Evaluation on low temperature characteristics of SBS/CR modified asphalt binder under different aging conditions

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Abstract. This study discussed the low temperature performance of styrene–butadiene–styrene (SBS)/crumb rubber (CR) modified asphalt under different aging process. The bending beam rheometer (BBR) test was conducted to compare the low temperature performance of SBS and SBS/CR modified asphalt at three different temperatures. The continuous low service temperature of two modified asphalt binders was calculated based on the ASTM method. The simple fractional viscoelastic model was implemented to better describe the creep behaviour of asphalt at low temperatures from the BBR test results. The damping ratio and dissipated energy ratio were also derived from the simple fractional model to assess the low temperature performance of asphalt from the aspect of energy. The analysis results showed that adding CR to SBS modified asphalt was beneficial to reduce the low service temperature and increase the values of damping ratio and dissipated energy ratio before and after the aging process. It has been proved that the low temperature performance of SBS/CR modified asphalt is much better than that of SBS modified asphalt under different aging conditions.

1. Introduction
In cold regions, low temperature cracking is one of the main diseases of asphalt pavement [1]. The anti-crack property of the asphalt pavement is directly related to the low temperature performance of the asphalt binder [2]. So the modification of asphalt by adding modifiers in neat asphalt has become an important means to improve the low temperature performance of asphalt pavement. On the one hand, the styrene–butadiene–styrene (SBS) modified asphalt has become one of the most widely used modified asphalts due to its superior comprehensive performance and mature production technology. However, SBS modified asphalt has insufficient anti-aging properties and high price, which limits its application range [3]. On the other hand, grinding waste rubber tires to obtain crumb rubber (CR) for asphalt modification is an important way to treat waste tires [4]. The low temperature performance and anti-aging performance of CR modified asphalt have been significantly improved compared with neat asphalt [5]. However, the CR modified asphalt has unsatisfied storage stability because of the poor compatibility between CR and asphalt [6]. Due to the shortcomings of both SBS modified asphalt and CR modified asphalt, the SBS and CR modifiers have been applied in the composite modification of neat asphalt [7,8]. The effective use of waste tires and SBS as the modifier for the asphalt is beneficial to protect the environment and save energy.

The bending beam rheometer (BBR) test based on the rheological theory is an effective tool to assess the low temperature performance of asphalt binders. The flexural creep stiffness and creep rate at time 60 s obtained from the BBR test are usually used as the indicators for the low temperature performance of asphalt binders. But there are often contradictions between the two indicators. It is
unilateral to evaluate the low temperature performance of SBS/CR composite modified asphalt by creep stiffness or creep rate alone because of the complex composition. The low service temperature, damping ratio, dissipated energy ratio and derivation of creep compliance were also used as the comprehensive indicators to investigate the low temperature performance [9,10]. The rheological models commonly used to describe the viscoelastic behaviour for the asphalt at low temperatures include CAM model, Burgers model and simple fractional viscoelastic model. The simple fractional model has been proved to be an effective and simple tool to predict the creep behaviour of asphalt binders at low temperatures [11].

Considering that the low temperature performance of asphalt has a certain relationship with the aging state of asphalt, but there are still few studies on the SBS/CR modified asphalt in this regard. The objective of this paper is to investigate the low temperature characteristics of SBS/CR modified asphalt under different aging conditions and SBS modified asphalt is selected as the comparative object. The BBR test was conducted for two asphalt binders and low service temperature was calculated according to the ASTM method. Based on the simple fractional model, the damping ratio and dissipated energy ratio were also adopted to compare the low temperature performance of two modified asphalt binders.

2. Experimental program

2.1. Materials

The SBS and SBS/CR modified asphalt binder used in this paper were provided by Jiangsu Baoli International Investment Co. Ltd. in China. The SBS content in the SBS modified was 5.5%. The SBS/CR modified asphalt was produced on the basis of SBS modified asphalt with the addition of liquefied rubber and carbon black.

