High-Temperature Property Evaluation and Index Research of Modified Asphalt before and After Aging

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Abstract. In order to better evaluate the composite modified asphalt of composite modified asphalt, this study through dynamic shear rheological (DSR) test, the three kinds of polymer modified asphalt before and after ageing: the compound modified asphalt (CCR), rubber powder modified asphalt (CR) and composite modified asphalt of SBS modified asphalt (SBS) analysis, to explore suitable for composite modified asphalt of modified asphalt evaluation index. The results show that: Compared with $G'/\sin \delta$, $G'/(\sin \delta)^9$ has higher accuracy for evaluating the composite modified asphalt of polymer modified asphalt and is more sensitive to changes in phase angle. The critical temperature of antirutting factor $T^{g}/\sin \delta$ is significantly higher than that of $T^{g}/\sin \delta$, especially for composite modified asphalt. This has an important impact on the PG classification in the Superpave asphalt binder specification. $G'/\sin \delta$ underestimates the high temperature grade of the modified asphalt. The equivalent viscosity measured with $\eta' = \sin \delta - 4.8628 G'*\omega$ has the best correlation with the antirutting factor $G'/(\sin \delta)^9$, and the highest correlation coefficient is 0.999, which is more suitable as a high-temperature property evaluation index of modified asphalt.

Keywords: Composite Modified Asphalt, High-Temperature Property, Evaluation Index, Dynamic Shearing Test, SBS, Equivalent Viscosity.

1. Introduction
There is a big difference in properties between modified asphalt and ordinary asphalt. At present, the conventional indicators used to evaluate the composite modified asphalt of asphalt at home and abroad mainly include softening point, equivalent softening point, 60°C viscosity and adopted in the US Strategic Highway Research Program (SHRP) $G'/\sin \delta$ measured by dynamic shear rheometer, etc. The softening point represents a conditional temperature of the softness and hardness of the asphalt, and is an important index of the high-temperature stability of the asphalt. However, many ordinary asphalts in China have high softening points, but the elevated temperature stability is not good. The reason is that the wax in the asphalt affects the determination of the softening point, causing the softening point to appear false. It is impossible to accurately distinguish the elevated temperature between the asphalts. Viscosity is a direct manifestation of the flow characteristics of asphalt materials, and the dynamic viscosity of asphalt at 60°C is directly related to the anti-rutting performance of asphalt mixtures. However, due to the low control accuracy of the vacuum capillary method, the 60°C dynamic viscosity measurement results of modified asphalt are not accurate [1]. Researchers have been looking for more suitable test methods to reduce the error generated in the test. The anti-rutting factor $G'/\sin \delta$ is proposed...
by SHRP in the road Performance specification of asphalt binder in the United States to evaluate the elevated temperature stability of asphalt. However, $G'/\sin\delta$ is applicable to evaluate ordinary asphalt, not modified asphalt, especially high-performance modified asphalt. The study found that the use of $G'/\sin\delta$ to evaluate the high temperature capability of asphalt has great limitations, especially for modified asphalt, it cannot get reliable and effective results [2]. FHWA [3] found in the study of 12 test sections that $G'/\sin\delta$ can reflect its composite modified asphalt very well when evaluating the road performance of ordinary asphalt, but it cannot get accurate conclusions when evaluating modified asphalt. The main reason for this difference is that the assumptions and related rheological models used during the development of the Superpave asphalt binder specification are no longer applicable to modified asphalt binders [4]. Searching for a more suitable high temperature capability evaluation index for modified asphalt has become the main task of researchers from all over the world. In the "Eighth Five-Year Plan" research, China proposed to use equivalent softening point $T_{800}$ instead of the actually measured ring and ball softening point to avoid the influence of the melting heat of the wax on the softening point determination results in the asphalt [5]. Witczak [1] pointed out that using the equivalent viscosity $\eta'$ to predict the dynamic viscosity of asphalt at 60°C can effectively improve the discrimination of composite modified asphalt. The equivalent viscosity can be directly determined by the DSR results $\eta'=G'/\omega$. The University of Arizona research report [1] pointed out that the equivalent viscosity calculated by the $\eta'=\sin\delta^{-4.8628}G'/\omega$ prediction model is consistent with the evaluation results of the dynamic stability of the rutting on the composite modified asphalt of the modified asphalt. Shenoy [6-7] thinks that the rutting resistance of asphalt materials can be directly evaluated by obtaining new indexes of the irreversible deformation part, and proposed an improved anti-rutting factor $G'/[1-(\sin\delta\tan\delta)^{-1}]$ and $G'/\sin\delta$. Sam Maccarrone [8] proposed the critical temperature $T_{G'}/\sin\delta$, which is the equivalent anti-rutting factor, to solve some defects in reflecting composite modified asphalt indexes.

