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Laboratory Evaluation of the Relationship of Asphalt Binder and Asphalt Mastic via a Modified MSCR Test

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Abstract: Asphalt mastic, which consists of an asphalt binder and a mineral filler, provides critical adhesion and viscoelasticity to an asphalt mixture. The rheological response of the asphalt mastic is mainly derived from its asphalt binder. In this study, a simple laboratory test method is proposed to estimate the relationship of asphalt binder and its mastic. Two modified binders (3.5% and 4.0% styrene–butadiene–styrene (SBS) of asphalt binder by mass) were blended with a limestone filler at six different mineral filler contents to produce mastic samples. A modified multiple stress creep-recovery (MSCR) test was conducted on both the asphalt binder and its mastic with the same testing protocols, and the stress conditions and rheological response of asphalt binder in the mastic with linear or nonlinear viscoelasticity were both investigated. The results show that the stress of the asphalt binder in its mastic decreased with increasing filler contents. However, for the linear-viscoelasticity mastic, the decrease rate of the stress began to slow down when the filler content had reached 100% or 120%. For the rheological properties of the asphalt binder in the mastic, the %*R* of the asphalt binder was improved by adding filler, especially for the nonlinear-viscoelasticity mastic. The asphalt binder of the linear-viscoelasticity asphalt mastic also showed a linear viscoelastic response and a good recovery property. The performance of the asphalt mastic and rheological properties of its asphalt binder were highly related to its filler content.

Keywords: asphalt binder effect; asphalt mastic; modified MSCR test; strain cumulation rate; rheological properties

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1. Introduction

The mechanical performance of an asphalt mixture is the result of the resistances and interactions formed by its components, including the asphalt binder, aggregates, mineral filler, and air voids [1]. The asphalt binder bonds every component together and provides the main viscoelasticity of the asphalt mixture [2]. The mineral filler, whose particle size is less than 0.075 mm, is commonly considered to be a part of the aggregate system. In addition, a major fraction of the filler embedded into the asphalt binder is observed microscopically, such that the adhesion among the aggregates in the asphalt mixture is not provided by the pure asphalt binder, but by the mastic, which consists of the asphalt binder and filler [3,4]. Therefore, the mastic plays real roles between coarse and fine aggregates, and its rheological properties directly affect the viscoelastic behaviors of the asphalt mixture, especially at high temperatures. The rheological response of asphalt mastic is highly correlated with the cracking resistance, fatigue behavior, and rutting performance of the asphalt mixture [5–7].

The asphalt mastic forms during the mixing process, and coats coarse and fine aggregates, thereby creating the main viscoelastic response of the asphalt mixture [8]. The stiffness of the asphalt mastic can be significantly improved through the addition of mineral

filler. The modulus of the asphalt mastic can be 3 to 5 times higher than that of an asphalt binder [1]. In addition, mineral fillers in the asphalt mastic can enhance its elastic response and decrease its susceptibility to permanent deformation [9]. Liu et al. [10] estimated the high-temperature rheological properties of polyphosphoric acid (PPA)-modified asphalt mastic. The filler/asphalt (F/A) ratio by mass had a significant effect on the stiffness of the mastic, and the optimal F/A ratio was chosen to be 90% for PPA-modified asphalt mastic. Tan et al. [11] found that filler contents between 90% and 140% by binder weight tended to produce the best high and low temperatures for asphalt mastic. Wang et al. [12] proposed the relative viscosity and relative J_{nr} ratios (mastic to binder) as indicators to evaluate the filler reactivity with asphalt binder, and the filler-stiffening effect was heavily dependent on the type of asphalt binder. The asphalt binder is the matrix phase providing elastic, viscous, and viscoelastic properties [13]. Adhesion between the asphalt binder and filler particles strongly affects the performance of the asphalt mastic and mixture [14,15]. There is no chemical reaction between the asphalt binder and filler particles in the mastic system [16]. The effect of the asphalt binder in the mastic is mainly determined by the asphalt binder type. The behavior of the mastic produced by the modified asphalt binder can be improved in terms of fatigue property, cracking resistance, and antirutting performance, and the modification mechanism for the mastic is identical to that of the modifier for the asphalt binder [17]. The asphalt binder type shows great correlation with the reinforcement of the mastic by adding mineral filler [18]. For the modified asphalt mastic, viscosity significantly increases with increasing filler content, but the increase is not significant for neat asphalt mastic [19]. The filler volume fraction is also determined for the mastic depending on the asphalt binder used [20]. In addition, the mastic exhibits both linear and nonlinear viscoelastic behavior like that of the asphalt binder. The strain is proportional to the stress in linear viscoelasticity, but not for nonlinear viscoelasticity [21]. Generally, the asphalt binder and mastic behave linearly at a low stress/strain level, and nonlinearly at a high stress/strain level [22,23]. The fixed binder-free binder ratio in the asphalt mastic also has a great effect on the performance of the mastic [24].