2.2. Test method

The aging condition considered in this paper included short-term aging and long-term aging, and the corresponding test was Thin-Film Oven Test (TFOT) and accelerated aging of asphalt binder using a Pressurized Aging Vessel (PAV). The samples of two asphalt binders were kept in the thin-film oven for 5 hours at 163 °C. Then the samples were put into the pressurized aging vessel for 20 hours at 90 °C under the pressure of 2.1 MPa. The BBR test was followed the test methods specified by the “Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering” (JTG E20-2011 in China). The asphalt binders under different aging conditions were used to prepare the prismatic specimens for the BBR test with the dimension of 127 ×6.35×12.7mm. The test temperature was selected as -12 °C, -18 °C and -24 °C. The mid-span displacement data of the specimens were recorded in 0.5s time steps for 240s. Two parallel tests were conducted at different temperatures and the averaged values were calculated as the final results. Then the flexural creep stiffness \( S(t) \) can be calculated by the following equation:

\[
S(t) = \frac{PL^3}{4bh^3\delta(t)}
\]

where \( P \) is the constant load applied on the mid-span of the specimen, \( L \) is the span length, \( b \) is the width of the specimen, \( h \) is the height of the specimen, and \( \delta(t) \) is the mid-span displacement. The creep rate \( m(t) \) is defined as:

\[
m(t) = \left| \frac{d \log S(t)}{d \log(t)} \right|
\]

3. Simple fractional viscoelastic model

It has been observed that the fractional viscoelastic model is suitable to characterize the creep behaviour of asphalt [11], as is shown in Figure 1. The simple fractional model requires fewer
parameters compared with the widely used Burgers model. The creep compliance $D(t)$ of the simple fractional model is presented as:

$$D(t) = At^\alpha$$  \hspace{1cm} (3)$$

in which $A$ and $\alpha$ are the model parameters, and $D(t)=1/S(t)$.

![Simple fractional viscoelastic model](image.png)

**Figure 1.** Simple fractional viscoelastic model

4. Results and discussion

4.1. Low service temperature

The low service temperature of two asphalt binders was determined according to the method in ASTM D7643. The logarithmic linear interpolation of $S(t=60s)$ and linear interpolation of $m(t=60s)$ at different temperatures were conducted. The continuous low service temperature was the maximum interpolation result when $S(t=60s)=300$ MPa or $m(t=60s)=0.3$. The results of low service temperature for two asphalt binders is illustrated in Figure 2.

It is observed from Figure 2 that the low service temperature of SBS modified asphalt decreases slightly after short-term aging while SBS/CR modified asphalt increases after short-term aging. In addition, the low temperature performance of SBS modified asphalt decreases significantly after long-term aging. The low service temperature of SBS modified asphalt increases by 27.9% after long-term aging while that of SBS/CR modified asphalt increases by 8.9%. It can be seen that SBS has poor resistance to long-term aging in terms of low temperature performance. However, this shortcoming has been greatly improved with the addition of CR modifier. Moreover, the low service temperature of SBS/CR modified asphalt before and after aging is lower than that of original SBS modified asphalt. Therefore, the effect of CR on the low temperature performance of SBS asphalt is very obvious.

4.2. Determination of simple fractional model parameters

The parameters of the simple fractional model for two asphalt binders at different temperatures were calculated based on the nonlinear regression method and listed in Table 1. It can be observed that the values of the parameters $A$ and $\alpha$ in the simple fractional model become smaller as the temperature decreases. The coefficient $\alpha$ shows a downtrend after short-term and long-term aging.

According to Equation (3) and the reciprocal relationship between the creep stiffness and creep compliance, the following equation can be obtained:

$$\log[S(t)] = -\log A - \alpha \log(t)$$  \hspace{1cm} (4)$$

then the $m$-value is calculated by simple fractional model based on the definition in the Equation (2):

$$m(t) = \frac{d \log[-\log A - \alpha \log(t)]}{d \log(t)} = \alpha$$  \hspace{1cm} (5)$$

