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Research Article

Effects of WMA Additive on the Rheological Properties of Asphalt Binder and High Temperature Performance Grade

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Sasobit additives with different dosages were added into 70# and 90# virgin asphalt binders to prepare WMA binders. The rheological properties, including G^* and δ, were measured by using DSR at the temperature ranging from 46°C to 70°C, and the effects of temperature, additive dosage and aging on $G^*/\sin\delta$, critical temperature, and H-T PG were investigated. The results indicate that WMA additive improves G^* but reduces δ, and the improvement on 70# virgin binder is more significant. $G^*/\sin\delta$ exponentially decreases with the increasing temperature but linearly increases with the increasing additive dosage. Aging effect weakens the interaction between binder and additive but significantly increases the binder's viscosity; that is why $G^*/\sin\delta$ is higher after short-term aging. In addition, the critical temperature increases with the increasing additive dosage, and the additive dosage should be more than 3% and 5% to improve H-T PG by one grade for 70# and 90# virgin binder, respectively.

1. Introduction

Warm mix asphalt (WMA) is a new way of energy saving and environmental protection material with relatively low mixing and compaction temperatures and relatively small energy consumption and exhaust emission compared with the traditional hot mix asphalt [1–3]. 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. Generally, the WMA by adding Sasobit is with better road performance than the others and is widely applied [4, 5].

Since asphalt binder is a kind of viscoelastic material and the rheological properties of asphalt binders directly affect the road performance of asphalt mixture, Strategic Highway Research Program (SHRP) reported that the evaluations of asphalt should be based on the rheology and developed dynamic shear rheometer (DSR), bending beam rheometer (BBR), direct tension tester (DTT), and Brookfield rotational viscometer, which are used to measure the rheological properties at high and medium temperatures, low temperatures (below −5°C), and higher temperatures (above 100°C). Many studies have been reported on the effects of WMA additives on the performances of asphalt binder, and it has been reported that the rheological properties are significantly influenced by the WMA additives. Wasiuddin et al. evaluated the rheological properties of two commonly used performance grade (PG) binders (PG 64-22 and PG 70-28) with Sasobit and Aspha-Min additives [6]. Giuliani and Merusi [7] took an extended program of rheological analyses to evaluate the effects of different type of wax on bitumen viscous flow and dynamic properties at high pavement service temperatures [7]. Xiao and Amirkhanian [8] investigated and evaluated the rheological properties and moisture susceptibility of the binder and mixture containing ASAs (antistrip additives) and Aspha-Min additive [8]. Kim et al. [9] studied a rheological investigation of three PMA (polymer modified asphalt) binders, graded as PG 76-22 and containing two warm additives (Aspha-Min and Sasobit) available commercially [9]. Wu et al. [10] studied the effects of warm mix additive on penetration and high-temperature performance grade (H-T PG) of asphalt binder and found that the relation between the penetration and high-temperature

Table 1: General technical properties of virgin asphalt.

Asphalt binders	Penetration at 25°C/0.1 mm	Softening point/°C	Ductility at 15°C/cm
70# virgin asphalt	64.0	48.2	126
90# virgin asphalt	83.0	46.0	150

PG of the asphalt containing Sasobit was related to asphalt type and aging condition [10].

In order to investigate the effect of WMA additive on the rheological properties of asphalt binder and the effect on high-temperature performance grade, two types of virgin asphalt binders were selected to prepare WMA binder with different dosage of additive, and the rheological properties of original and short-term aged asphalt were measured using DSR at different temperatures ranging from 46°C up to 70°C, including complex modulus G^*, phase angle δ, rutting factor $G^*/\sin\delta$, and critical temperature. Then, the effects of temperature, WMA additive, and aging on the rutting factor were discussed. How WMA additive affects the critical temperature and the improvement of high-temperature performance grade was also analyzed.

2. Experimental Programs and Procedures

2.1. Raw Materials and Specimen Fabrication. Two virgin asphalt binders are selected that are 90# virgin asphalt and 70# virgin asphalt. 90# and 70# are named as the penetration degree of asphalt binder at 25°C ranging from 80 to 100 (units in 0.1 mm) and from 60 to 80 (units in 0.1 mm) according to the Chinese code [11]. The general technical properties of the two virgin asphalt binders are shown in Table 1.