In this paper, through the results of routine test and dynamic shear rheological test (DSR), the high temperature capability of three polymer modified asphalts commonly used in Inner Mongolia area before and after aging was evaluated, and the composite modified asphalt evaluation indexes applicable to modified asphalt were analyzed. It can offer reference for objectively and effectively evaluating the high temperature capability of asphalt.

2. Raw Materials and Experiment

2.1 Experimental Materials

90# Liaohe asphalt was used as the matrix asphalt. 18% of compound modified asphalt (CCR) was blended with 30 mesh rubber powder and 2% SBS. Rubber powder (30 mesh) in rubber modified asphalt (CR) is 20%. In SBS modified asphalt (SBS), the SBS content was 4%. Short-term aging: Rotary film oven aging test (RTFO): 163°C/85min), simulating the aging of asphalt after elevated temperature mixing, transportation and paving compaction. Long-term aging: The pressure aging test (PAV):90°C/2.1MPa/20h) simulated the aging of asphalt under various actions after 5-7 years of service. The technical indexes of matrix asphalt and modified asphalt are shown in Table 1.

Table 1. Matrix asphalt and modified asphalt technology index

| Technical index | 90# Matrix asphalt | CCR | CR | SBS |
|-----------------|-------------------|-----|----|-----|
| Needle penetration (25°C)/0.1mm | 86.5 | 63.9 | 73.8 | 84.9 |
| Softening point /°C | 43.8 | 59.3 | 57.2 | 55.7 |
| Ductility /cm | 17.6/(5°C) | 24.3/(5°C) | 21.5/(5°C) | 23.8/(5°C) |
| Flashing point /°C | 290 | 277 | 273 | 269 |

It can be seen from Table 1 that compared with the matrix asphalt, the three major indexes of the modified asphalt have been improved, while the flash point has been reduced. Among them, CCR had
the lowest penetration, the highest softening point, and relatively high ductility. It had good high and low temperature performance, followed by CR.

2.2 Experimental Program
Penetration test: Perform a penetration test on the sample at different temperatures, the temperature range was 5°C, 15°C, 25°C, the load was 100g, and the penetration time was 5s.

DSR experiment: The experimental instrument was the Discovery HR-1 dynamic shear rheometer produced by TA Company to perform temperature sweep (Temperature Sweep). The temperature range of the temperature sweep test was 20℃-80℃, the temperature step was 10℃. The load frequency was 10rad/s. The diameter of the sample was 25mm (the original asphalt and the asphalt after short-term aging) and 8mm (the asphalt after pressure aging). The test adopted the sine wave method to load and control the target value of the stress for the test.

