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Rheological properties of warm mix asphalt binder by DSR test at medium temperature

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Abstract: The rheological properties including the complex modulus G^* and the phase angle δ of matrix and warm mix asphalt (WMA) binders were measured by using the dynamic shear rheometer (DSR) test at the medium temperature ranging from 16 to 40 ℃, and the relationships between the fatigue factor $G^*\sin\delta$ and the matrix binder property, WMA additive and test temperature were established. It is found that G^* decreases with the increasing temperature while δ increases inversely, and G^* of the asphalt binder with high WMA additive dosage is large, and δ is small. $G^*\sin\delta$ exponentially decreases with the increasing temperature and linearly increases with the increase in additive dosage, and the amplitudes of variation are large at low temperatures and high additive dosages. The effect of WMA additive on the rheological property is more remarkable for the matrix asphalt binder with low G^*. Besides, aging has a great effect on the property of matrix asphalt binder, and a slight effect on the interaction between asphalt and additive. The high additive dosage can increase the fatigue cracking potential of the asphalt binder.

Key words: warm mix asphalt; dynamic shear rheometer (DSR) test; medium temperature; rheological property; fatigue factor

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Warm mix asphalt(WMA) is a new type of energy saving and environmental protection material with relatively low mixing and compaction temperatures, and has relatively small energy consumption and exhaust emissions compared with the traditional hot mix asphalt[1-2]. Nowadays, there are three methods to produce WMA, including adding organic additive such as aspha-min and Sasobit®, using emulsified asphalt and foamed asphalt technologies.

Since the asphalt binder is a kind of viscoelastic material, the rheological properties of asphalt binder directly affect the road performance of the asphalt mixture. It has been reported that the rheological properties of the WMA asphalt binder are significantly influenced by the additives. Kok et al.[3] evaluated the rheological properties of SBS with the Sasobit modified binder. Morea et al.[4] investigated and evaluated the rheological properties of asphalt binders with chemical tensoactive additives. Kim et al.[5] studied the rheological properties of WMA binders and long-term aged binders containing two warm additives (Aspha-min and wax Sasobit®). Qin et al.[6] investigated the rheology of Sasobit modified WMA binders, including four matrix asphalt binders and two Sasobit concentrations. Banerjee et al.[7] evaluated the effect of long-term aging on the rheology of WMA binder. Arega et al.[8] analyzed the influence of extended aging on the properties of asphalt composites produced using hot and warm mix methods and estimated the influence of long-term aging on fatigue resistance.

In order to investigate the effect of WMA additive on the rheologial properties of asphalt binder at medium temperature, two types of matrix asphalt binders were selected to prepare WMA binder with different dosages of additives, and the rheological properties were measured by using DSR at the temperatures ranging from 16 to 40 ℃, including complex modulus G^*, phase angle δ, fatigue factor $G^*\sin\delta$. Then, the effects of temperature, WMA additive and aging on the rheologial properties were discussed.

1 Experiments

1.1 Raw materials and specimen fabrication

Two matrix asphalt binders are selected and they are 70# and 90# matrix asphalt binders. For 70# and 90# matrix asphalt binders, the penetrations at 25 ℃ are 64 and 83 (0.1 mm), respectively; the softening points are 48.2 and 46.0 ℃, and the ductilities at 15 ℃ are 126 and 150 cm. Sasobit® was selected as the WMA additive and added into the matrix asphalt binders with the dosages of 0%, 1%, 3% and 5% to prepare the WMA binders. The WMA binders were produced with a laboratory-scale mixing device with a four-blade impeller at a temperature of 120 ℃ for 30 min at a rotation speed of 1 000 r/min.

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1.2 Test methods and evaluation indices

DSR tests were conducted to measure the complex modulus G^* and phase angle δ of matrix asphalt binders without aging first, and then the matrix asphalt binders and their binders with 3% Sasobit® were long-term aged by the pressure aging vessel (PAV) for DSR test to study the effects of aging. DSR tests were conducted at the temperature ranging from 16 to 40 ℃, and the temperature interval is 3 ℃.

To avoid fatigue cracking, $G^* \sin\delta$ is proposed as the evaluation index of fatigue performance in Superpave™ specification[9], and it is found to be also a good index to evaluate the fatigue performance of WMA asphalt binders by Cao et al[10-12]. Therefore, in this paper, $G^* \sin\delta$ is selected to evaluate the anti-fatigue property and analyze the effect of Sasobit® additive.

2 Results and Discussion

2.1 DSR test results

The measured G^* and δ of matrix and WMA binders are shown in Fig. 1. Obviously, G^* decreases with the increasing temperature, but δ increases inversely. At the same temperature, G^* of the asphalt binder with high dosage of WMA additive is large, and the phase angle is small.