Sasobit is selected as a WMA additive in this paper. Sasobit is a long chain aliphatic hydrocarbon (chain lengths of 40–115 carbon atoms) obtained from coal gasification using the Fischer-Tropsch process. The melting point of Sasobit is around 85–115°C. Sasobit forms a homogeneous solution with the virgin binder on stirring and produces a marked reduction in the binder's viscosity [12]. Sasobit additives were added into the virgin asphalt binders with the different dosage of 1%, 3%, and 5% to prepare the WMA binders. In order to study the effect of aging, the 70# virgin asphalt binders and the 70# WMA binders with 3% Sasobit were short-term aged by RTFOT.

2.2. Test and Evaluation Methods. DSR is mainly used to evaluate the high-temperature performances of unaged asphalt binders and the aged asphalt binders with RTFO. The rheological properties at high temperature, such as complex modulus G^* and phase angle δ, were measured at 46, 52, 58, 64, and 70°C. The total reactions of asphalt binders due to DSR loading consist of two parts: elastic and viscous components, and asphalt binder needs enough stiffness to resist the deformation at higher temperatures, which can be evaluated by the rutting factor $G^*/\sin\delta$. So, the complex modulus G^* and phase angle δ were measured to calculate the rutting factor $G^*/\sin\delta$ and then study the effects of temperature and dosage of WMA additive.

In addition, the high-temperature performances grade is defined as the critical temperature at which $G^*/\sin\delta$ of original asphalt binders is not less than 1.0 kPa and $G^*/\sin\delta$ of the aged asphalt binders with RTFO is not less than 2.2 kPa. Therefore, the critical temperature of different asphalt binders was calculated according to the DSR results to study the effects of dosage of WMA additive.

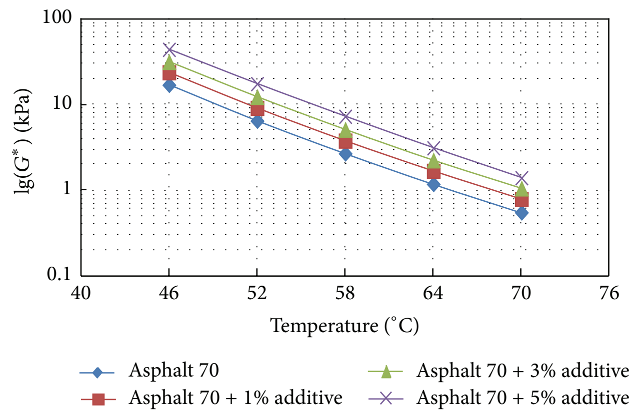

Figure 1: G^* of 70# virgin asphalt and WMA binder versus temperature.

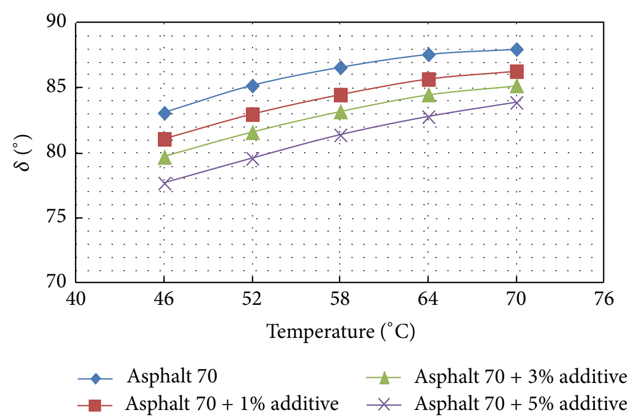

Figure 2: Phase angles of 70# virgin asphalt and WMA binder versus temperature.

3. Results and Discussions

3.1. DSR Test Results. The complex modulus G^* and phase angle δ of 70# virgin asphalt and WMA binders with Sasobit of 1%, 3%, and 5% are shown in Figures 1 and 2. The complex modulus G^* and phase angle δ of 90# virgin asphalt and WMA binder with Sasobit of 1%, 3%, and 5% are shown in Figures 3 and 4.