3. Experimental Results and Analysis

3.1 Analysis of Softening Point and Equivalent Softening Point
The equivalent softening point T800 has all the advantages that the softening point represents the composite modified asphalt of asphalt, and overcomes the influence of waxy asphalt. It is calculated matrixd on the penetration of three temperatures. In theory, it truly follows the softening point of the asphalt as the iso-viscosity temperature. Therefore, some scholars [5] proposed the application of equivalent softening point T800 to evaluate the elevated temperature stability of asphalt. In this study, the penetration of different asphalts at 5°C, 15°C and 25°C was tested, and the regression coefficients A and K were calculated according to \( \text{lg } P = AT + K \), and then calculated by formula (1), T800 can be calculated. The softening point and equivalent softening point results of various asphalts are shown in Figure 1.

\[
T_{800} = \frac{(\text{lg800-K})}{A}
\]

![Figure 1](image)

Figure 1. \( T_{R&B} \) and \( T_{800} \) of different asphalt

Figure 1 shows the softening point and equivalent softening point of various modified asphalts. It can be seen from Figure 1 that (1) As the aging degree of the three modified asphalts deepened, the softening points \( T_{R&B} \) and T800 of the asphalt became higher and higher. This is because the gradual deepening of aging reduced the oil content in the asphalt. The gradual increase of gum and asphaltene hindered the drop of the pellets and increased the softening point. Among them, the softening point \( T_{R&B} \) and T800 of the composite modified asphalt were the highest, indicating that it has better high-temperature stability; (2) Whether before or after aging, the softening point T800 of different modified
asphalts was much smaller than $T_{R&B}$, which just eliminated the factor of high softening point caused by wax, because the three temperature needles required to calculate T800 The penetration test is measured at a temperature of 30°C and below. At this temperature, most of the wax in the asphalt will be in a crystalline state, which will not affect the test results. Most of the asphalt in China is waxy asphalt, so T800 is used reasonably to evaluate the high temperature capability comparison; (3) But for modified asphalt, this phenomenon cannot be simply judged to be completely affected by the wax in the asphalt. Although the softening point $T_{R&B}$ is affected by the wax and its value will be higher, but the modifier in the modified asphalt It will also make the measurement of the softening point $T_{R&B}$ appear false. For example, SBS expands in asphalt to form a continuous network structure, and the balls are wrapped when falling, resulting in a high softening point. The swelling of the rubber powder in the asphalt gradually forms a semi-solid continuous phase system with greater consistency, which hinders the drop of the ball and increases the softening point. This shows that T800 is reasonable to evaluate the elevated temperature stability of modified asphalt.

3.2 Anti-Rutting Factor and Critical Temperature Analysis

The Superpave specification proposes to use $G*/\sin \delta$ to evaluate the high temperature capability of asphalt, but the study found that using $G*/\sin \delta$ to evaluate the high temperature capability of modified asphalt has certain limitations, and no effective results can be obtained [1]. The deformation of asphalt binder is mainly composed of two parts, recoverable deformation and non-recoverable deformation. The non-recoverable deformation part usually shows rutting phenomenon. Shenoy [6-7] believes that the anti-rutting ability of asphalt materials can be directly evaluated by obtaining a new index of irreversible deformation. Shenoy and Plazek used the Burges model to improve the cumulative strain concept proposed by Buldin, and deduced the expression of the unrecoverable strain $\gamma_{unr}$ of the asphalt cement under the action of a given constant stress $\sigma_0$, as shown in equation (2) [9].

$$\gamma_{unr} = 100 \sigma_0 G*/[1-(\sin \delta \cdot \tan \delta)^{-1}]$$  

(2)

To make the asphalt material have good high-temperature flow and deformation performance, the irreversible deformation is required to be small, that is, make $G*/[1-(\sin \delta \cdot \tan \delta)^{-1}]$ the largest. Because the irreversible deformation $\gamma_{unr}$ cannot be 0, that is, $1-(\sin \delta \cdot \tan \delta)^{-1}>0$, the phase angle needs to meet the condition of $\delta>51.8^\circ$. Therefore, it is not applicable when the phase angle is less than 51.8°. In response to this defect, Shenoy found that there is an excellent correlation between $G*/(\sin \delta)$ and $G*/[1-(\sin \delta \cdot \tan \delta)^{-1}]$ [7], and the phase angle range of the new index $G*/(\sin \delta)$ is between 0° and 90°, so $G*/(\sin \delta)$ can be used instead of $G*/[1-(\sin \delta \cdot \tan \delta)^{-1}]$ as an optimization index, which can comprehensively analyze the viscoelastic behavior of modified asphalt materials at different temperatures.

