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Study on viscoelastic performance of asphalt mixture based on CAM model

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Abstract: In order to study the viscoelastic characteristics of asphalt mixtures in the whole-frequency range, a dynamic shearing rheometer is used to carry out dynamic frequency sweeps for asphalt mixtures, which obtains the three-dimensional relationships among G^*, temperature and frequency. Then the time-temperature shift principle is used to translate the relationships from three dimensions to two dimensions, so master curves are obtained regarding dynamic modules changing along with the frequency over 15 amount levels. The Christensen-Anderson-Marasteanu (CAM) model, a kind of the rheological model, is used to analyze and compare rheological performances of several asphalt mixtures based on the obtained master curves. The results indicate that the dynamic rheological test is an effective method for obtaining the master curve. Besides, the CAM model can describe well the viscoelastic deformation characteristics of asphalt mixtures.

Key words: asphalt mixture; CAM model; master curve

Investigators have studied many rheological models for asphalt and asphalt mixtures[1-2]. The representative models include the power-law model, the CA model, the CAS model, etc. Though these are all mathematical models, their parameters have appropriate physical meanings after being amended again and again by many tests. The CAM model is an improvement on the CA model. And its parameters can describe well the viscoelastic characteristics of asphalt and asphalt mixtures, providing a reliable basis for material analysis, performance evaluation and structure calculation, with considerable engineering value. The CAM model is used based on the whole-temperature-whole-frequency master curve, whose frequency or temperature range covers the whole range of the engineering application, and even tends to utmost state at high frequency or low frequency. If it is beyond this range, viscoelastic performances of materials will not vary along with frequencies or temperatures. So the master curve covers all effective frequency ranges.

Usually, the single dot frequency sweep or temperature sweep is adopted for obtaining the master curve of dynamic module, such as a simple performance tester and a material test system. However, it has certain limitations in obtaining a whole-frequency master curve based on a limited sample. At the same time, due to destructive tests, lots of samples are needed for a whole-frequency master curve. The differences among samples can also affect the precision of the master curve. Therefore, obtaining the master curve of an asphalt mixture accurately and quickly is the most important challenge.

The investigators of SHRP found that the master curve of a dynamic module changing along with the frequency or temperature obtained by a simple performance test can also be obtained by a dynamic frequency sweep (DFS)[3]. So, according to the researches, the AR-2000 advanced rheometer is used to carry out a DFS for asphalt mixtures in order to obtain the master curves of the dynamic module in this investigation, and the time-temperature shift principle is needed.

1 CAM Model

In 2001, Zeng et al. brought forward a mathematical model, the CAM model, which can well characterize rheological properties of asphalt mixtures and binders. Most models are concentrated on asphalt[4]. The CAM model is not only for characterizing asphalt binders and mixtures, but it is also advantageous for several different load modes. Its parameters have unambiguous meanings in physics. This model is used to describe the rheological behavior of mixtures based on the master curves of dynamic modules. Fig. 1 illustrates the complex modulus of the master curve. It can be seen that G_g^* is the horizontal asymptote at $f \to \infty$, and G_e^* is the horizontal asymptote at $f \to 0$. m_e is the slope of the third asymptote. Two asymptotes of G_g^* and m_e intercept at f_c. Two asymptotes of G_e^* and m_e intercept at f_c'.

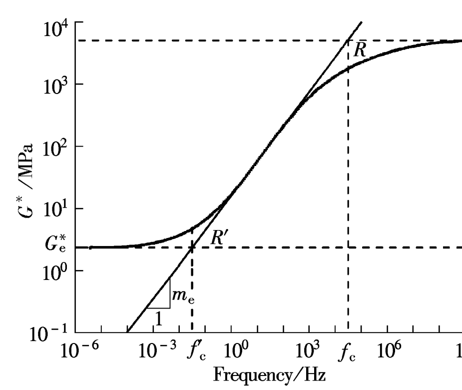

Fig. 1 Illustration of the CAM model[4]

The CAM model is given by

$$G^* = G_e^* + \frac{G_g^* - G_e^*}{\left[1 + \left(\frac{f_c}{f'}\right)^k\right]^{m_e/k}} \tag{1}$$

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where $G_e^* = G^*(f \to 0)$ is the equilibrium complex modulus, $G_e^* = 0$ for binders and $G_e^* > 0$ for mixtures in shear; $G_g^* = G^*(f \to \infty)$ is the glass complex modulus; f_c is the location parameter with dimensions of frequency; f' is the reduced frequency, which is a function of both temperature and strain; k and m_e are shape parameters, and they are dimensionless. The physics meanings of these parameters are as follows:

1) G_e^* is the equilibrium modulus representing the minimum modulus which a mixture can offer in shear. This asymptotic value is assumed to represent the ultimate interlock between aggregates when the contribution of the binder in a mixture is assumed to be negligible. It also represents the modulus at very low frequencies or very high temperatures.