Obviously, the phase angle increases with the increase of temperature for all of the virgin asphalt and WMA binders,

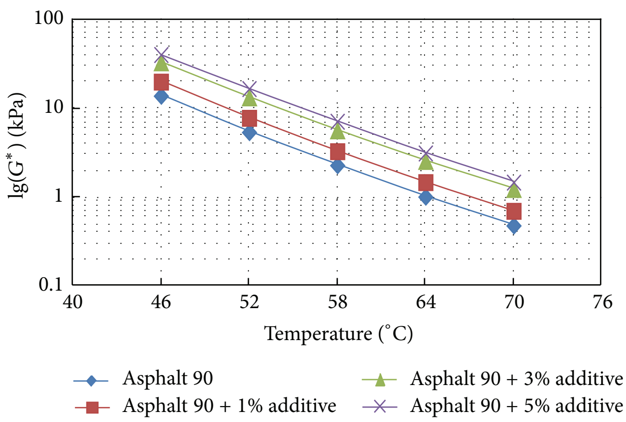

FIGURE 3: G^* of 90# virgin asphalt and WMA binder versus temperature.

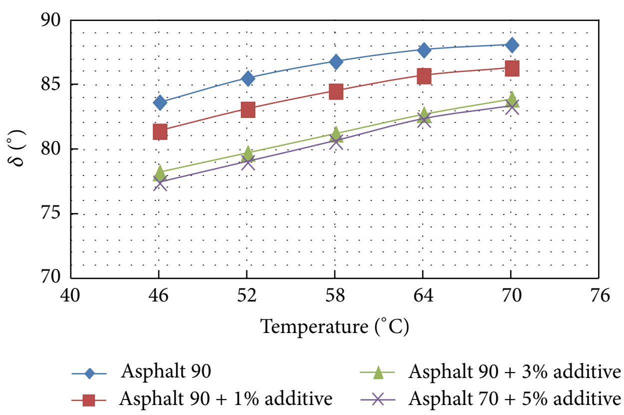

FIGURE 4: Phase angles of 90# virgin asphalt and WMA binder versus temperature.

meaning that the viscous components increase, while the phase angle decreases with the increase of the dosage of WMA additives at the same temperature, meaning that the elastic components increase. However, complex modulus G^* decreases with the increase of temperature and increases with the increase of the dosage of WMA additives.

The rutting factor $G^*/\sin\delta$ can be calculated for all of the asphalt binders, as shown in Figures 5 and 6. The rutting factor $G^*/\sin\delta$ decreases with the increase of the temperature but increases with the increase of the dosage of additive. We can induce that the WMA additive can improve the complex modulus and decrease the phase angle, and the asphalt binders with higher content of additives are more elastic. Therefore, the rutting factor $G^*/\sin\delta$ increases and rutting resistance at high temperature is better.

3.2. Effects of Temperature on the Rutting Factor. The effects of temperature on the rutting factor of different virgin asphalt and WMA binders could be represented by the exponential function, expressed as follows:

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

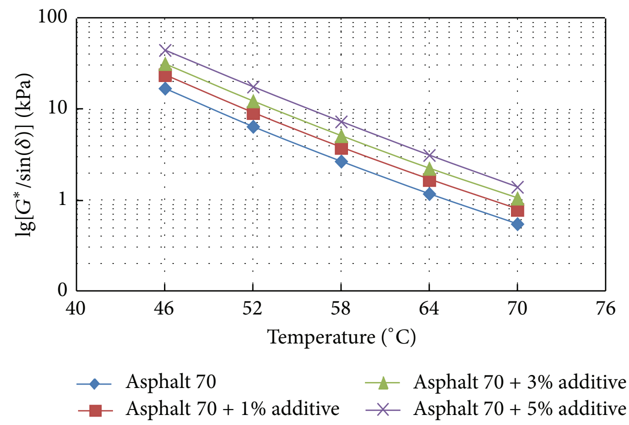

FIGURE 5: Rutting factors of 70# virgin asphalt and WMA binder versus temperature.