In this paper, the evaluation indexes of high temperature capability of modified asphalt were analyzed and studied. The results of temperature scanning test and frequency scanning test of conventional DSR test do not affect the comparative analysis of evaluation indexes, that is, the data at different temperatures and different frequencies do not affect the indexes. This paper took the temperature scanning test of the conventional DSR test as an example to analyze the use of the equivalent anti-rutting factor $G*/(\sin \delta)$ for the three modified asphalts before and after aging, and analyze the anti-rutting factor $G*/(\sin \delta)$ and the equivalent at different temperatures. The rutting resistance factor $G*/(\sin \delta)$ was compared. The experimental results are shown in Table 2, Table 3, and Table 4.
This shows that the rubber powder + SBS compositemodified asphalt was significantly higher than that of rubber powdertransformed from elastic to viscous, increasing the phase angle δ. At the same temperature, the anti-rutting factor G′/sinδ change according temperature of original asphalt, RTFO asphalt and PAV asphalt.

It can be seen from Table 2, Table 3 and Table 4 that (1) Whether before or after aging, with the increase of temperature, the anti-rutting factor G′/sinδ gradually decreased. This is because the increase of temperature makes the modification effect of the modified asphalt attenuation, resulting in the reduction of its modulus. On the other hand, as the temperature rose, the asphalt gradually transformed from elastic to viscous, increasing the phase angle δ. At the same temperature, the anti-rutting factor of composite modified asphalt was significantly higher than that of rubber powder modified asphalt and SBS modified asphalt. This shows that the rubber powder + SBS composite modifier is better than the rubber powder or SBS modifier alone in promoting the viscosity and elasticity.
of the asphalt under the same conditions, so that the asphalt exhibits stronger elevated temperature resistance to deformation. (2) Whether before or after aging, the $G'/\sin\delta$ value of each modified asphalt at the same temperature was much smaller than $G'/(\sin\delta)^9$, and the smaller the phase angle $\delta$, the greater the difference between the two. Since the composite modified asphalt had the smallest value before and after aging, the difference between $G'(\sin\delta)^9$ and $G'/\sin\delta$ was much larger than that of rubber powder and SBS. This shows that $G'/\sin\delta$ is not very sensitive to changes in phase angle $\delta$, while $G'(\sin\delta)^9$ is more sensitive to changes in phase angle $\delta$. As the phase angle decreases, the sensitivity gap between the two goes larger. Therefore, it is more reasonable to use $G'(\sin\delta)^9$.

The semi-logarithmic curves of $G'/\sin\delta$ vs. $T$ and $G'(\sin\delta)^9$ vs. $T$ were used for exponential regression, and the correlation coefficients were more than 90%. The critical temperatures $TG'/\sin\delta$ and $TG'(\sin\delta)^9$ of equal resistance to rutting factor were calculated and compared with the curve equation after exponential regression. The critical temperature of the equal anti-rutting factor was estimated matrixed on the rutting factor value at each temperature. When the rutting factor reached the temperature corresponding to Superpave’s standard value, that is, when the temperature of the rutting factor of the original asphalt reached 1.0Kpa, the temperature when the asphalt rutting factor reached 2.2Kpa after the rotating film oven was aged. The higher the critical temperature of the anti-rutting factor, the better the composite modified asphalt of the asphalt. See Table 5 for the critical temperature of the equivalent anti-rutting factor of different asphalts.