An investigation into the rheological properties of the asphalt mastic is essential to better understand the asphalt mixture behavior in terms of its rutting potential [25]. Similar to an asphalt binder, a mastic shows a time- and temperature-dependent response, and the dynamic shear rheometer (DSR) test is typically adopted in the literature to measure the rheological performance of asphalt mastics [26,27]. The complex modulus (G^*), phase angle (δ), and the master curves are established under linear viscoelastic conditions for the mastics [22]. In addition, the rutting parameter ($G^*/\sin\delta$) was proposed as one possible measure of linear viscoelasticity [28]. However, this parameter had poor correlation to asphalt mixture rutting performance, and may not be able to reliably evaluate the high-temperature performance of asphalt binders and mastics (especially for modified asphalt binders) [29]. Moreover, it was observed in the literature that asphalt mastic might behave in a nonlinear manner with an increase in applied stress, indicating that nonlinear viscoelasticity needs to be considered in the understanding of mastic behavior [30]. Other researchers utilized the viscous component of repeated creep stiffness G_v derived from repeated creep–recovery (RCR) tests to evaluate the rheological responses of asphalt mastic at high temperatures [11,31]. While the RCR test can be used to evaluate the rheological properties of the asphalt mastic with consideration to elastic recovery [32], this test is typically conducted at the creep-stress level. Hence, it is not able to evaluate the responses of the asphalt mastic when subjected to varying stress levels. Considering these limitations of rheological evaluation of asphalt mastic, the multiple stress creep-recovery (MSCR) test is commonly adopted in the literature to measure the rheological properties of an asphalt mastic [33–35]. On the basis of the AASHTO T350-14 standard [36], the MSCR test is performed at stress levels of 0.1 and 3.2 kPa for an asphalt binder at 64 °C by using the DSR to measure the creep and recovery of the asphalt binder and mastic, and their linear and nonlinear viscoelasticity. In addition, nonrecoverable compliance (J_{nr}) can be determined via the average strain of nonrecovery for 10 cycles divided by the applied stress for those

cycles. Another parameter from the MSCR test, the recovery percentage (%R), reflects the degree of recovery to the initial shape of the asphalt binder or mastic after being repeatedly sheared and relaxed. J_{nr} and %R can both illustrate the rheological response of asphalt binder and mastic with good correlation to asphalt mixture rutting performance. They are widely used instead of the rutting parameter ($G^*/\sin\delta$) to evaluate the rutting potential of asphalt binders and mastics [35]. For the viscoelastic properties of asphalt binders, their viscous and elastic components can be well-represented by J_{nr} and %R. In addition, viscous indicator J_{nr} shows significant correlation with the rutting resistance of asphalt mixtures. Elastic indicator %R was not a significant factor for the rutting performance of asphalt mixtures, especially for well-packed aggregate mixtures [37]. Jafari et al. [38] assessed the rutting potential of a polyphosphoric acid (PPA)-modified binder using the MSCR test. The standard stress levels of 0.1 and 3.2 kPa could not present the stress sensitivities of the asphalt binder. As the stress increased to 12.8 kPa, the stress sensitivities of the asphalt binder became more significant. In addition, the higher degree of the nonlinear behavior of the asphalt binder was associated to the higher stress levels [39]. Hamid et al. [40] investigated the stress and temperature sensitivities of an asphalt binder modified with fly-ash-based geopolymer (GF), styrene–butadiene–styrene (SBS), and a combination of GF and SBS using the MSCR test. The relationship between temperature and J_{nr} could help in selecting the suitable modifiers for an asphalt binder in asphalt pavement design. Moreover, the indicators of J_{nr} and %R of modified asphalt binders can be predicted well via an artificial neural network (ANN) model [41]. Al-Adham et al. [42] proposed some indicators, including strain recovery rates, absolute recovery percentage, and creep compliance recovery rate, of polymer-modified asphalt (PMA) on the basis of the MSCR test. The strain recovery rate base indicators presented statistically better correlation with the rutting performance of the asphalt mixture. Therefore, the MSCR test shows some advantages in evaluating the high-temperature performance and rutting potential of asphalt binders. For asphalt mastics, a wider range of temperature, applied stress, and loading time might be considered [43].

As a review of the literature suggests, many studies on the performance of asphalt mastics have focused on the stiffening effect of the mineral filler. For the role of asphalt binders in the mastic, there is currently only phenomenon-based analysis on the asphalt binder. Most results have just regarded the viscoelastic behavior of the asphalt mastic and how to change it among different asphalt binders or with the filler content changed. The real stress status of an asphalt binder in a mastic under stress loading remained unclear in previous studies. The real rheological properties of an asphalt binder should be found in the mastic system because the rheological status of the asphalt binder is highly related to the performance the asphalt mastic and mixture. In addition, the potential of the strain curves of asphalt binders and mastics obtained from MSCR test should be further investigated. More effective indicators of the MSCR test need to be explored. To address these issues, a simple and innovative experimental method to estimate the stress status of the asphalt binder in the mastic is proposed here. Then, a new rheological indicator of asphalt binders and mastics is proposed on the basis of the strain curves of the MSCR test. This can better demonstrate the relationship between the rheological response and MSCR stress. The development of an asphalt binder in the mastic of both linear and nonlinear viscoelasticity is also discussed in this study.

The rest of paper is structured as such: First, a new indicator, the strain cumulation rate (SCR), is proposed on the basis of the strain response of the modified MSCR test, through which the relationship between an asphalt binder and its mastic can be established. Second, the stress status of an asphalt binder in its mastic was investigated on the basis of SCR analysis. Lastly, the rheological properties of the asphalt binder in its mastic with linear- and nonlinear-viscoelasticity conditions are discussed.

2. Basic Hypothesis

In order to better estimate the stress and rheological properties of an asphalt binder in its mastic via laboratory testing, some hypotheses need to be proposed, and they are listed as follows:

(a) The rheological behavior of an asphalt mastic is totally derived from its asphalt binder. In addition, via the same testing protocol, the indicator obtained from the asphalt mastic represents the rheological status of its asphalt binder in the mastic system.

(b) The asphalt binder did not show deformation and present recovery behavior when creep stress was not applied. In this case, when the stress was zero, the creep strain and recovery strain of the asphalt binder were zero.

On the basis of these hypotheses, the stress of the asphalt binder in the mastic could be calculated with the MSCR test. Then, the rheological properties of the asphalt binder could be determined in its asphalt mastic.