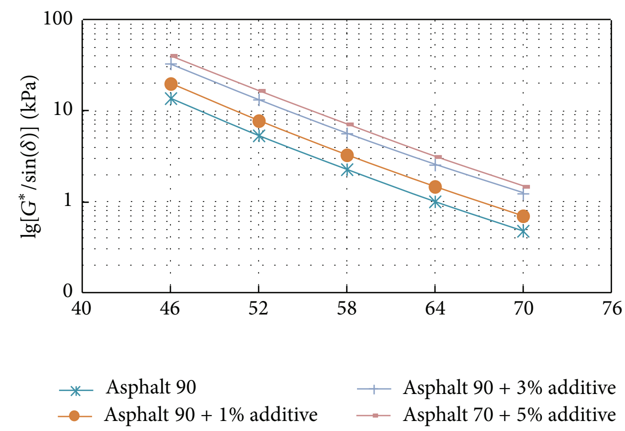

FIGURE 6: Rutting factors of 90# virgin asphalt and WMA binder versus temperature.

TABLE 2: α and β of asphalt with different dosage of additives.

Asphalt binder	Regression parameters		R^2
	α	β	
Asphalt 70#	11319	−0.14	0.993
Asphalt 70# + 1% additive	15301	−0.14	0.994
Asphalt 70# + 3% additive	20571	−0.14	0.999
Asphalt 70# + 5% additive	33004	−0.14	0.996
Asphalt 90#	8028	−0.14	0.998
Asphalt 90# + 1% additive	11382	−0.14	0.997
Asphalt 90# + 3% additive	17207	−0.14	0.998
Asphalt 90# + 5% additive	22901	−0.14	0.996

where $G^*/\sin\delta$ is the rutting factor, kPa; α is the properties of asphalt binder; β is the influence coefficient of temperature; T is the test temperature, °C.

According to the test results of different asphalt binders at different temperatures, we can obtain the model parameters by regression analysis, and the model parameters are shown in Table 2.

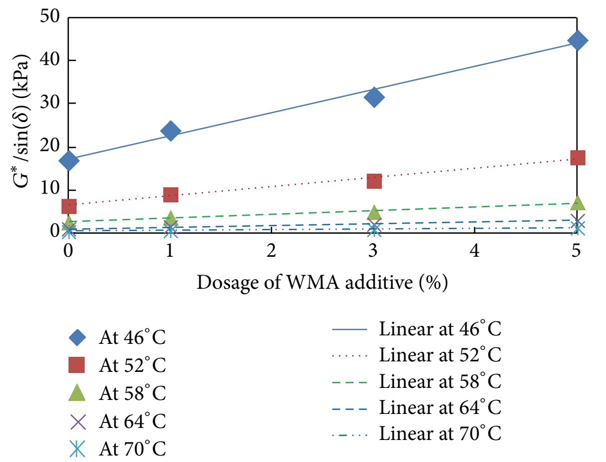

FIGURE 7: Rutting factors of 70# virgin asphalt and WMA binder.

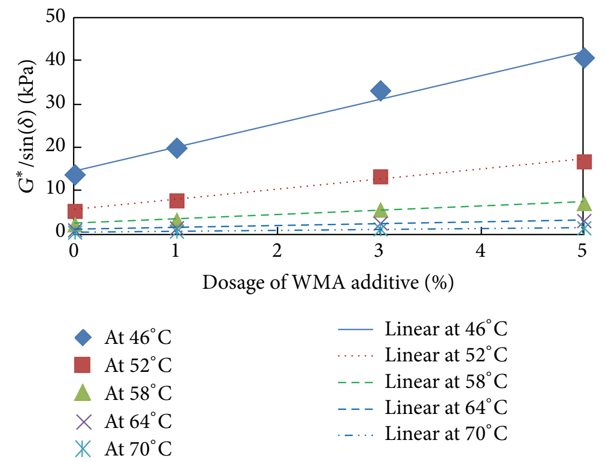

FIGURE 8: Rutting factors of 90# virgin asphalt and WMA binder.