| Asphalt state | CCR | RTFO | CR | RTFO | SBS | RTFO |
|--------------|-----|------|----|------|-----|------|
| $TG'/\sin\delta$ | 126.48 | 111.89 | 105.91 | 95.81 | 84.84 | 87.08 |
| $TG'(\sin\delta)^9$ | 149.63 | 129.52 | 109.06 | 97.75 | 87.06 | 90.33 |

It can be seen from Table 5 that the critical temperature determined by the regression of $G'(\sin\delta)^9$ was higher than that of $G'/\sin\delta$ regardless of whether it was before or after short-term aging. This is because $G'/\sin\delta$ wasn’t able to separate the delayed recovery deformation from the unrecoverable deformation, so it was partially affected by the delayed elasticity, resulting in the high temperature capability of modified asphalt with high delay elasticity was underestimated and the critical temperature was low. Meanwhile, $G'(\sin\delta)^9$ took into account the influence of partial delay elasticity, so that the high temperature capability of the modified asphalt was significantly improved, and the accuracy was high and the sensitivity was good. It can be seen from Table 5 that the critical temperature $TG'/\sin\delta$ of the anti-rutting factors of the three modified asphalts was higher than that of $TG'/\sin\delta$. Among them, the composite modified asphalt had the most obvious increase. Before aging, $TG'/\sin\delta$ value increased by 23.15°C compared with $TG'/\sin\delta$. After short-term aging, $TG'/\sin\delta$ value increased by 17.63°C compared with $TG'/\sin\delta$, which had a significant influence on the PG grading of Superpave asphalt cement specification, while $G'/\sin\delta$ underestimated the elevated temperature grade of modified asphalt. This shows the rationality of using $G'(\sin\delta)^9$. Among the three modified asphalts, the critical temperature $G'(\sin\delta)^9$ of the composite modified asphalt was the highest before and after aging, indicating that its composite modified asphalt is better than the other two modified asphalts.

3.3 Equivalent Viscosity Analysis

Viscosity is a direct manifestation of the flow characteristics of asphalt materials. The viscosity at 60°C can better reflect the actual use of the road in summer. Dynamic viscosity at 60°C is directly related to the anti-rutting performance of the asphalt mixture. For modified asphalt, Chen Huaxin et al. [10] studied modified asphalt with different modifiers and found that $\eta'$ can effectively predict the dynamic viscosity at 60°C, which is similar to the measured value. Witeczak [1] pointed out that the equivalent viscosity $\eta'$ is used to estimate the dynamic viscosity of asphalt at 60°C, and $\eta' = G'/\omega$ can be directly determined from the DSR results. A research report from the University of Arizona [1] pointed out that when the
temperature and phase angle are less than 90℃, η´ must be corrected. The equivalent viscosity should be calculated using the η´ = sinδ-4.8628 G*/ω prediction model. This paper analyzed the equivalent viscosity of each modified asphalt before and after aging at 60℃, and used equations (3) and (4) to convert into the equivalent viscosity value at the corresponding temperature. See Table 6.

Table 6. 60℃ equivalent viscosity of different asphalt

| Index (kpa·s) | CCR | CR | SBS |
|--------------|-----|----|-----|
| ORI          | RTFO| PAV| ORI | RTFO| PAV| ORI | RTFO| PAV|
| 1η1          | 16.33 | 17.32 | 29.58 | 7.18 | 15.59 | 18.18 | 1.41 | 3.20 | 3.86 |
| 1η2          | 3.23  | 3.52  | 3.66  | 1.12 | 1.63 | 1.61  | 0.89 | 1.73 | 1.59 |

η1 represents sinδ-4.8628 G*/ω, η2 represents G´/ω

It can be seen from Table 6 that (1) As the degree of aging deepened, the equivalent viscosity of each modified asphalt gradually increased at 60℃. This is because the asphalt undergoes chemical changes during the aging process, in which chemical bonds break. Recombination and polymerization lead to changes in viscosity. At the same time, the oxidation of asphalt molecules also increases the content of asphaltenes, while the amount of light oils decreases, which increases the resistance to movement and increases the viscous force of the flow between asphalt layers, which increases the viscosity of the asphalt. (2) Under different aging degrees, the equivalent viscosity of composite modified asphalt was the largest, followed by rubber powder modified asphalt. This shows that the addition of rubber powder particles can effectively improve the composite modified asphalt of asphalt, while SBS has an effect on the elevated temperature of modified asphalt. Performance improvement is limited.