3. Material Preparation

In this study, two asphalt binders and one mineral filler were selected to prepare the asphalt mastic samples. For the asphalt binder, both types were styrene–butadiene–styrene (SBS)-modified binder with SBS contents of 3.5% and 4.0% of the asphalt binder by weight. The SBS-modified asphalt binders were both prepared in an asphalt plant, and they are commonly used in asphalt pavement construction in Jiangsu province. Generally, the SBS-modified asphalt binder is obtained by adding SBS modifier in a #70 neat asphalt binder. High temperature and high speed were used during the plant mixing process to ensure the stability and homogeneity of the modified asphalt binder. The main physical properties of the SBS-modified asphalt binders were measured as per the Chinese highway standard [44]. In addition, performance grading at high temperature was determined with the Superpave protocol [45]. The results for these two asphalt binders are shown in Table 1. The performance grading was used to name these two asphalt binders in this paper, namely, PG76 and PG70.

Table 1. The performance of two asphalt binders.

Index	Asphalt Binder 1	Asphalt Binder 2
SBS content	3.5%	4.0%
Softening point (°C)	65	76
Ductility (cm, 5 cm/min, 5 °C)	50	43
Penetration (0.1 mm, 100 g, 15 °C, 5 s)	21	21
Penetration (0.1 mm, 100 g, 25 °C, 5 s)	52	54
Penetration (0.1 mm, 100 g, 30 °C, 5 s)	87	86
Penetration index (PI)	−0.2280	−0.1153
Performance grading	PG 70-xx	PG 76-xx

A limestone mineral filler with a specific gravity of 2.705 g/cm^3 was selected and consisted of particles that passed a 0.075 mm sieve. The filler content in the asphalt mastic should be consistent with the filler usage in the asphalt mixture. In the design of asphalt mixtures, the amounts of mineral filler and asphalt binder are controlled via the mass percentage of aggregates [44]. Then, the mastic is determined via the equivalent mass ratio of the filler and asphalt binder. Therefore, the filler content of the mastic could be defined in this study and is expressed in Equation (1).

$$\text{Filler content} = \frac{\text{Mass of filler}}{\text{Mass of binder}} \quad (1)$$

The filler content for commonly used asphalt mixtures varies from 50% to 150%, approximately based on the aggregate gradation of the mixtures [30]. In addition, an appropriate filler content was verified to range from 60% to 120% in Superpave design [10]. In order to investigate the mastic behavior in a wide range of filler content, the limestone filler was mixed with the PG70 and PG76 asphalt binders at 0%, 50%, 80%, 100%, 120%, 150%, and 180% filler content to fabricate mastics in this study. For the homogeneity of the produced mastic, the following preparation procedures were used [9]. The asphalt binder and filler were heated in a constant-temperature oven at 170 °C for 2 h. Then, the filler was slowly added into the asphalt binder and blended with a high-speed mechanical mixer at 170 °C. The mixing speed was gradually increased with the addition of the filler, and the entire process took almost 10 min. Then, the mixing processing was continued for 30 min at a constant speed of almost 3000 r/min to avoid filler segregation. The prepared mastic samples were preserved in cans, and the storage temperature was maintained at 25 °C. In terms of the asphalt binder test, to satisfy the testing protocol of AASHTO and simulate the aging condition in the mixing process of the mastics at high temperature, the two asphalt binders (PG70 and PG76) were short-term aged using the rolling thin-film oven (RTFO) procedure [36]. The prepared asphalt binder and mastic were molded into samples of 20 mm in diameter and 2–3 mm thickness using silicone molds, and they were then subjected to the MSCR test. The main asphalt mastic preparation process is shown in Figure 1.

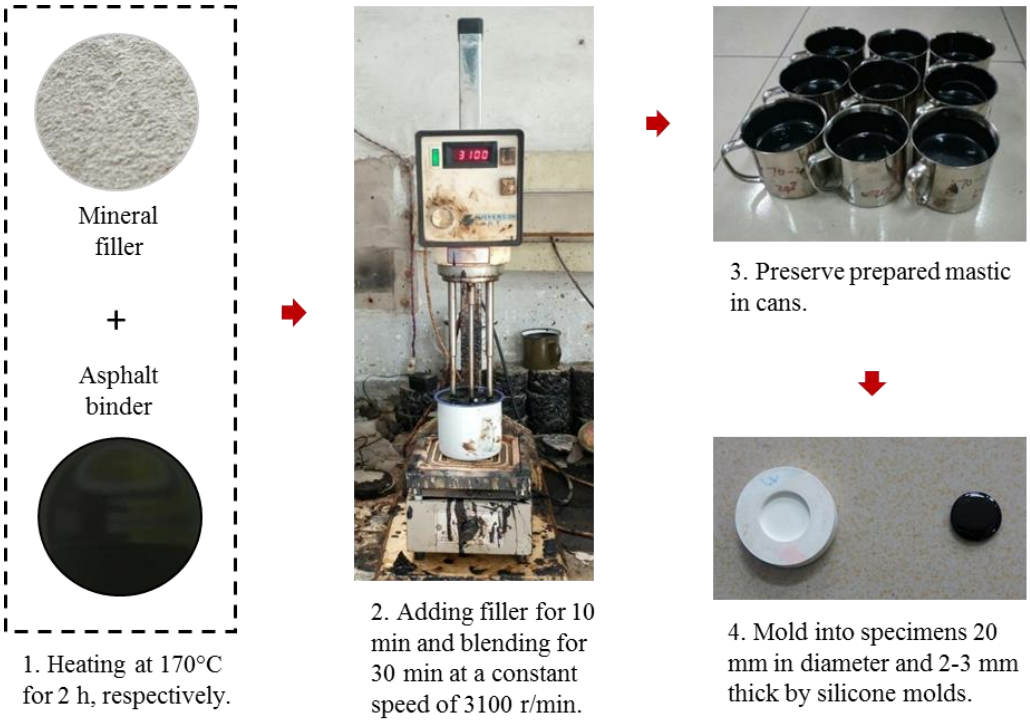


Figure 1. Asphalt mastic preparation.