We can find that the parameter β reflects the influence of temperatures, and they are close to −0.14. For all of the asphalt binders, the temperature has the same influence on the rutting factor. The parameter α reflects the influence of the properties of virgin asphalt and WMA additive, but they vary a lot because the properties of 70# and 90# virgin asphalt are different and the dosage of WMA additive is also different. The linear relationship between α value and the dosage of additive could be expressed as

$$\alpha_{\text{asphalt70}} = 417.5 \times 10^3 C + 10.65 \times 10^3 \quad R^2 = 96.3\%, \quad (2)$$

$$\alpha_{\text{asphalt90}} = 295.5 \times 10^3 C + 8.23 \times 10^3 \quad R^2 = 98.5\%, \quad (3)$$

where $\alpha_{\text{asphalt70}}$ and $\alpha_{\text{asphalt90}}$ are α values of asphalt 70# and asphalt 90#, respectively, and C is the dosage of additive.

We can find that the intercept of the fitted straight line of asphalt 70# is bigger than asphalt 90# because the penetration of virgin asphalt 70# is less and the viscosity of virgin asphalt 70# is bigger. Also, we can find that the slope of the fitted straight line of asphalt 70# is bigger, and it indicates that the improvement of WMA additive on the rutting factor of asphalt 70# is more significant because the viscosity of virgin asphalt 70# is higher. By substituting (2) and (3) into (1), respectively, we can obtain the relation model of rutting factor by taking the dosage of additive and temperature as the parameters, expressed as follows:

$$\frac{G^*}{\sin \delta_{\text{asphalt70}}} = \left(417.5 \times 10^3 C + 10.65 \times 10^3\right) e^{-0.14T}, \quad (4)$$

$$\frac{G^*}{\sin \delta_{\text{asphalt90}}} = \left(295.5 \times 10^3 C + 8.23 \times 10^3\right) e^{-0.13T}. \quad (5)$$

3.3. Effects of WMA Additive on the Rutting Factor. Figures 7 and 8 show the effects of WMA additive on the rutting factor of virgin asphalts and WMA binders at different temperature. The relationship between the dosage of additive and rutting factor could be represented by the linear function, expressed as follows:

$$\frac{G^*}{\sin \delta} = \lambda C + \kappa, \quad (6)$$

where $G^*/\sin\delta$ is the rutting factor, kPa; C is the dosage of additive; λ and κ are the regression parameters.

According to the test results of asphalt binders with different dosage of additive, the model parameters can be obtained through regression analysis, and the model parameters are shown in Table 3.

The parameter λ reflects the influence of the dosage of WMA additive, and parameter κ reflects the influence of the properties of virgin asphalt. Both parameters λ and κ are affected by the temperature, and the relationship between λ and κ and the temperature could be expressed as

$$\lambda_{\text{asphalt70}} = 4.23 \times 10^3 e^{-0.14T} \quad R^2 = 99.3\%, \quad (7)$$

$$\lambda_{\text{asphalt90}} = 2.96 \times 10^3 e^{-0.14T} \quad R^2 = 99.5\%, \quad (8)$$

$$\kappa_{\text{asphalt70}} = 10.72 \times 10^3 e^{-0.14T} \quad R^2 = 99.7\%, \quad (9)$$

$$\kappa_{\text{asphalt90}} = 8.23 \times 10^3 e^{-0.14T} \quad R^2 = 99.7\%, \quad (10)$$

where $\lambda_{\text{asphalt70}}$ and $\lambda_{\text{asphalt90}}$ are λ values of asphalt 70# and asphalt 90#, respectively; $\kappa_{\text{asphalt70}}$ and $\kappa_{\text{asphalt90}}$ are κ values of asphalt 70# and asphalt 90#, respectively; T is the temperature, °C.

By substituting (7) and (9) into (6) and substituting (8) and (10) into (6), we can obtain the relation model of rutting factor by taking the dosage of additive and temperature as the parameters, expressed as follows:

$$\frac{G^*}{\sin \delta_{\text{asphalt70}}} = \left(423.4 \times 10^3 C + 10.72 \times 10^3\right) e^{-0.14T}, \quad (11)$$

$$\frac{G^*}{\sin \delta_{\text{asphalt90}}} = \left(296.1 \times 10^3 C + 8.23 \times 10^3\right) e^{-0.13T}. \quad (12)$$

Table 3: λ and κ of asphalt at different temperature.

