is significantly greater than the static modulus, and the dynamic modulus of the EAM is greater than that of SBS mixtures and the common hot mixed asphalt (HMA). The study results can provide a theoretical basis for the design and mechanical analysis of the steel deck pavement.

Key words: dynamic modulus; epoxy asphalt mixture (EAM); master curve; time-temperature superposition principle

Bridge deck pavements have been extensively used to protect the bridge deck against moisture as well as provide good service quality^[1-2]. Only a few materials can meet these requirements, among which is the thermosetting material epoxy asphalt concrete. The epoxy asphalt mixture (EAM) is mixed by the thermosetting epoxy asphalt binder and high quality aggregates. Because of the thermosetting of the binder, the EAM usually performs differently from the normal thermoplastic material such as the HMA. Therefore, further study on the EAM is necessary.

As an irreversibly cure material, the thermosetting material can be completed through heating and chemical reactions, by which the curing process transforms the resin into plastic or rubber by a cross-linking process. Due to the added energy or catalysts, the molecular chains react at chemically active sites and are linked into a rigid, 3-D structure. Theoretically, the material can obtain a higher melting point when compared to the surrounding ambient temperature because of the greater molecular weight caused by the cross-linking

process. However, uncontrolled reheating causes the material to reach the decomposition temperature before the melting point is obtained. Therefore, a thermosetting material cannot be melted and re-shaped after it is cured^[3].

The dynamic modulus $|E^*|$ is one of the important material performance measures of the HMA to determine the elastic response of the pavement under wheel load. As pointed out by the mechanistic empirical pavement design guide, $|E^*|$ can be predicted at any combinations of temperature and frequency, using the $|E^*|$ master curve prepared at the reference temperature with reduced frequencies and the shift factors. Moreover, $|E^*|$ can be used to evaluate performances against permanent deformation and fatigue cracking, which are the primary modes of diseases that affect the durability of steel bridge deck pavements. Therefore, the dynamic modulus $|E^*|$ of the EAM is selected and investigated.

There are many researches conducted to study the modulus of steel bridge paving materials. Metcalf^[4] evaluated the fatigue and stiffness of bridge deck pavements based on the flexure loading tests in 1967. The National Cooperative Highway Research Program (NCHRP) of America carried out a series of researches on the dynamic modulus of the HMA^[5-7], and the test procedure and application of $|E^*|$ are concluded through the researches. Widyatmoko et al.^[8] used a stone mastic asphalt mixture with a polymer modifier on a steel bridge deck to improve the stiffness and the durability of the mixtures. Luo et al.^[9] researched rutting, low temperature cracking and fatigue characteristics of the epoxy asphalt mixture. However, these researches were often conducted on thermoplastic materials, and few researches on the dynamic modulus of thermosetting materials can be retrieved.

In order to investigate the dynamic performance of the thermosetting steel deck pavement material EAM, this paper presents an experimental study on the dynamic modulus of the EAM based on the simple performance test (SPT), which was recommended by NCHRP.

1 Materials and Specimen preparation

1.1 Materials preparation

Two main materials are involved in the $|E^*|$ test. The detail information of materials and specimen preparations are described as follows.

1.1.1 Epoxy asphalt

The binder used in the test is 2910-type domestic epoxy asphalt, which is composed of two components marked as A and B. Component A is the epoxy resin while component B consists of petroleum asphalt and the curing agent. The basic information of the binder is given in Tab. 1.

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Biographies: Chen Leilei (1985—), male, graduate; Qian Zhendong (corresponding author), female, doctor, professor, qianzd@seu.edu.cn.

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Tab. 1 Technical indices of 2910-type domestic epoxy asphalt

Technical indices	Measured value	Criteria	Test method
Mass ratio(A: B)	100: 290	100: 290	
Tensile strength(23 ℃)/MPa	3. 26	≥2. 0	ASTM D 638
Fracture elongation(23 ℃)/%	242	≥200	ASTM D 638
Viscosity from 0 to 1 Pa·s/min	110	≥50	JTJ052-2000

1. 1. 2 Aggregate

Aggregates make up about 93% to 94% of the weight for the total mixture. Therefore, careful considerations should be given to the selection of type and quality of the aggregates. In this study, the basalt aggregate and the limestone powder special for steel bridge pavements are selected based on the engineering practice. The maximum aggregate diameter is 13. 2 mm and the gradation curve is shown in Fig. 1.