Thus it can be seen that the coefficient $\alpha$ has a clear physical meaning because it reflects the creep rate of asphalt binders. The $m$-value of two asphalt binders at different temperature and aging stage calculated by ASTM method and simple fractional model is compared in Figure 3. It can be seen that the $m$-value obtained by the two methods has a good linear correlation with an acceptable coefficient of determination. Therefore, it is feasible to predict the creep rate of asphalt binder by the simple fractional model with sufficient accuracy.
Table 1. Parameters of creep compliance based on the simple fractional model

| Aging condition | Type of modifier | -12°C | -18°C | -24°C |
|-----------------|------------------|-------|-------|-------|
|                 | A               | a     | R²    | A     | a     | R²    | A     | a     | R²    |
| Origin          | SBS             | 0.001083 | 0.4206 | 0.9960 | 0.000765 | 0.2907 | 0.9864 | 0.000704 | 0.1792 | 0.9661 |
|                 | SBS/CR          | 0.002790 | 0.5002 | 0.9982 | 0.001484 | 0.4137 | 0.9959 | 0.000881 | 0.2903 | 0.9936 |
| TFOT            | SBS             | 0.001329 | 0.3890 | 0.9972 | 0.000858 | 0.2710 | 0.9942 | 0.000745 | 0.1356 | 0.9747 |
|                 | SBS/CR          | 0.003271 | 0.5005 | 0.9981 | 0.001588 | 0.3716 | 0.9967 | 0.000832 | 0.2529 | 0.9956 |
| PAV             | SBS             | 0.001264 | 0.3027 | 0.9976 | 0.000889 | 0.1858 | 0.9766 | 0.000745 | 0.1160 | 0.9618 |
|                 | SBS/CR          | 0.002876 | 0.4404 | 0.9984 | 0.001489 | 0.3324 | 0.9974 | 0.000881 | 0.2077 | 0.9860 |

Figure 2. Low service temperature

Figure 3. Comparison of m-value using simple fractional model

4.3. Damping ratio

The damping ratio describes the ratio of viscous component to elastic component for the viscoelastic materials. For the simple fractional model, the damping ratio is calculated in the following expression:

\[
\text{damping ratio} = \tan \left( \frac{\pi \alpha}{2} \right)
\]  

(6)

It can be seen from Equation (6) that the damping ratio calculated by the simple fractional model is directly related to the coefficient \( \alpha \) and increases with the increase of \( \alpha \). The damping ratio of two asphalt binders at different temperatures under different aging condition is shown in Figure 4. It can be observed that the damping ratio decreases as the temperature decreases due to the dominant elastic behaviour at low temperatures. In general, the damping ratio of SBS/CR modified asphalt is greater than that of SBS modified asphalt at different temperatures. The greater damping ratio means better performance at low temperatures, which indicates the good anti-crack property of SBS/CR modified asphalt binder at low temperatures.

Table 2. Linear regression results of damping ratio versus temperature

| Type            | Regression equation | \( R^2 \) | Crossover temperature(°C) |
|-----------------|---------------------|----------|--------------------------|
| SBS-origin      | y=0.0407x+1.2512    | 0.9903   | -6.2                     |
| SBS-TFOT        | y=0.0403x+1.1830    | 0.9999   | -4.5                     |
| SBS-PAV         | y=0.0276x+0.8291    | 0.9714   | 6.2                      |
| SBS/CR-origin   | y=0.0425x+1.5156    | 0.9989   | -12.1                    |
| SBS/CR-TFOT     | y=0.0485x+1.5669    | 0.9902   | -11.7                    |
| SBS/CR-PAV      | y=0.0408x+1.3157    | 0.9996   | -7.7                     |

4
Then the crossover temperature at which the storage modulus is equal to loss modulus is calculated based on the linear regression method, as is listed in Table 2. It can be seen that the crossover temperature of SBS/CR modified asphalt is much lower than that of SBS modified asphalt. It is indicated that SBS/CR modified asphalt has sufficient viscous components to dissipate energy at low temperatures, which is beneficial to resist low temperature cracks. In addition, the crossover temperature of the long-term aged SBS/CR modified asphalt is at the same level as that of origin SBS modified asphalt. This proves the superiority of CR in terms of anti-aging performance.

