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Study on the Dynamic Performance of PU and SBS-Modified Asphalt Mixtures with Dense Gradation

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Abstract: A polyurethane (PU) mixture with excellent strength is regarded as an alternative to a modified asphalt mixture, but characteristic analysis on them is lacking. In this paper, the dynamic modulus of PU- and SBS-modified asphalt mixtures with the same gradation, aggregate type, and binder content was investigated and compared in terms of dynamic and viscoelastic properties. Compared with the SBS-modified asphalt mixture, the PU mixture with an extremely high dynamic modulus and reduced phase angle at high temperatures had lower temperature sensitivity, which allowed it to resist high-temperature deformation. While the phase angle did not show a statistically significant correlation, the dynamic modulus between the two mixtures did. The dynamic modulus and phase angle values of the PU mixture showed relatively small deviations and could be fitted to produce acceptable master curves, which exhibited obvious differences compared to those of the SBS-modified asphalt mixture. The PU mixture exhibited elastic properties during the test temperature range and, since its thermal rheological property is much smaller than that of the SBS-modified asphalt mixture, it is closer to viscoelastic material. This study provides an understanding of the PU mixture's dynamic and viscoelastic properties, as well as material information for pavement design and performance prediction with PU mixture layers.

Keywords: polyurethane mixture; SBS-modified asphalt mixture; dynamic modulus; phase angle; viscoelastic; black diagram; stiffness parameter; correlation analysis

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1. Introduction

Asphalt is the most widely used binder in pavement engineering and exhibits a certain viscoelastic property, which shows different mechanical behaviors at different temperatures. In other words, the asphalt exhibits elastic properties at lower temperatures and viscous properties at higher temperatures, as well as thermal rheological performance [1]. Therefore, the asphalt mixture cannot resist stress at high temperatures and would generate permanent deformation at designed traffic loads and temperatures. Limited by the capability of the base asphalt binder to resist distress [2,3], many kinds of additives are added to perform modifications to improve the target property [4–9], e.g., chemicals, polymers, rubber powder, styrene−butadiene−styrene (SBS), and rubber resin (PR). Many researchers have made great efforts to solve this inherent problem in the asphalt binder. One study [10] demonstrated that modification of the base asphalt binder is expected to improve one or two basic properties of the base asphalt related to one or more types of pavement distress, including rigidity, elasticity, brittleness, storage stability, and durability. Therefore, modification could enhance the rheological and mechanical properties to a certain degree, but cannot thoroughly solve the rheology deformation problem caused by traffic loading and environment. Permanent deformation is still a research hot spot due to the intrinsic temperature sensitivity of asphalt. Polyurethane (PU) is a new kind of chemical synthetic material that displays excellent strength and deformation resistance performance. A PU mixture is mixed with PU binder, aggregate, and limestone mineral filler. The splitting strength of the PU mixture is about 4−7 times that of the modified asphalt mixture, and many researchers have pointed out that the PU could be used to replace the asphalt binder in pavement engineering to enhance long-life performance.

Under sufficiently low-level loading conditions, the asphalt mixture showed linear viscoelastic characteristics [11,12]. Studies demonstrated that the asphalt mixture manifested linear viscoelastic characteristics at a minor strain level (<100 $\mu\varepsilon$) and a limited number of cycles [13]. The pavement design adopts various methods to consider the viscoelastic characteristics of the asphalt mixture [14], including mechanical models, creep compliance curves, and a dynamic complex modulus [15–17]. The dynamic modulus is proven to be a fundamental parameter for capturing the stress−strain relationship of the linear viscoelastic material under the action of external force [18,19], and plays a crucial role in the evolution of the material behavior and stiffness performance under different temperatures and loading frequencies [20,21]. The dynamic modulus has been identified as the primary input parameter of the Mechanistic-Empirical Pavement Design Guide (MEPDG) due to its effectiveness in characterizing the mechanical and time-temperature-dependent properties of the asphalt pavement. The MEPDG uses the dynamic modulus master curve for determining the structural capacity of pavements [15]. Additionally, the dynamic modulus is proven to be a crucial index in relation to the road performance of the asphalt mixture [22–24]. It is employed as an important material property indicator to predict the asphalt mixture's performance concerning rutting and fatigue [25,26], as well as pavement response (i.e., stress and strain) for structural design in light of traffic-induced distresses, climate, and mix characteristics [27–29].