2) G_g^* is the maximum asymptotic modulus in shear which represents the response at very high frequencies or very low temperatures, at which the binder in a mixture can contribute the most to the mixture modulus.

3) The parameter f_c is a location parameter indicating the frequency at which the elastic component is approximately equal to the viscous component. A higher value of f_c is an indication of a higher phase angle and thus a greater overall viscous component in the behavior.

4) k and m_e are shape parameters. R is a shape index related with the ratio of m_e to k, which is shown in Fig. 1. This index is an indicator of the width of the relaxation spectrum. A higher value expresses a more gradual transition from the elastic behavior to the viscous behavior. It indicates less sensitivity to frequency changes. The distance (one logarithmic decade being unity) between $G^*(f_c)$ and G_g^* for asphalt binders is given by

$$R = \log \frac{2^{m_e/k}}{1 + (2^{m_e/k} - 1)\dfrac{G_e^*}{G_g^*}} \tag{2}$$

5) This research introduces another parameter n, a ratio value of G_g^* to G_e^*, which is called ultimate viscoelastic ratio, given by

$$n = \frac{G_g^*}{G_e^*} \tag{3}$$

2 Experiment

2.1 Experimental principle

The AR-2000 advanced rheometer can be used to carry out DFS, and the equipment and experimental principles are given in Fig. 2. During the course of the experiment, the sine load is brought to bear by an air driver. Two kinds of modes can be chosen, that is, stress control and strain control. G^* can be calculated by

$$G^* = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \tag{4}$$

where τ_{max}, τ_{min} are the maximum stress and the minimum stress, respectively; γ_{max}, γ_{min} are the maximum strain and the minimum strain, respectively[5].

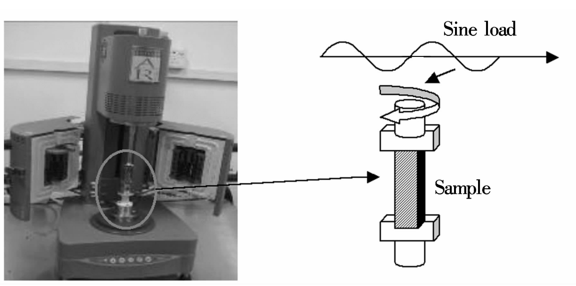

Fig. 2 Experimental principle and equipment

2.2 Materials

The sample is made into a small girder of 50 mm × 10 mm × 10 mm[3]. And 0.2 mm is the maximal error required by the AR-2000. Four kinds of mixtures (A, B, C and D) with two gradations and three kinds of asphalt are researched. Mixture A, B and C adopt AC-5 gradation with asphalt A-70, A-90 and SBS modified asphalt, respectively; and mixture D adopts AC-13 gradation with asphalt A-70.

Tab. 1 Aggregate gradations

Size of sieve/mm	Percentage passing sieves/%	
	AC-5	AC-13
16.0	100	100
13.0	100	97.5
9.50	100	79.0
4.75	97.7	55.0
2.36	74.1	42.0
1.18	56.5	32.0
0.60	42.7	24.0
0.30	22.0	17.0
0.15	14.3	10.0
0.075	8.5	6.0
Asphalt aggregate ratio/%	6.5	

2.3 Sample preparation and fixing

In order to heighten the precision, the vibratory roller compact equipment and the double sides cutter are used to mold samples of asphalt mixtures[6].

When fixing the samples, it is important to ensure that the sample and the axletree are on the same axis, as shown in Fig. 2. In the experiment, the equipment brings to bear torsion by two clamps. So, the wrench with an ergometer must be used to give upper and lower setscrews an equal force, and 10 N is adopted in this research.

2.4 Experimental condition

The strain is less than 0.01% in order to ensure within linear viscoelastic range. The test frequency is from 1 to 10 Hz, and 20 test points can be obtained at every amount level in logarithm form. The test temperature is from −20 to 90 ℃ with interval temperature of 10 ℃. And it needs 1 h for initiative temperature equilibrium before every sweep.