$G^* \sin\delta$ can be calculated by the DSR test results, as shown in Fig. 2 and Fig. 3. It is found that $G^* \sin\delta$ exponentially decreases with the increasing temperature, but linearly increases with the increasing additive dosage. At the low temperature and high additive dosage, the amplitudes of variation are large, which means that the effect of the WMA additive is more remarkable in these cases and can increase the fatigue cracking potential.

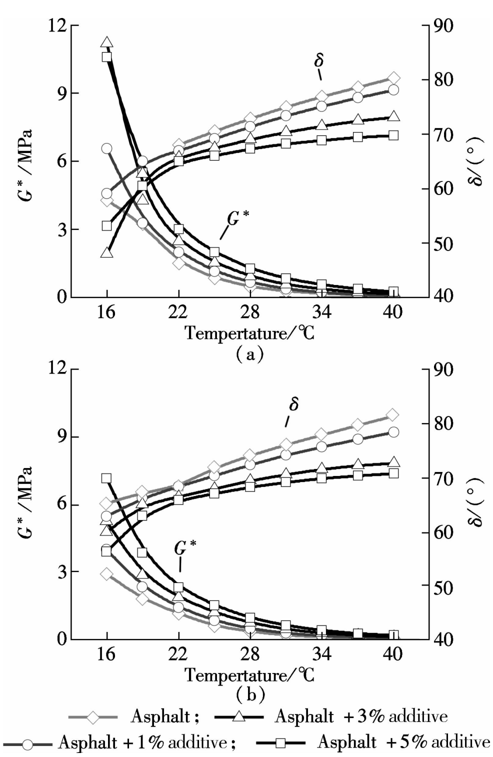

Fig. 1 DSR test results of 70# and 90# matrix and WMA binders. (a) 70# binder; (b) 90# binder

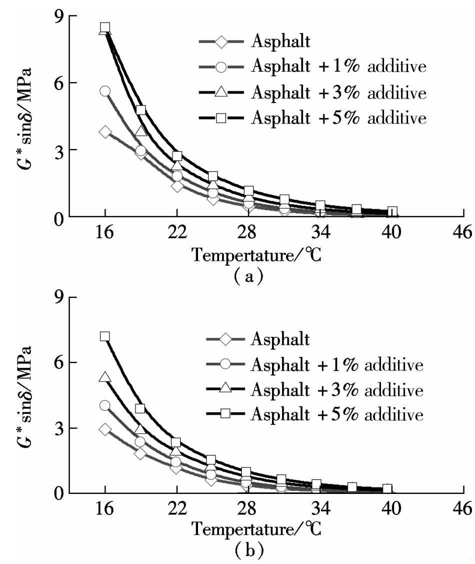

Fig. 2 $G^* \sin\delta$ vs. temperature. (a) 70# binder; (b) 90# binder

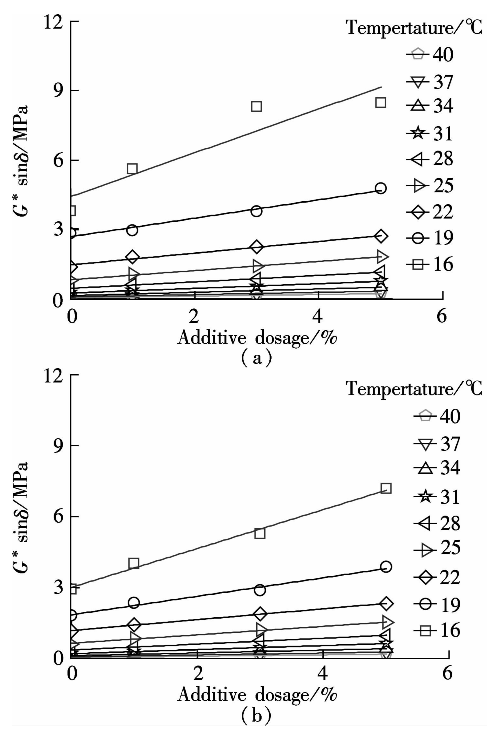

Fig. 3 $G^* \sin\delta$ vs. additive dosage. (a) 70# binder; (b) 90# binder

2.2 Relationship between fatigue factor and temperature

The relationship between $G^* \sin\delta$ and the test temperature can be expressed as

$$G^* \sin\delta = \alpha e^{\beta T} \tag{1}$$

where $G^* \sin\delta$ is the fatigue factor, MPa; T is the test temperature, ℃; α is the parameter related to the properties of asphalt binder; β is the parameter related to the temperature.