A viscoelastic material is the most common material in engineering applications, and it exhibits both elastic and viscous properties under loading conditions. The mechanical characteristic of viscoelastic material depends on temperature, loading frequency, loading history, and is time-dependent. The viscous and elastic components of the dynamic modulus are described by the loss and storage modulus, respectively, which are separated from the dynamic modulus by the phase angle. It is crucial to quantify both components for the viscoelastic material. The dynamic modulus, phase angle, and the corresponding master curves for a range of temperature and frequency combinations were used for evaluating the rheological property and temperature-time dependency behavior (viscoelasticity) of the asphalt mixture. The dynamic modulus test has an extremely important role in characterizing the material properties of all dense-graded asphalt mixtures.

Tentative experiments have been performed on porous PU mixture (PPM), and studies [30–33] discovered that the PPM has better performance in comparison with the traditional porous asphalt mixture (PAM), e.g., anti-deformation, anti-fatigue, anti-crack, and anti-corrosion properties, and good resistance to light and heat aging. One researcher [34] demonstrated that the PPM's mechanical properties are closer to those of the asphalt mixture, rather than those of the concrete. PPM has three times the stability of the open graded friction course mixture (OGFC) [35,36], a fatigue life that is one order of magnitude longer, and improved resistance to clogging because of suspended solid infiltration of soil [37]. In addition, one study [38] compared the dynamic modulus, static modulus, and creep test results of a stone mastic PU mixture and Superpave dense PU mixture with test results of asphalt mixtures with similar gradation in other literature. The effect of temperature and loading frequency on the dynamic modulus and static modulus were analyzed, and the relationship between the two moduluses was established. One study [39] evaluated the temperature moisture stability and fatigue performance of the PU mixture, which has a skeleton interlocking aggregate structure. When the PU mixture's anti-ice, deicing, noise absorption properties, and compaction characteristics were compared with those of the traditional asphalt mixture, the PU mixture performed better [40–42]. In another study [43], the mechanical properties of the PU mixture were analyzed through the dynamic modulus test, uniaxial penetration test, and fatigue test. The tested parameters were then adopted in the finite element theory calculation, and the PU mixture composite structure was recommended. Further research [44] analyzed the influence factors of water stripping of a PU mixture, etc., binder-to-aggregate ratio, gradation type, and fine aggregate content using the Cantabro test, the splitting test, and the water stability test. There are few studies conducted on the impact of the PU on improving dynamic properties, excluding the effect of gradation, aggregate type, etc., and little research was performed on the viscoelastic properties of PU mixtures.

The accuracy of characterizing material properties greatly influences the mechanical analysis of pavement. Therefore, it is of fundamental importance to comprehend the PU mixture's properties for material response analysis [45,46] and pavement design [21,47]. The PU mixture needs to be fully characterized to capture the viscoelastic behavior and to understand its performance. The information and performance reflected by a dynamic modulus parameter are better suited for pavement design using the mechanical experience method [48]. Since the PU binder cannot be heated to melting point as asphalt after being cured, it is challenging to analyze how the temperature and loading frequency affect the PU binder itself. This paper compared the characteristic difference between the SBS-modified asphalt and PU mixture with the same gradation, aggregate type, and binder content using a dynamic modulus. The dynamic modulus results were used to analyze the influence of PU on the performance improvement of the mixture compared with the SBS-modified asphalt mixture. Additionally, the linear viscoelastic characteristics of the PU mixture were explored using the dynamic modulus analysis, which also served to demonstrate the PU mixture's applicability to the time-temperature superposition principle. This study first attempted to fully compare the dynamic performance of the SBS-modified asphalt and PU mixture, and to provide comprehensive information about the characteristics of the PU mixture. This will help researchers and designers to understand and apply the PU mixture in pavement structure researching and designing.