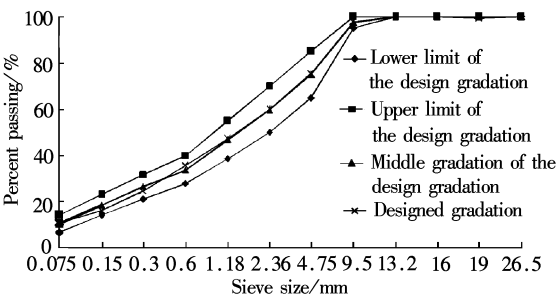


Fig. 1 Designed gradation in the test

1. 2 Specimen preparation

The $|E^*|$ test requires a cylindrical sample with a diameter of 100 mm and a height of 150 mm^[7]. 6. 5% is determined as the optimum asphalt content based on the Marshall mixture design procedure. The standard superpave mix procedure is employed to prepare the final test specimen. The specimen preparation procedure of the EAM is a little more complicated than that of the HMA for the thermosetting. First, the binder and the aggregate are mixed at 125 ℃. After reserving for 40 min at 120 ℃, a cylindrical specimen with a diameter of 150 mm and a height of 165 mm is shaped using a gyratory compactor, as shown in Fig. 2(a). After curing for 5 h at 130 ℃, the gyratory sample is cored and sawed to the target specimen as shown in Fig. 2(b). For each mixture, three replicates are prepared.

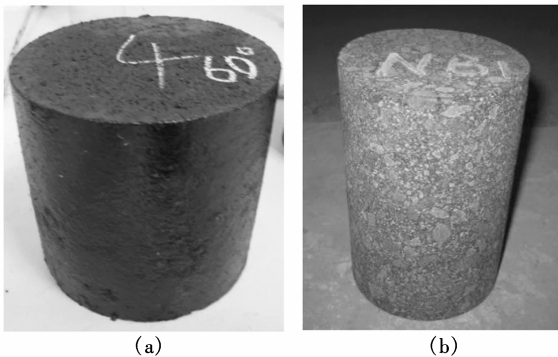


Fig. 2 Preparation of the specimen. (a) Cylinder specimen shaped by gyratory compactor; (b) Target specimen after coring and sawing

2 Parameters Selection

The experiments are conducted using the IPC simple performance tester, and the following testing parameters are selected according to the test equipment and the engineering practice.

2. 1 Test temperature

The simple performance tester can provide a temperature range from 4 to 60 ℃. In order to study the $|E^*|$ developing law and determine its values at various temperatures, 4, 20, 40 and 60 ℃ are chosen as test temperatures according to the engineering practice.

2. 2 Test frequency

The loading frequency is another important parameter for the tests. A continuous haversine axial compressive load is applied to the specimen. In order to study the developing law and determine the values of $|E^*|$ at various loading frequencies, 0. 1, 0. 2, 0. 5, 1, 2, 5, 10, 20 and 25 Hz are chosen as test loading frequencies.

2. 3 Test load

The $|E^*|$ tests are completed in a controlled stress mode, which produces strains smaller than 125 microstrains. This ensures that the response of the material is linear across the test temperatures used in this paper. The dynamic stress levels are set to 600, 300, 100 and 20 kPa corresponding to the test temperatures 4, 20, 40 and 60 ℃, respectively. The tests are conducted in a temperature-controlled chamber that is capable of holding temperatures from 4 to 70 ℃.

The test method DM-1 proposed by NCHRP 1-37A^[10] is followed. For each test specimen, the $|E^*|$ tests are conducted at selected temperatures and frequencies. A 60 s rest period is used between each frequency to allow some specimen recovery before applying the new loading at a lower frequency.

3 Test Results

3. 1 Effect of temperature

As stated above, epoxy resin and base asphalt are two major components of the epoxy asphalt. The epoxy resin is a thermosetting material affected little by temperature after curing, while the base asphalt is a thermoplastic material which shows plasticity as the temperature rises. In the test, the EAM appears more and more plastic but does not melt with the increase in the temperature. Thus a reduction of $|E^*|$ values with the temperature increasing is observed as shown in Fig. 3.

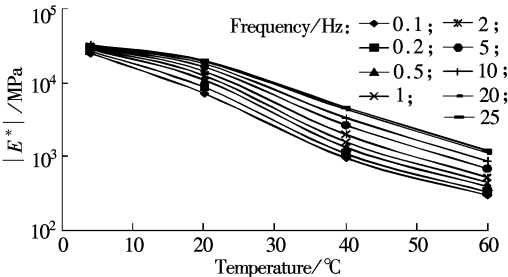


Fig. 3 Dynamic modulus $|E^*|$ of EAM at different temperatures

3.2 Effect of frequency

Fig. 4 shows the test results of $|E^*|$ at different frequencies. It is observed that the dynamic modulus of the EAM becomes greater with the increase of the frequency. This can be explained by the definition of the dynamic modulus. Mathematically, the dynamic modulus is defined as the absolute value of the complex modulus as $|E^*| = \delta_0 / \varepsilon_0$, where