In order to verify which of the two equivalent viscosity indexes can better evaluate the composite modified asphalt of modified asphalt, correlation analysis was carried out between the two indexes η´ = sinδ-4.8628 G*/ω and G*/(sinδ)9 of different modified asphalt, respectively, as shown in Table 7. Where R1 and R2 are the correlation coefficients of η´ = sinδ-4.8628 G*/ω and G´/ω with rut factors G´/sinδ and G´/(sinδ)9 of different modified asphalt, respectively, and R3 and R4 are the correlation coefficients of η´ = G´´/ω and G´/ sinδ and G´/(sinδ)9 respectively.

Table 7. Correlation coefficient of equivalent viscosity and rutting factor

| correlation coefficients | CCR | CR | SBS |
|--------------------------|-----|----|-----|
|                           | ORI | RTFO| PAV | ORI | RTFO| PAV| ORI | RTFO| PAV|
| R1                       | 0.998 | 0.996 | 0.996 | 0.990 | 0.987 | 0.986 | 0.995 | 0.994 | 0.992 |
| R2                       | 0.999 | 0.997 | 0.998 | 0.996 | 0.999 | 0.998 | 0.998 | 0.999 | 0.999 |
| R3                       | 0.996 | 0.994 | 0.994 | 0.989 | 0.986 | 0.982 | 0.994 | 0.992 | 0.990 |
| R4                       | 0.986 | 0.966 | 0.968 | 0.931 | 0.985 | 0.966 | 0.965 | 0.981 | 0.986 |

It can be seen from Table 7 that the correlation between the equivalent viscosity of each modified asphalt and the rutting factor was very high, all reaching above 0.9, which can better reflect the high temperature capability of the asphalt. However, the correlation coefficients between η´ = sinδ-4.8628 G´/ω and rutting factor were all larger than those of η´ = G´/ω and rutting factor, which means that η´ = sinδ-4.8628 G´/ω is better to evaluate the composite modified asphalt of modified asphalt. By comparing the correlation coefficients R1 and R2, it is found that η´ = sinδ-4.8628 G´/ω had the best correlation and consistency with G´/(sinδ)9, which again proves that G´/(sinδ)9 can effectively characterize the high temperature capability of modified asphalt. Therefore, the equivalent viscosity η´ = sinδ-4.8628 G´/ω can better evaluate the composite modified asphalt of the modified asphalt.
4. Conclusion

(1) The equivalent viscosity measured by $\eta' = \sin\delta - 4.8628 \frac{G^*/\omega}{4.8628} \sin\delta$ has the best correlation with the equivalent anti-rutting factor, and the correlation coefficient is up to 0.999, which is more suitable as a high temperature capability evaluation index of modified asphalt.

(2) Compared with $G^*/\sin\delta$, $G^*/(\sin\delta)^9$ is more sensitive to changes in phase angle, and $G^*/(\sin\delta)^9$ takes into account the effects of partial delay elasticity and has high accuracy and good sensitivity, etc. The advantage is a better and more reliable evaluation index for high temperature capability of modified asphalt; for composite modified asphalt, the critical temperature $TG^*/\sin\delta$ value of anti-rutting factors before and after aging is greatly increased compared with $TG^*/\sin\delta$, thus improving its elevated temperature grade. It has an important influence on the accurate classification of PG grade of composite modified asphalt.

(3) Composite modified asphalt shows stronger elevated temperature resistance to deformation in all optimized indexes, followed by rubber powder modified asphalt.

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