4. Laboratory Test and Methods

In this study, all rheological measurements for the asphalt binder and mastic samples were conducted through a modified MSCR test using a dynamic shear rheometer (DSR). A 25 mm parallel plate geometry with a 1 mm gap was used in the MSCR test for both the asphalt binder and the mastic. The test was performed at 64 °C with 1 s constant creep loading and 9 s recovery duration. The modified MSCR test was selected for a wider range of loading stress for both the asphalt binder and mastic samples. Multiple creep stresses were selected for the test (0.1, 3.2, 6.4, 12.8 and 25.6 kPa) for 10 cycles at each stress level [46]. Each test was started at the lowest stress level, which was increased at the end of each set of 10 cycles with no time lag between cycles.

According to AASHTO T350-14 [36], conventional observations regarding J_{nr} and $\%R$ were obtained from the MSCR test. For the case of the PG70 binder and its mastic with 100% filler content, their strain curves obtained from the MSCR test are shown in Figure 2. At the first cycle of the strain curve for one creep stress, the initial strain (ε_o) value at the beginning of the creep stress loading and the strain value (ε_c) at the end of the creep stress loading (after 1 s) were determined. Because of the recovery portion of each cycle, the strain value (ε_r) at the end of the recovery (after 10 s) was also obtained. Therefore, the strain increased with the stress loading, and decreased when the stress unloaded in one creep cycle. Obviously, for the other nine cycles of stress, the creep stain at each cycle had an almost identical response with that of the first cycle. Then, a recoverable strain and nonrecoverable strain, termed $\varepsilon_r(N)$ and $\varepsilon_{nr}(N)$, could be calculated and are expressed as Equations (2) and (3), respectively.

$$\varepsilon_r(N) = \varepsilon_c - \varepsilon_r \tag{2}$$

$$\varepsilon_{nr}(N) = \varepsilon_r - \varepsilon_0 \tag{3}$$

Then, the nonrecovery creep compliance and recovery percentage for each of the 10 cycles at creep stress, σ, could be obtained and are expressed as Equations (4) and (5), respectively.

$$J_{nr}(\sigma, N) = \frac{\varepsilon_{nr}}{\sigma} \tag{4}$$

$$\%R(\sigma, N) = \frac{\varepsilon_r}{\varepsilon_c - \varepsilon_0} \times 100 \tag{5}$$

where, N is the order of 10 cycles for N = 1 to 10.

The values of J_{nr} and $\%R$ are the average values obtained from 10 conducted cycles during the MSCR test at each creep stress. Their expressions are shown in Equations (6) and (7), respectively.

$$J_{nr} = \frac{\sum_{N=1}^{10} J_{nr}(\sigma, N)}{10} \tag{6}$$

$$\%R = \frac{\sum_{N=1}^{10} \%R(\sigma, N)}{10} \tag{7}$$

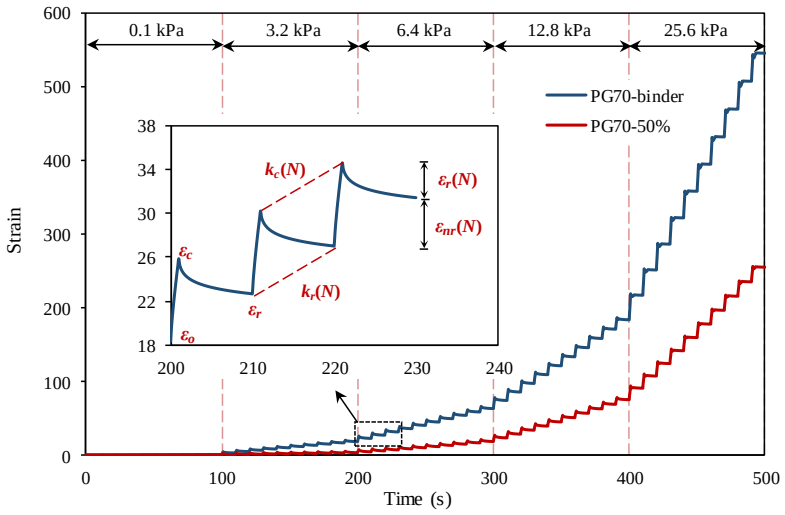


Figure 2. Strain curves of the asphalt binder and mastic during the MSCR test.

As shown in Figure 2, the total strain of each cycle for both the asphalt binder and the mastic linearly cumulated with time at 1 stress, although strain recovery appeared

after each creep. The values of the strains (i.e., creep strain and recovery strain) generally showed trends of linear increase at each stress level. The slope of the total cumulated strain (10 cycles at 1 stress) represents the rate of the strain cumulated at each stress. The high-temperature rutting potential of the asphalt binder and mastic was also indicated via the MSCR test. The slope of cumulated strain showed strong stress dependence and obviously increased with increasing stress. It could then be regarded as an indicator, termed the strain cumulation rate (*SCR*) in this study, to exhibit the creep and recovery properties of the asphalt binder and mastic at a high temperature. The *SCR* also presents the total tend of the strain curve increased at each stress. Obviously, the *SCR* exhibited a significant difference between the asphalt binder and mastic. The difference in *SCR* mainly resulted from the addition of mineral filler into the asphalt mastic. The relationship between asphalt binder and mastic could be investigated by comparing their *SCR* values.

Figure 2 shows the value of *SCR* at 1 stress that was the average value of the slop of creep strain (ε_c) and slop of recovery strain (ε_r) for 10 cycles. Therefore, the creep-strain cumulation rate and recovery-strain cumulation rate, termed $k_c(N)$ and $k_r(N)$ in Figure 2, could be calculated via Equations (8) and (9), respectively. The final value of *SCR* was the total average value of $k_c(N)$ and $k_r(N)$ for 10 cycles at 1 stress. The calculated expression is shown in Equation (10).

$$k_c(\sigma, N) = \frac{\varepsilon_c(N+1) - \varepsilon_c(N)}{t} \tag{8}$$

$$k_r(\sigma, N) = \frac{\varepsilon_r(N+1) - \varepsilon_r(N)}{t} \tag{9}$$

$$SCR = \frac{1}{2} \cdot \frac{\sum_{N=1}^{9} [k_c(\sigma, N) + k_r(\sigma, N)]}{9} \tag{10}$$

where N is the order of the cycle at creep stress σ and N = 1 to 9 for the calculation of $k_c(N)$ and $k_r(N)$. t is the time lag between strains, t = 10 s for both the $k_c(N)$ and $k_r(N)$.