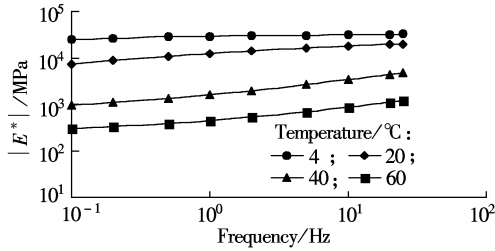


Fig. 4 Dynamic modulus $|E^*|$ of EAM at different frequencies

Tab. 2 Comparisons between static and dynamic modulus of EAM (20 °C)

Static modulus	Dynamic modulus								GPa
	0.1 Hz	0.2 Hz	0.5 Hz	1 Hz	2 Hz	5 Hz	10 Hz	20 Hz	
977	7 280	8 775	10 889	12 591	14 299	16 446	17 992	19 481	19 922

It is observed that the dynamic modulus of the EAM is significantly greater than the static modulus. The frequency of 10 Hz is often taken in the pavement design corresponding to the actual vehicle speed. The test results show that the modulus of the EAM at 10 Hz is over 18 times greater than the static modulus. Therefore, it is meaningful to replace of the static modulus with the dynamic modulus in the pavement design.

3.4 Comparisons with other asphalt mixtures

To evaluate the properties of the EAM, comparisons are

Tab. 3 Comparisons between $|E^*|$ of different mixtures

Binder types	Temperature/°C	Dynamic modulus $ E^* $ /GPa						
		25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.2 Hz
Epoxy asphalt	20	19 922	19 481	17 992	16 446	14 299	12 591	8 775
	40	4 687	4 349	3 410	2 691	1 988	1 594	1 087
SBS	20	14 360	13 718	11 931	10 262	8 305	6 978	4 388
	547	40	4 135	3 836	2 921	2 211	1 515	1 091
AH-70	20	14 086	13 622	11 877	10 291	8 291	6 894	4 074
	40	3 323	3 056	2 104	1 432	850	570	261

4 Master Curve Construction

4.1 Time-temperature superposition of $|E^*|$

The principle of time-temperature superposition is usually used to construct the master curve at a reference temperature. The data at various temperatures are shifted with respect to time until the curves merge into the single smooth function. As a function of time, the master curve of the modulus describes the time dependency of the material^[11]. The different shifting amounts at each temperature describe the temperature dependency of the material. Mathematically, the master modulus curve can be mathematically modeled by a sigmoidal function described as^[12]

$$\log |E^*| = \delta + \alpha / [1 + e^{\beta + \gamma(\log \omega_r)}] \quad (1)$$

δ_0 is the maximum stress and ε_0 is the maximum strain. When the continuous loading operates on the EAM specimen, strain appears correspondingly. However, there is a strain-lag due to the visco-elasticity, and the flow is smaller when the frequency is higher. Therefore, under the same amplitude of stress, a higher $|E^*|$ value is obtained with a higher frequency because of the smaller strain.

3.3 Comparisons with static modulus

To investigate the dynamic effect of the EAM, the static modulus of the EAM under 20 °C are tested according to ASTM D1074. The specimens for static tests are shaped using the same method as stated above. Cylinder specimens with a diameter of 100 mm and a height of 100 mm are shaped and tested. The comparisons between the static and dynamic modulus of the EAM are presented in Tab. 2.

made between the dynamic modulus of the EAM and other two typical mixtures cemented with SBS and AH-70, respectively. $|E^*|$ of these two mixtures are tested using the same method as that of the EAM at 20 and 40 °C. The comparisons of the dynamic modulus for three different mixtures are conducted and the results are summarized in Tab. 3. It can be seen that $|E^*|$ of the EAM is greater than that of the other two mixtures under the same test conditions, indicating that the EAM has a better resistance to permanent deformation and fatigue cracking.

where ω_r is the reduced time of loading at a reference frequency; δ is the minimum value of $|E^*|$; $\delta + \alpha$ is the maximum value of $|E^*|$; β and γ are the parameters describing the shape of the sigmoidal function.

The shift factor can be shown in the following form:

$$\log \omega_r = \log a(T) + \log \omega \quad (2)$$

where $a(T)$ is the shift factor as a function of temperature; ω_r is the reduced frequency of loading at a reference temperature; T is the temperature of interest.