Virgin asphalt type	Test temperature (°C)	Regression parameters λ	Regression parameters κ	R^2
Asphalt 70#	46	5.34	17.34	0.988
	52	2.17	6.54	0.987
	58	0.89	2.71	0.988
	64	0.38	1.21	0.988
	70	0.16	0.58	0.991
Asphalt 90#	46	5.49	14.57	0.985
	52	2.33	5.59	0.989
	58	1.00	2.35	0.990
	64	0.44	1.06	0.983
	70	0.21	0.51	0.974

Table 4: ψ, μ, and β of virgin asphalt 70# and asphalt 90#.

Virgin asphalt type	Regression parameters ψ ($\times 10^3$)	μ	β
Asphalt 70#	10.69	39.3	−0.14
Asphalt 90#	8.23	35.9	−0.14

Comparing (11) with (4) for asphalt 70#, it is found that these models are very similar, and we take the average of the model parameters to establish a new relation model. The new relation model for asphalt 90# is also established. The models can be changed to another expression as follows, and the model parameters are listed in Table 4. Consider

$$\frac{G^*}{\sin\delta} = \psi\left(\mu C + 1\right)e^{\beta T}, \tag{13}$$

where ψ is the property of the virgin asphalt binder; μ is influence coefficient of WMA additive; C is the dosage of additive; T is the temperature, °C; β is the influence coefficient of temperature.

According to (13) and the parameter values in Table 4, we can calculate the rutting factors of different asphalt binders. Plot a graph of calculated values (Y-axis) versus measured values (X-axis), as shown in Figure 9. It can be seen that the calculated values are close to the measured values at low level, and the error becomes bigger at higher level. However, the coefficient of correlation is 97.4%, which means that the model well describes the relationship between rutting factor and temperature and dosage of additive.

Because parameter ψ is defined as the property of the virgin asphalt binder and the penetration of virgin asphalt 70# is less, which means the viscosity of virgin asphalt 70# is bigger, ψ value of asphalt 70# is obviously bigger than that of asphalt 90#. Parameter μ is defined as the influence coefficient of WMA additive, and the μ value of asphalt 70# is bigger, which means that the improvement of WMA additive on the rheological properties of asphalt 70# is better than that of asphalt 90#.

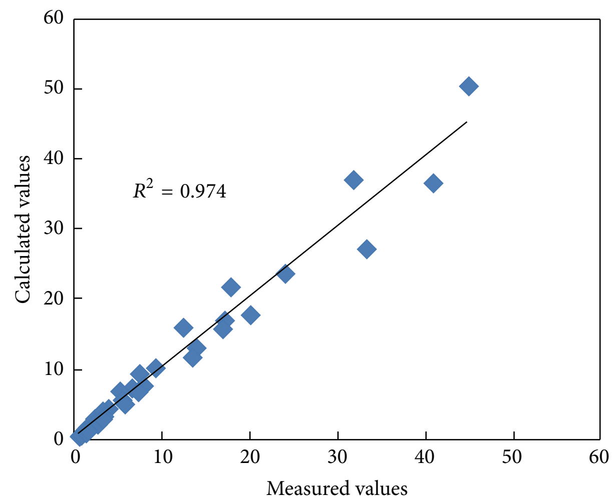

Figure 9: Graph of calculated values versus measured values.

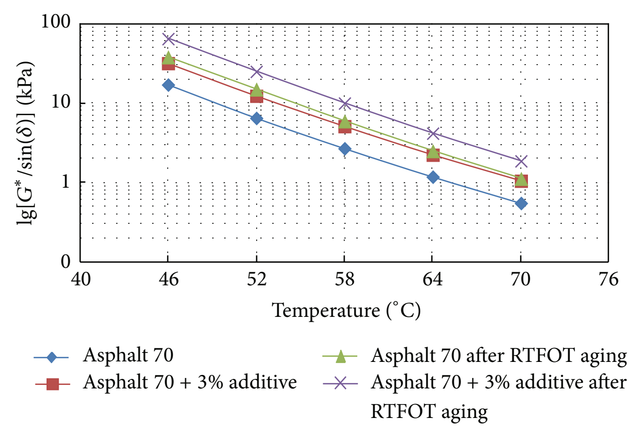

Figure 10: Rutting factor versus temperature for 70# virgin asphalt and WMA binder with 3% additive after short-term aging.