5. Results and Discussion

In this section, an appropriate rheological indicator is proposed and used to establish the relationship between the rheological behavior and stress of an asphalt binder. Then, the stress condition and rheological status of the asphalt binder in its mastic are investigated.

5.1. Results and Analysis of the MSCR Test Results of the Asphalt Binder

Here, on the basis of the MSCR test results of PG70 and PG76 asphalt binders, the relationship between the rheological behavior of the asphalt binder and its applied stress is established, and an appropriate rheological indicator is determined. Figure 3 presents the results of all rheological indicators of the asphalt binder, including the J_{nr}, $\%R$, and *SCR* obtained from the MSCR test on the basis of Equations (2)–(10).

For the asphalt binder, rheological indicators J_{nr}, $\%R$, and *SCR* all showed significant sensitivity to the stress. However, an appropriate indicator should satisfy Basic Hypothesis (b) of the asphalt binder, so that the relationship between indicator and stress can be built well. The strain was zero when no stress was applied to the asphalt binder. In this case, $\%R$ should be 100%, and the values of J_{nr} and *SCR* should be zero. As shown in Figure 3a, J_{nr} and $\%R$ are both well-defined linear functions of stress. The regression results are listed in Table 2. However, when the value of stress approached zero, the values of J_{nr} and $\%R$ were not close to zero and 100%, respectively. This might be attributed to the minimal creep stress in the MSCR test (i.e., 0.1 kPa) not being small enough. Obviously, because of the limitations of the loading conditions of the MSCR test, using J_{nr} and $\%R$ did not accurately illustrate the relationship between rheological properties and stress. It also did not meet Basic Hypothesis (b) of the asphalt binder. In Figure 3b, on the other hand, the *SCR* of the asphalt binder shows a quadratic polynomial expression of the stress. In addition, when the stress was zero, the value of *SCR* greatly approached zero in terms of PG76 and

PG70. Obviously, the *SCR* indicator satisfied Hypothesis (b) of the asphalt binder. When considering the condition of nonstress loading, *SCR* showed good regression results with stress that are also presented in Table 2. Therefore, the expressions of *SCR* and stress in terms of the PG76 and PG70 asphalt binders were established. On the basis of Hypothesis (a), when the *SCR* values of asphalt mastics were plugged into the expression of the *SCR* and stress for the asphalt binder, the stress of the asphalt binder in its mastic could be estimated. The stress status of the asphalt binder in the mastic can be approximately investigated. In addition, similar to indicators J_{nr} and $\%R$, the *SCR* could be used to evaluate the rutting potential of asphalt material. On the basis of the definition of the *SCR*, the asphalt binder with better rutting performance that would present lower strain cumulation and a lower value of *SCR* was obtained.

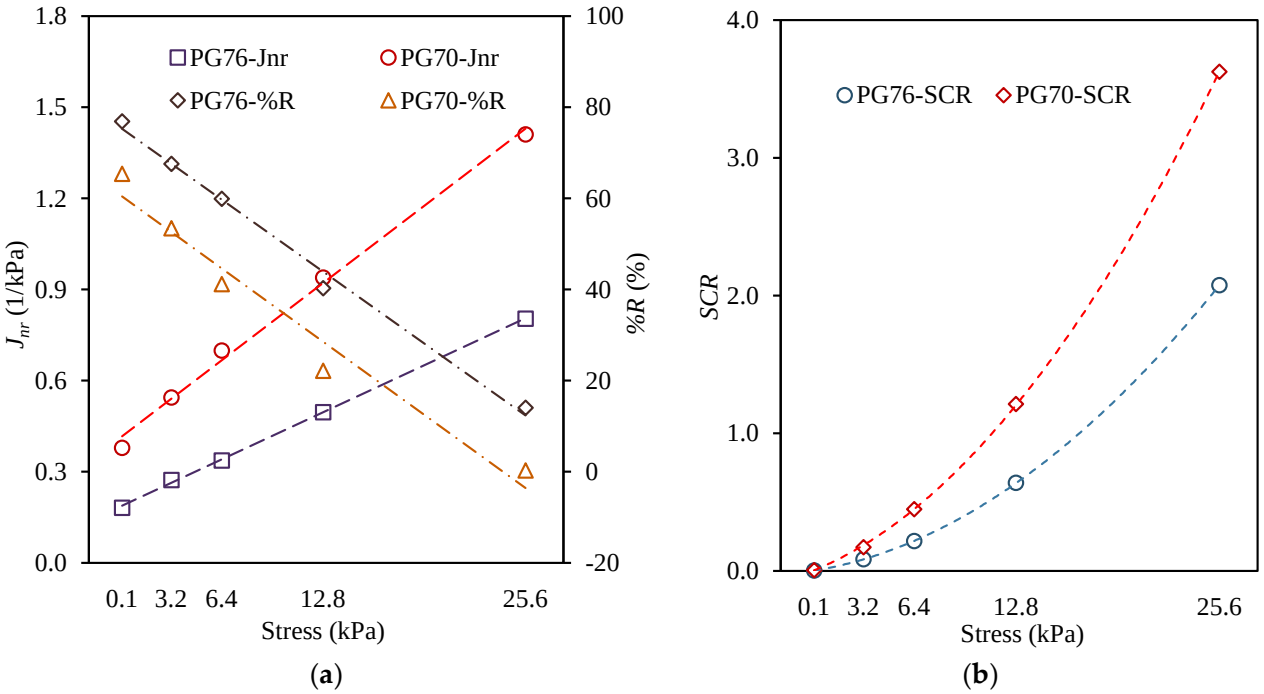


Figure 3. Results of the rheological indicators of the asphalt binder. (**a**) J_{nr} and $\%R$ vs. stress; (**b**) *SCR* vs. stress.