4.4. Dissipated energy ratio
The dissipated energy ratio (DER) is defined as the ratio of dissipated energy to stored energy. The higher the DER, the better the low temperature performance of the asphalt binder. The DER calculated using the simple fractional model is expressed as:

\[
\text{DER} = \frac{2^{\alpha-1}}{1-2^{\alpha-1}}
\]  

(7)

It can be seen from Equation (7) that the DER is independent of time and is only related to the parameter \(\alpha\) of the simple fractional model. The DER of two modified asphalt binders before and after aging at different temperatures is illustrated in Figure 5.
temperature decreases, the effect of long-term aging on the DER is getting smaller and smaller. In addition, it can be found that the evaluation results of the low temperature performance for the two asphalt binders are the same when using DER and damping ratio [9,10]. The DER has been widely used to evaluate the low temperature performance of asphalt binders. So the damping ratio can be an effective indicator for the evaluation of low temperature performance of modified asphalt binders.

5. Conclusions
In this study, the low temperature performance of SBS modified asphalt and SBS/CR modified asphalt under different aging conditions were compared based on the BBR test. The main conclusions of this study are summarized as follows:

- The low temperature performance of SBS/CR modified asphalt is much better than that of SBS modified asphalt under different aging conditions. The low service temperature of SBS/CR modified asphalt after long-term aging is much lower than that of original SBS modified asphalt.
- The simple fractional viscoelastic model is an effective tool to characterize the creep behaviour of two modified asphalt binders at low temperatures.
- The coefficient $\alpha$ in the simple fractional model has a good linear correlation with the m-value and can be an index to describe the low temperature performance of asphalt binders.
- The two indicators, damping ratio and dissipated energy ratio, also confirm the superiority of low temperature performance of SBS/CR modified asphalt from the aspect of energy.
- The performance of SBS/CR modified asphalt at medium and high temperatures will be further discussed in the future studies.

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References
[1] Liu J, Zhao S, Li L, Li P and Saboundjian S 2017 Low temperature cracking analysis of asphalt binders and mixtures Cold Reg. Sci. Technol. 141 78–85
[2] Luo X, Gu F, Ling M and Lytton R L 2018 Review of mechanistic-empirical modeling of top-down cracking in asphalt pavements Constr. Build. Mater. 191 1053–70
[3] Cuciniello G, Leandri P, Filippi S, Lo Presti D, Losa M and Airey G 2018 Effect of ageing on the morphology and creep and recovery of polymer-modified bitumens Mater. Struct. 51
[4] Shu X and Huang B 2014 Recycling of waste tire rubber in asphalt and portland cement concrete: An overview Constr. Build. Mater. 67 217–24
[5] Wang S, Cheng D and Xiao F 2017 Recent developments in the application of chemical approaches to rubberized asphalt Constr. Build. Mater. 131 101–13
[6] Liang M, Xin X, Fan W, Luo H, Wang X and Xing B 2015 Investigation of the rheological properties and storage stability of CR/SBS modified asphalt Constr. Build. Mater. 74 235–40
[7] Dong F, Yu X, Liu S and Wei J 2016 Rheological behaviors and microstructure of SBS/CR composite modified hard asphalt Constr. Build. Mater. 115 285–93
[8] Kosma V, Hayrapetyan S, Diamanti E, Dhwale A and Giannelis E P 2018 Bitumen nanocomposites with improved performance Constr. Build. Mater. 160 30–8
[9] Liu S, Cao W, Shang S, Qi H and Fang J 2010 Analysis and application of relationships between low-temperature rheological performance parameters of asphalt binders Constr. Build. Mater. 24 471–8
[10] Aflaki S and Hajikarimi P 2012 Implementing viscoelastic rheological methods to evaluate low temperature performance of modified asphalt binders Constr. Build. Mater. 36 110–8
[11] Hajikarimi P, Aflaki S and Hoseini A S 2013 Implementing fractional viscoelastic model to evaluate low temperature characteristics of crumb rubber and gilsonite modified asphalt binders Constr. Build. Mater. 49 682–7