The nonlinear regression analysis is conducted, and it is found that the β value can be fixed as −0.17, the α values are 60 697, 81 590, 115 149 and 125 718 for $70^\#$ matrix asphalt binder and its WMA binder with the additive dosages of 1%, 3% and 5%. The α values are obtained as 45 072, 60 511, 78 672 and 105 697 for the $90^\#$ matrix asphalt binder and its WMA binder with the additive dosages of 1%, 3% and 5%, respectively. The linear relationship between the α value and the additive dosage can be established for $70^\#$ and $90^\#$ asphalt binder, respectively.

$$\alpha_{\text{asphalt70}} = 131 \times 10^4 C + 66.27 \times 10^3, \quad R^2 = 90.9\% \quad (2)$$

$$\alpha_{\text{asphalt90}} = 117 \times 10^4 C + 46.16 \times 10^3, \quad R^2 = 98.8\% \quad (3)$$

where $\alpha_{\text{asphalt70}}$ and $\alpha_{\text{asphalt90}}$ are values of $70^\#$ and $90^\#$ asphalt; C is the additive dosage. The intercept in Eq. (2) is larger than that in Eq. (3) due to the larger complex modulus of the $70^\#$ matrix asphalt.

2.3 Relationship between fatigue factor and WMA additive

The relationship between $G^* \sin\delta$ and additive dosage can be expressed as

$$G^* \sin\delta = \lambda C + k \quad (4)$$

where λ and κ are the regression parameters related to the WMA additive and matrix binder property, respectively.

The linear regression analysis is conducted and it is found that the λ values range from 35.5 to 946.7 and the κ values range from 47.6 to 4416.2 for $70^\#$ asphalt; the λ values range from 28.3 to 822.3, and the κ values range from 42.9 to 3005.8 for $90^\#$ asphalt. Both the λ values and κ values exponentially decrease with the increasing temperature, and the relationship can be expressed as

$$\lambda_{\text{asphalt70}} = 13.06 \times 10^3 e^{-0.17T}, \quad R^2 = 95.3\% \quad (5)$$

$$\lambda_{\text{asphalt90}} = 66.27 \times 10^3 e^{-0.17T}, \quad R^2 = 99.7\% \quad (6)$$

$$\kappa_{\text{asphalt70}} = 11.7 \times 10^3 e^{-0.17T}, \quad R^2 = 97.5\% \quad (7)$$

$$\kappa_{\text{asphalt90}} = 46.16 \times 10^3 e^{-0.17T}, \quad R^2 = 99.8\% \quad (8)$$

Substituting Eq. (2) and Eq. (3) into Eq. (1), or Eq. (5) to (8) into Eq. (4), the fatigue factor can be expressed as

$$G^* \sin\delta = \psi(\mu C + 1) e^{\beta T} \quad (9)$$

where ψ is the parameter related to the property of the matrix asphalt binder; μ is the parameter related to WMA additive; C is the dosage of additive; T is the temperature, ℃; β is the parameter related to temperature.

The regression results of Eq. (9) are shown in Tab. 1, and the relationship between the calculated values and measured values are shown in Fig. 4. When the value of $G^* \sin\delta$ is quite small, the calculation value is close to the measured value; however, when the value of $G^* \sin\delta$ increases, the error becomes greater accordingly. However, the coefficient of correlation is 98.6%, meaning that Eq. (9) describes the relationship between the fatigue factor, temperature, and dosage of additive well. In addition, the ψ value of asphalt $70^\#$ is large due to the large complex modulus of $70^\#$ matrix asphalt. However, the μ value of asphalt $90^\#$ is large, which means that the effect of WMA additive on the complex modulus and fatigue factor of asphalt $90^\#$ is more remarkable.

Tab. 1 ψ, μ and β values of the $70^\#$ and $90^\#$ asphalt binders

Asphalt binder	Regression parameters		
	$\psi/10^3$	μ	β
Asphalt $70^\#$	66.3	19.7	−0.17
Asphalt $90^\#$	46.2	25.4	−0.17

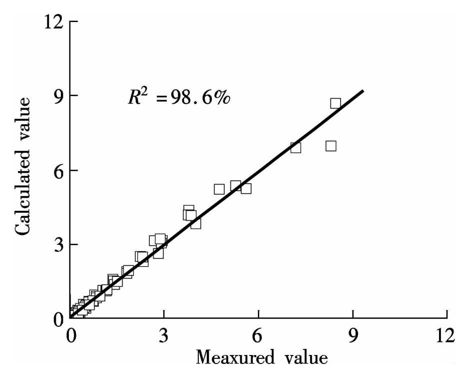

Fig. 4 Graph of calculated values vs. measured values

2.4 Effects of aging on the fatigue factor

Fig. 5 shows the fatigue factors of matrix asphalt binders and WMA binders with 3% Sasobit® after long-term aging by PAV, and it is found that $G^* \sin\delta$ of asphalt binders are high after long-term aging obviously, and the $G^* \sin\delta$ of WMA binders is larger than that of the matrix asphalt binders.