Table 2. Results of the regressions of rheological indicators with stress.

Indicators	Binder Type	Regression Equation	Expression Type	R^2
J_{nr}	PG76	$J_{nr} = 0.0242\,\sigma + 0.1859$	Linear	0.9993
	PG70	$J_{nr} = 0.0397\,\sigma + 0.4129$	Linear	0.9950
$\%R$	PG76	$\%R = -2.4666\,\sigma + 75.5103$	Linear	0.9925
	PG70	$\%R = -2.5093\,\sigma + 60.6730$	Linear	0.9650
SCR	PG76	$SCR = 0.0024\,\sigma^2 + 0.0185\,\sigma$	Quadratic polynomial	0.9999
	PG70	$SCR = 0.0037\,\sigma^2 + 0.0464\,\sigma$	Quadratic polynomial	0.9999

5.2. Results and Analysis of the SCR of Asphalt Mastic

In order to investigate the role of the asphalt binder in the mastic, the same test protocol was followed for both the asphalt-binder and mastic samples. Then, the MSCR test consisting of multiple stresses of 0.1, 3.2, 6.4, 12.8, and 25.6 kPa was also used to examine the rheological response of the asphalt mastic, and their corresponding *SCR*s were calculated with Equations (8)–(10). The results of *SCR*s at multiple creep stresses are shown in Figure 4.

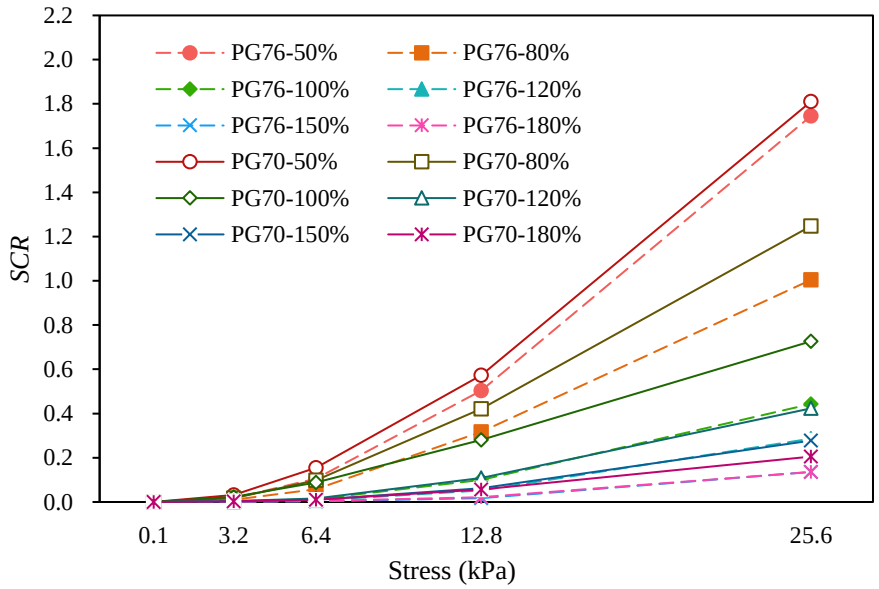


Figure 4. Results of the *SCR* of the asphalt mastics.

Similar to the results of the *SCR* of the asphalt binder in Figure 3, Figure 4 shows that the *SCR* is a stress-dependent index in an evaluation of the rheological properties of asphalt mastics. Generally, the *SCR* increases with an increase in creep stress regardless of the filler contents and types of binder. In addition, adding filler decreased the value of *SCR* and improved the rutting potential of the asphalt mastic. The PG70 mastics had larger *SCR*s than those of mastics produced from PG76 at each creep stress level. Obviously, the PG76 mastics showed greater antirutting property in comparison with that of PG70 mastics in the same conditions of stress and filler content. The asphalt binder properties significantly affect the mechanical response of the mastic. The decline in the sensitivity of the *SCR* to the stress with increasing filler content is also shown in Figure 4. In addition, for the asphalt mastic with different filler contents, the values of *SCR* were insensitive to the change in stress at a small stress region (0.1–3.2 kPa), whereas the *SCR* evidently changed at a large stress region (6.4–25.6 kPa). This can be explained by the fact that, like most viscoelastic materials, a mastic exhibits linear and nonlinear viscoelastic behaviors at different stress conditions. To investigate the asphalt binder role in the mastic at different conditions, the mastics at creep stresses of 3.2 and 25.6 kPa were selected to represent linear- and nonlinear-viscoelasticity performance, respectively; then, the effect of the asphalt binder in the mastics with either linear or nonlinear viscoelasticity could be evaluated in this study.

5.3. Stress of the Asphalt Binder in the Mastic

On the basis of the basic hypothesis of the asphalt binder, the rheological indicator of the mastic indicated the properties of the asphalt binder in the mastic. The *SCR* of the mastic was obtained from the MSCR test, which was consistent with the testing procedure of the asphalt binder. Then, the *SCR* values of the mastic were substituted into the expressions built with the *SCR* of the asphalt binder and stress. Then, the stress of the asphalt binder in the mastic could be estimated. In this case, the stress condition of the asphalt binder in its mastic could be calculated approximately with a simple laboratory method. Then, the rheological properties of the asphalt binder in its mastic could be investigated well.