3 Experimental Results

3.1 Results of DFS

In fact, a three-dimensional relationship among the viscoelastic characteristic function, temperature and frequency is obtained. Fig. 3 shows the three-dimensional relationship

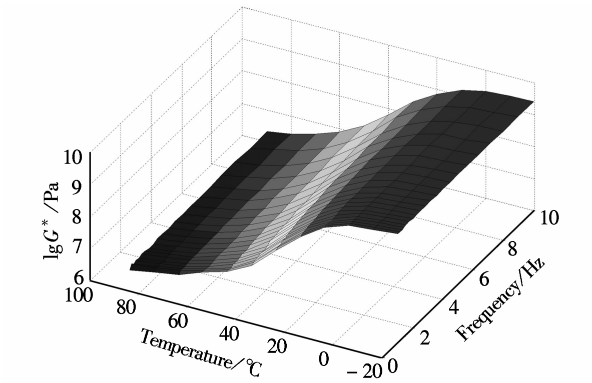

Fig. 3 Three-dimensional distribution of G^*

among G^*, temperature and frequency for mixture A.

3.2 Master curve

Here, the time-temperature shift principle is used to translate the relationships from three dimensions to two dimensions and prolong the frequency or temperature range, and the master curve is finally obtained. The Williams-Landel-Ferry (WLF) formulation[7] is used to express the temperature-shift factor in this research as

$$\lg\alpha_T = \frac{-C_1^g(T - T_g)}{C_2^g + T - T_g} \tag{5}$$

where C_1^g and C_2^g are material constants; T is the reference temperature; T_g is the transition temperature of the glass state.

In this research, 40 ℃ is chosen as the reference temperature, and temperature-shift factors for mixture A at every temperature are shown in Tab. 2.

Tab. 2 Results of shift factors

Temperature/℃	Mixture A
-20	8.410
-10	6.627
0	5.394
10	3.745
20	2.311
30	0.985
40	0
50	-0.861
60	-1.610
70	-2.463
80	-3.191
90	-3.669

As a result, for mixture A, the master curve is obtained in two dimensions, as shown in Fig. 4. Fig. 4 shows that the master curve of the dynamic module changing along with the frequency exhibits an "S" shape, which covers 15 amount levels. At 40 ℃, the frequency change of mixture A is from 0.1 to 10^4 MHz. The master curve provides a fundamental rheological understanding of viscoelastic materials and is the fundamental condition for the application of the CAM model.

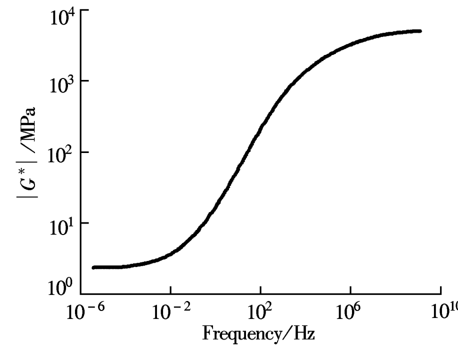

Fig. 4 G^* master curve in two dimensions

4 Fitting

4.1 Fitting results

The properties at the beginnings and ends often illuminate important performances of the materials. However, the fitting deviations at the curve beginnings and ends are always bigger, which raises serious questions regarding the master curve fitting. In this research, the Origin software is used to fit the whole-temperature-whole-frequency master curve by the CAM model. It is non-linear fitting. Fortunately, the fitting result is good and correlation coefficient reaches 0.997 2. Especially, at the beginnings and ends, the fitting curve overlaps the primary master curve approximately. Fig. 5 shows the fitting results of asphalt mixture A.

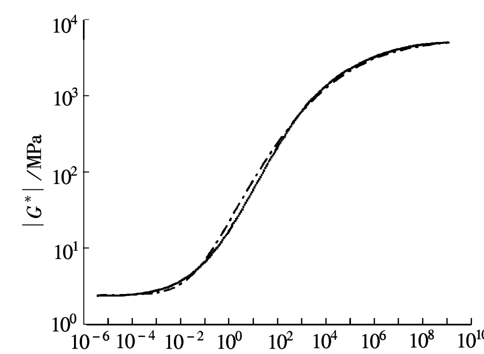

Fig. 5 Fitting results of the CAM model of asphalt mixture A

According to the same method, the master curves of mixtures B and C are obtained and fitted. The fitting results of the three mixtures are shown in Tab. 3.