Table 5: ψ, μ, and β of aged and unaged asphalt.

Asphalt type	Regression parameters ψ ($\times 10^3$)	μ	β
Aged asphalt 70#	31.48	25.6	−0.14
Unaged asphalt 70#	10.69	39.3	−0.14
Unaged asphalt 90#	8.23	35.9	−0.14

3.4. Effects of Aging on the Rutting Factor. The rutting factor $G^*/\sin\delta$ of 70# virgin asphalt and WMA with 3% Sasobit after short-term aging by RTFOT are shown in Figure 10. It is found that $G^*/\sin\delta$ of asphalt binders after short-term aging is higher at different temperatures, and the $G^*/\sin\delta$ of WMA binders is obviously bigger than the virgin asphalt binders.

According to (13) and the measured values in Figure 10, the model parameter values can be obtained in Table 5, and we found that the ψ value of aged asphalt binder is bigger, and the μ value of aged asphalt binder is smaller than that of unaged asphalt. It is mainly because the chemical component of asphalt will be changed, and the viscosity of

Table 6: Critical temperature and high-temperature performance grade.

Asphalt binders	Requirement of $G^*/\sin\delta$ for H-T PG (kPa)	Critical temperature (°C)	H-T PG
Asphalt 70#	1.0	66.7	PG-64
Asphalt 70# + 1% additive		68.8	PG-64
Asphalt 70# + 3% additive		70.9	PG-70
Asphalt 70# + 5% additive		74.3	PG-70
Aged asphalt 70#	2.2	68.3	PG-64
Aged asphalt 70# + 3% additive		72.4	PG-70
Asphalt 90#	1.0	64.2	PG-64
Asphalt 90# + 1% additive		66.7	PG-64
Asphalt 90# + 3% additive		69.7	PG-64
Asphalt 90# + 5% additive		71.7	PG-70

asphalt increases and the interaction between asphalt and additive will be weakened after aging [13–15].

3.5. Analysis on the Critical Temperature and the Improvement of High-Temperature PG. The requirement of $G^*/\sin\delta$ for high-temperature performance grade (H-T PG) is not less than 1.0 kPa for the unaged asphalt binder and 2.2 kPa for the aged asphalt binder. According to (1) and parameters values in Table 2, the critical temperature at which the requirement is satisfied can be calculated. For example, the requirement is 1.0 kPa, α and β values are 11319 and −0.14, respectively, for virgin asphalt 70#, then the calculated critical temperature is 66.7°C, and the H-T PG is PG 64. The other calculated critical temperature and H-T PG are shown in Table 6.

When the dosage of additive increases from 0 to 5%, the critical temperature increment is 7.6°C and 7.5°C for asphalt 70# and asphalt 90#, respectively. If the dosage of additive is bigger than 3% for asphalt 70# and the dosage of additive is bigger than 5% for asphalt 90#, the critical temperature exceeds 70°C; that is to say, the high-temperature grade of WMA binder is improved to PG 70 from PG 64. If the H-T PG of WMA binders is expected to be changed by one grade, the dosage of additive should be more than 3% for virgin asphalt 70# and 5% for virgin asphalt 90#.

4. Conclusions

This paper explored the effect of WMA additive on the rheological properties of asphalt binder and the effect on high-temperature performance grade through lab testing. Some major conclusions and observations can be drawn from the results and are listed as follows.

(1) WMA additive increases the complex modulus but decreases the phase angle, so the rutting factor $G^*/\sin\delta$ increases, meaning that rutting resistance of WMA binder at high temperature is better. But the improvement of WMA additive on the rutting resistance of asphalt 70# is more significant.

(2) The rutting factor decreases with the increase of temperature exponentially, while increasing linearly with the increase of dosage of WMA additive. Aging effects weaken the interaction between asphalt binder and additive but significantly increase the viscosity of asphalt binder. So, the rutting factor of short-term aged asphalt is higher.

(3) The H-T PG of asphalt binder is improved by adding WMA additive, and if it is expected to be improved by one grade, the dosage of WMA additive should be more than 3% for 70# virgin asphalt and 5% for 90# virgin asphalt.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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