In this section, a set of *SCR*s of mastics produced from PG70 and PG76 with different filler contents at stresses of 3.2 and 25.6 kPa were collected and substituted into quadratic polynomial regression models in terms of the *SCR* of the asphalt binder, as listed in Table 2. Then, the stresses of the asphalt binder in the mastic at small (3.2 kPa) and large (25.6 kPa) stresses were obtained. Results approximately representing the stress status of the asphalt binder in linear- and nonlinear-viscoelasticity mastics are shown in Figure 5.

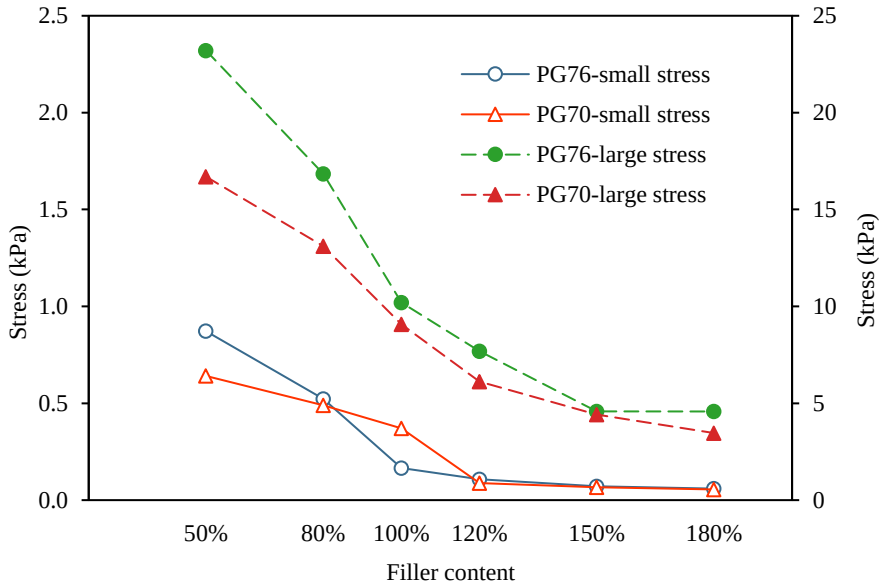


Figure 5. Stress of the asphalt binders in the mastics.

On the basis of the previous discussion, at the creep stress of 3.2 kPa, the *SCRs* of mastics produced from PG70 and PG76 were insensitive to the change in filler contents (see Figure 4). However, Figure 5 shows that the stresses of the asphalt binder in these two mastics highly depended on the filler content. The stress of PG70 and PG76 in their mastics decreased with increasing filler contents, although their mastics showed insensitivity to the filler content. However, the decrease rate of the stresses gradually decreased, and the stresses lastly remained constant. Obviously, when the filler content of the mastic increased to 120% and 100% for PG70 and PG76, respectively, the asphalt binder would be insensitive to the filler content, and the stress supplied to the asphalt binder was the minimum for itself. Obviously, for the mastic with a high filler content, the filler particles were concentrated in its mastic system, and its filler particles played a majority role in the bearing load of the asphalt mastic. When a small stress (3.2 kPa) was applied to these asphalt mastics, their asphalt binder supported smaller stress, and the stress of the asphalt binder did not change significantly with increasing filler content.

With regards to the stress of the asphalt binder in the mastic with nonlinear viscoelastic behavior at large stress (25.6 kPa), the stress of the asphalt binder also decreased with increasing filler content in the mastic. In addition, both PG70 and PG76 in the mastics supported higher stress than the stress condition in the linear viscoelastic mastics. Regarding the change trend of the stress of the asphalt binder in the mastic at large stress, the stress of PG70 continually decreased with the increase in filler contents and did not exhibit an insensitivity property. For the PG76 asphalt binder, insensitivity behavior was exhibited when the filler content increased to 150%. Obviously, at high stress, the filler particles of the asphalt mastic with a high filler content were not enough to resist the applied stress of the asphalt mastic. The stress of the asphalt binder was higher than the stress of asphalt binder in the mastic regarding linear viscoelasticity, and the stress values showed significant dependence on the filler content. Asphalt binder PG76 performed better regarding rutting potential, and supported higher stress than that of asphalt binder PG70 in the same condition of the asphalt mastic, especially for the mastic at large stress. Therefore, the stress condition of asphalt binder was affected by the applied stress of asphalt mastic, filler content, and the type of asphalt binder.

5.4. Rheological Properties of the Asphalt Binder in the Mastic

After the discussion of the stress of the asphalt binder in the mastic, the rheological properties of the asphalt binder in its mastic could be investigated on the basis of the relationship between the stress and rheological indicators of asphalt binder (see Table 2).

For the MSCR test, J_{nr} and $\%R$ are important output indicators to evaluate the high-temperature rheological behavior of an asphalt binder and mastic. Because of the simple physical meaning, only the $\%R$ indicator was selected in this part to illustrate the rheological status of the asphalt binder in the mastic. The linear expressions of $\%R$ and stress in terms of PG70 and PG76 are listed in Table 2; the values of $\%R$ of PG70 and PG76 could be calculated on the basis of the stress results discussed in the last section. The results are presented in Figure 6.