According to Eq. (9) and the test results, the model parameters for aged asphalt binders are shown in Tab. 2. After aging, the chemical component of asphalt will be changed. For example, with the increase in the content of the asphaltene component, the viscosity of asphalt increases[13-14]. Therefore, the ψ value of the aged asphalt binder is much larger. However, aging may weaken the interaction between the asphalt and additive, and the μ value of aged asphalt binder is a little smaller than that of unaged asphalt binder. It means that aging has a remarkable effect on the properties of matrix binder, but a slight effect on the interaction between the asphalt and additive. Therefore, aging also increases the fatigue cracking potential of the asphalt binder.

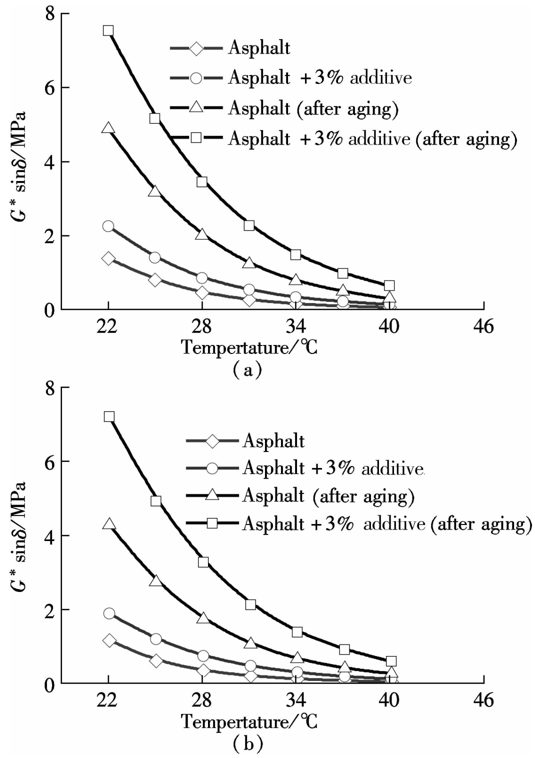

Fig. 5 $G^*\sin\delta$ vs. temperature for asphalt binders after long-term aging. (a) 70# binder; (b) 90# binder

Tab. 2 ψ, μ and β values of aged 70# and 90# asphalt binders

Asphalt binder	Regression parameters		
	$\psi/10^3$	μ	β
Aged asphalt 70#	213.0	20.0	−0.17
Aged asphalt 90#	186.0	25.0	−0.17

3 Conclusions

1) The fatigue factor exponentially decreases with increasing temperature, linearly increases with the increasing additive dosage, and the amplitudes of variation are large at the low temperature and high additive dosage, which means that high additive dosage and low temperature can increase the fatigue cracking potential.

2) A uniform expression is established and validated to represent the relationship between the fatigue factor and matrix binder property, WMA additive and test temperature, and it is found that the effect of the WMA additive on the complex modulus and fatigue factor is more remarkable for the matrix asphalt binder with a low complex modulus.

3) Aging has a great effect on the property of matrix asphalt binder, and a slight effect on the interaction between the asphalt and additive. Therefore, aging increases the fatigue cracking potential of the asphalt binder.

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基于 DSR 试验的 WMA 沥青结合料中温流变性能分析

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摘要: 采用动态剪切流变仪(DSR)在 16 ~40 ℃中等温度下测试、分析了基质沥青及其温拌沥青的复数剪切模量 G^*、相位角 δ 等流变性能,进而建立了疲劳因子 $G^*\sin\delta$ 与基质沥青性质、试验温度和拌剂掺量的关系模型. 结果表明,复数剪切模量 G^* 随温度升高而减小,而相位角 δ 随温度升高而增大;温拌剂掺量越高,复数剪切模量 G^* 越大,相位角越小;疲劳因子 $G^*\sin\delta$ 随着温度升高呈指数减少,随温拌剂掺量增加呈线性增大;在较低温度和较高掺量下,疲劳因子的变化幅度更大;基质沥青复数模量越小,温拌剂对温拌沥青流变性能的影响更为显著,而老化对基质沥青性能的影响高于对沥青-温拌剂相互作用的影响;掺量越高的温拌沥青结合料,越容易疲劳开裂.

关键词: 温拌沥青;动态剪切试验;中温;流变性能;疲劳因子

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