The frequency shift factor is a function of temperature and it can be approximated using a quadratic relationship^[13],

$$\log a(T) = aT^2 + bT + c \quad (3)$$

4.2 Construction of $|E^*|$ master curve

Based on the time-temperature superposition of $|E^*|$, the dynamic modulus results for all the specimens are compiled to construct the master curve for the EAM at a reference temperature of 20 °C. According to a quadratic polynomial relationship between $\log a(T)$ and the temperature, the data at various temperatures are shifted with respect to frequency until the curves merge into a single sigmoidal function. The time-temperature superposition can be obtained by solving Eq. (1) and Eq. (3) to find the values for the parameters of δ , α , β , and γ as described in Eq. (1) and the parameters of a , b , and c as described in Eq. (3). In this paper, a nonlinear optimization is conducted in the software of Matlab to find the optimal solutions by minimizing the sum of squares of the errors between the fitted model and the experimental data.

Fig. 5(a) presents the construction process for the master curve, and the final master curve of the EAM at a reference temperature of 20 °C is shown in Fig. 5(b). From the master curve of the EAM, the $|E^*|$ of the EAM at any frequency can be estimated. For example, 10 Hz is usually selected to simulate the actual vehicle speed in the bridge pavement design, and at the loading frequency of 10 Hz, we can find that the $|E^*|$ of the EAM is about 18 GPa. In addition, a dynamic modulus tested at a frequency of 6×10^{-5} Hz can be estimated for a static module of 977 MPa for the EAM at 20 °C as presented in Tab. 2. This proves that the dynamic modulus is more practical than the static modulus in the pavement design.

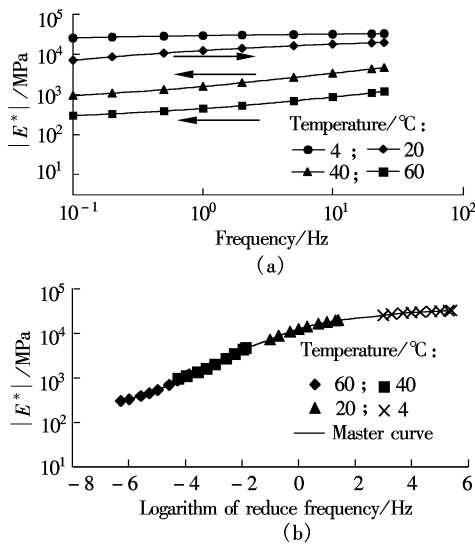


Fig. 5 Construction of $|E^*|$ master curve. (a) Shifting process of $|E^*|$ master curve; (b) $|E^*|$ master curve of EAM at 20 °C

5 Conclusion

The dynamic modulus $|E^*|$ of the EAM is proposed to investigate its time and temperature dependency. The master curve of $|E^*|$ is also constructed to predict the $|E^*|$ of the EAM at any other temperature and frequency.

The EAM becomes more and more plastic when the test temperature rises but it does not melt within the range of the test temperature, indicating that the EAM exhibits the

properties of both epoxy resin and base asphalt. On the other hand, $|E^*|$ values reduce with the decrease in test frequencies, which is consistent with the theoretical analysis. Moreover, the dynamic modulus of the EAM is significantly greater than that of the static modulus. Further comparisons of $|E^*|$ between the EAM and the other two common asphalt mixtures show that the EAM has a more excellent resistance to permanent deformation and fatigue cracking. Finally, the master curve of the EAM at a reference temperature of 20 °C is constructed based on the time-temperature superposition principle, which can be used to predict the $|E^*|$ values at any frequencies and temperatures.

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钢桥面铺装用热固性环氧沥青混合料动态模量试验研究

陈磊磊 钱振东 罗 桑

(东南大学智能运输系统研究中心, 南京 210096)

摘要: 为了研究热固性环氧沥青混合料的动态性能, 对环氧沥青混合料的动态模量进行了试验研究. 首先, 通过简单性能试验(SPT)测试了不同温度与加载频率下的环氧沥青混合料动态模量, 并分析了温度与加载频率对动态模量的影响. 然后, 分别对环氧沥青混合料的静态模量及其他常用沥青混合料的动态模量进行了试验测试, 并将其与环氧沥青混合料的动态模量做了对比. 最后, 利用时温等效原理建立了环氧沥青混合料动态模量主曲线. 研究结果表明: 环氧沥青混合料的动态模量随加载频率的增加而增加, 随加载温度的升高而降低; 更符合实际车辆作用的环氧沥青混合料的动态模量较静态模量大得多; 环氧沥青混合料的动态模量较 SBS 改性沥青混合料与普通沥青混合料大. 研究成果可为钢桥面铺装的设计及力学分析提供理论依据.

关键词: 动态模量; 环氧沥青混合料; 主曲线; 时温等效原理

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