Tab. 3 Fitting results of the CAM model based on full-frequency master curve for asphalt mixtures

Mixture	G_e^*/MPa	G_g^*/GPa	f_c/Hz	k	m_e	R	$n/10^3$
A(AC-5/A-70)	2.40	5.80	750	0.220	0.75	1.025	2.6
B(AC-5/A-90)	1.20	4.56	850	0.245	0.65	0.798	3.8
C(AC-5/SBS)	3.50	18.20	370	0.121	0.70	1.315	5.2
D(AC-13/A-70)	4.89	8.30	106	0.185	0.79	1.281	1.7

4.2 Results analysis

Some conclusions can be reached by analyzing the fitting results as follows:

1) The values of the equilibrium modulus G_e^* show that the mixtures vary within a wide range. This parameter depicts the minimum capacity value that a mixture resists distortion at high temperatures. Tab. 3 shows that G_e^* of mixture B is minimum and D maximum. It indicates that when gradation is the same, G_e^* of the mixture with ordinary asphalt is small; and with a higher grade of asphalt, it becomes smaller. At the same time, G_e^* of the mixture with modified asphalt is greater than that of ordinary asphalt. The coarse mixture has a higher value of G_e^* than the relatively fine mixture. For example, mixture D has the highest value among the four mixtures, and has the best capability to resist distortion at extremely high temperatures. These indicate that in the range of high temperatures or low frequencies, asphalt can be approximately regarded as a Newtonian liquid and the module of the mixture mainly lies on the interlocked structure between the aggregates.

2) The value of the glass complex modulus G_g^* depicts the maximum capacity value that the mixture resists distortion at low temperatures. The order from high to low for the above four mixtures is C > D > A > B. Under the condition of extremely low temperatures or extremely high frequencies, the module of an asphalt mixture depends on both asphalt and aggregates. Modified asphalt mixture has the best capability to resist distortion at extremely low temperatures among the four mixtures.

3) The ultimate viscoelastic ratio n is the ratio value of G_g^* to G_e^*. The higher value of n indicates that the mixture need experience a relatively longer course from a solid elasticity state to a flowing viscidity state, and it has a better capability to resist distortion not only under instantaneous loads but also under long-term loads. In engineering, the mixture with a higher value of n has a better capability to resist distortion when outside conditions are changed. In Tab. 3, the n value of mixture C is the highest.

4) The parameter f_c is a frequency at which the elastic component is approximately equal to the viscous component. A higher value is an indication of a bigger phase angle, which shows more viscous component. The f_c value of mixture B is the highest in three mixtures. In engineering application and science research field, f_c is an important index. Viscoelastic performance of asphalt mixture before f_c is opposite to that after f_c. So, when studying some performance of asphalt mixture, the results may be opposite before f_c and after f_c.

5) A higher value of the rheological coefficient R indicates that the mixture has more sensitivity to frequency changes. The order of relaxation spectrum widths is C > D > A > B. Ref. [8] considered that the asphalt mixture of the coarse gradations showed higher R values than the fine gradations. For A-70 asphalt, the R value of the AC-13 mixture is higher than that of the AC-5. And the R value of the SBS modified asphalt mixture is the highest, showing that it has wider relaxation spectrum than others.

It can be found that the parameters of the CAM model have unambiguous meanings in physics. They can be comprehended as morphological parameters of an asphalt mixture to a certain extent.

5 Conclusions

1) The DFS is a precise method for obtaining the whole-temperature-whole-frequency master curve of an asphalt mixture. The master curve provides a basis for studying viscoelastic materials at wide ranges of temperatures and frequencies.

2) The CAM model is an effective model to study viscoelastic performance of asphalt mixtures. It can overcome the defects where fitting effects are worse at the beginnings and ends. It can objectively compare the performances of different asphalt mixtures.

3) This research brings forward the concept of an ultimate viscoelasty ratio, which presents a course of the mixture from a solid elasticity state to a flowing viscidity state, providing foundations for studying morphologic transformations of asphalt mixtures.

4) It is found that the CAM model can become the basis of morphologic research on asphalt mixtures. And this research will be carried out in subsequent work. Besides, the relationship between phase angle and frequency, which can be found in Ref. [9], is not illuminated in this paper.

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基于 CAM 模型的沥青混合料粘弹性能研究

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摘要:为了在全频范围内研究沥青混合料的粘弹特性,采用动态剪切流变仪对沥青混合料进行连续动态频率扫描,得到温度-频率-动态模量的三维关系. 利用时温等效原理,将频率扫描试验得到的三维关系进行温-频转换,获得了跨越 15 个数量级的动态模量随频率变化的二维全频主曲线. 基于试验所得到的全频主曲线,利用 CAM 流变模型对几种沥青混合料的流变性能进行了比较分析. 结果表明,动态流变试验是获得沥青混合料全温全频主曲线的有效方法,基于全频域的 CAM 模型能够很好地描述沥青混合料的粘弹变形特性.

关键词:沥青混合料;CAM 模型;主曲线

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