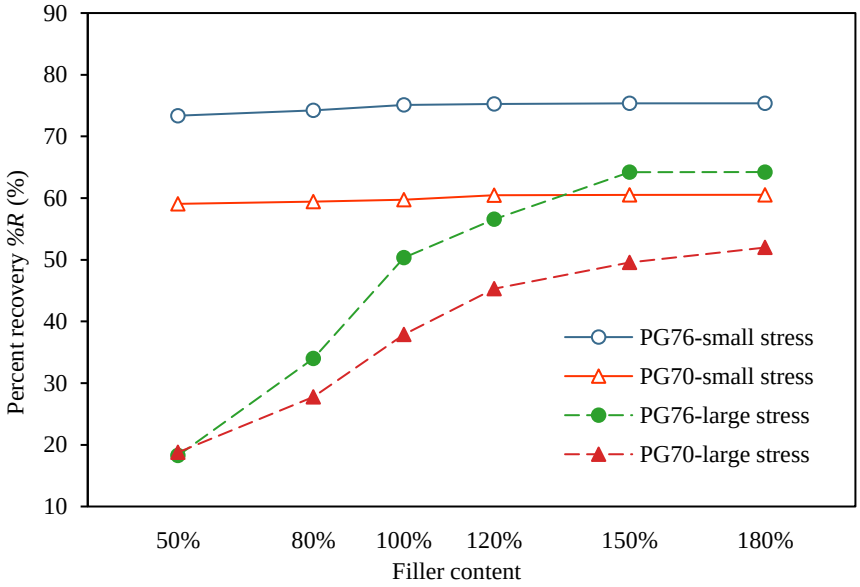


Figure 6. Rheological properties of the asphalt binders in the mastics.

As shown in Figure 6, $\%R$ indicates the rheological status of PG70 and PG76 in the mastics at small (3.2 kPa) and large (25.6 kPa) stress corresponding to its linear and nonlinear viscoelasticity, respectively. Obviously, the asphalt binders exhibited great difference in rheological response when their corresponding mastics were in different viscoelastic conditions. In the linear viscoelastic mastic with small stress, the $\%R$ of PG70 and PG76 approximately stayed constant with the increase in filler content. The $\%R$ of PG70 changed from 59.06% to 60.53%, and the $\%R$ of PG76 changed from 73.36% to 75.36%. Therefore, these two asphalt binders exhibited good viscoelastic recovery property when their mastics had been supplied with low creep stress and had linear viscoelastic behavior. In the linear viscoelastic mastic, the stresses of PG70 and PG76 were strongly sensitive to the change in filler content, as shown in Figure 5. However, Figure 6 shows that their recovery property did not significantly change with increasing filler content or deceasing stress, and the maximal change amplitude did not exceed 2%. Generally, asphalt binders PG70 and PG76 exhibited linear viscoelastic behavior with the change in filler content and stress. Therefore, when the mastic was at small creep stress and presented linear viscoelasticity, its asphalt binder also exhibited linear viscoelastic properties and good recovery performance.

With regards to the applied mastic creep stress of 25.6 kPa, because of the nonlinear viscoelasticity of the mastic, the $\%R$ of its asphalt binder was significantly sensitive to the filler content, and increased with the increase in filler content. For asphalt binder PG76, when the filler content increased to 150%, $\%R$ began to appear insensitive to the filler content, which is consistent with the sensitivity of the asphalt binder stress to the filler content in the linear-viscoelasticity mastic. Therefore, the asphalt binder in the mastic of nonlinear viscoelasticity also showed nonlinear viscoelastic behavior. Only when the filler content increased to a very high level did the asphalt binder in the mastic present a linear viscoelastic response.

In addition, adding filler improved the rheological properties of the asphalt binder. It could be that the stiffening effect of the filler in the mastic resulted in the decreasing

loading of the asphalt binder. The filler effect of improving viscoelastic recovery in the asphalt binder was more significant for the nonlinear-viscoelasticity mastic. The %R of PG70 increased from 18.78% to 51.98% when the filler content increased from 50% to 180%; the %R of PG76 increased from 18.26% to 64.22%. Obviously, adding the filler could highly improve the rheological performance of the asphalt binder, and PG76 presented a better recovery property than that of PG70 in the mastic at large creep stress. Therefore, the high filler content and high-temperature performance grading asphalt binders can improve the mechanical performance of a nonlinear-viscoelasticity mastic. According to the results shown in Figure 6, when a large stress was applied on the asphalt mastic, the rheological performance of its asphalt binder could be improved by adding filler particles. In this case, changing the filler content could significantly improve the asphalt mastic performance and rheological properties of its binder, and the design of asphalt mixture can be further modified well.

6. Conclusions

In this study, a laboratory method to evaluate the role of the asphalt binder in mastics was proposed. A new indicator was used to build the relationship between the asphalt binder and its mastic. Then, the stress status and rheological properties of the asphalt binder in the mastic were investigated. The main conclusions from this study are as follows:

(a) Strain cumulation rate (SCR) was proposed as a new rheological indicator to evaluate the asphalt binder and mastic's rheological responses. On the basis of SCR analysis, the relationship between the asphalt binder and mastic in terms of respective stress was established.

(b) The stress status of the asphalt binder in the mastic was estimated. The stress of the asphalt binder in the mastic generally decreased with the increase in filler content. For the mastic with linear viscoelasticity, the stress of the asphalt binder decreased with increasing filler content until the filler content had increased to a certain value (120% for PG70 and 100% for PG76). In addition, strong sensitivity to the filler content occurred for the asphalt binder in the mastic, which exhibited nonlinear viscoelasticity at high creep stress.

(c) For the rheological properties of the asphalt binder in the mastic, the viscoelastic recovery of the asphalt binder was improved with the increase in filler content. In the linear-viscoelasticity mastic, the asphalt binder had almost linear viscoelastic behavior and a good recovery property. In the nonlinear-viscoelasticity mastic, the rheological behavior of the asphalt binder was significantly improved by adding filler.

The asphalt mastic selected in this work was produced from one type of mineral filler (limestone) and one asphalt binder modifier (SBS), both of which are commonly used in pavement engineering. All conclusions are based on the mastic produced from limestone filler and SBS-modified asphalt binder in this paper. More types of fillers and modifiers will be considered, and more performance experiments of asphalt mastic will be conducted in further studies. The effects of different fillers, modifiers, and test conditions on the recovery property of an asphalt binder in its mastic will be discussed. SCR methods in this paper also provide an interesting and simple laboratory estimation of the relationship between an asphalt binder and its mastic. A micromechanical methodology will be established, and numerical simulation analysis will be performed in further studies.

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