2. Materials and Methods

2.1. Materials

The asphalt used in this study was SBS-modified asphalt supplied by Shandong Hi−Speed Huarui Road Materials Technologies CO., LTD (Jinan, China), and the results of the indexes are listed in Table 1. The PU binder, a single-component wet-setting type of polyurethane, consisting of diphenylmethane diisocyanate and polyether polyol, was supplied by Wanhua Chemical Group Co., Ltd. (Yantai, China), and the index results are shown in Table 2.

Table 1. Index results of SBS-modified asphalt.

Index	Test Result
Penetration (25 °C, 100 g) (0.1 mm)	57
Softening Point (°C)	78
Ductility (5 °C) (cm)	27
Rotary Viscosity (135 °C, mPa·s)	321

Table 2. Index results of PU.

Index	Test Result
Viscosity (25 °C) (mPa·s)	1707
Dry Time (30 °C, 90% RH) (min)	70
Tensile Strength (MPa)	24.5
Breaking Elongation (%)	212

The aggregate used in this study was limestone, and the selected gradation was AC−20, which is shown in Figure 1. The optimum binder content for the selected gradation was discovered to be 4.3%.

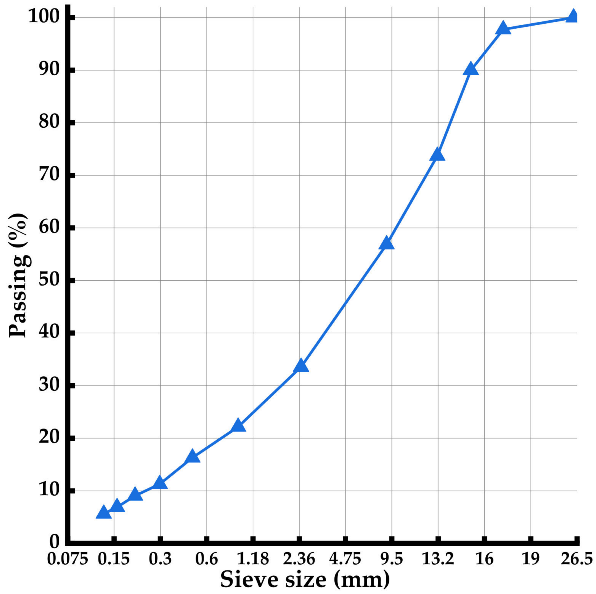


Figure 1. Gradation of AC−20 mixture.

2.2. Specimen Preparation

According to the determined gradation and binder content, the specimens with SBS-modified asphalt and PU had the same aggregate gradation and binder content and were fabricated using the Superpave gyratory compactor (SGC), with a target size of 170 mm in height and 150 mm in diameter.

The following procedures were performed to prepare the specimen for the SBS-modified asphalt mixture: (a) the limestone aggregates and limestone mineral powder were prepared following the gradation determined; (b) the limestone aggregates were heated in a forced-draft oven at 180 °C for at least four hours; (c) the SBS-modified asphalt was heated to 170 °C with an induction cooker; (d) the mixing pot was preheated to 170 °C before mixing, the heated limestone aggregates and SBS-modified asphalt were poured into the mixing pot in order, and the asphalt mixture was mixed for 90 s; (e) after 90 s mixing, the fillers were added into the mixing pot and the asphalt mixtures was mixed for another 90 s; (f) the loose asphalt mixture was compacted 100 times by SGC; (g) the compacted specimens were kept at room temperature for 48 h before the next test.

The procedure employed for the specimen preparation for the PU mixture was as follows: (a) the limestone aggregates and limestone mineral powder were prepared following the determined gradation; (b) the limestone aggregates and the fillers were heated in an oven at 180 °C for at least four hours, and then cooled down to the room temperature; (c) the aggregates, the fillers, and the PU were added into the mixing pot in order and mixed for 90 s, the PU and mixing pot did not need to be heated during the mixing process; (d) the PU mixture was kept at room temperature for 1.5 h before compacting; (e) the loose PU mixture was compacted 100 times by SGC; (f) the compacted specimens were kept at 35 °C and 70% RH conditions for 5 days before the next test.

The specimens were then cored and sawed into cylindrical specimens measuring 100 mm in diameter and 150 mm in height after curing.

2.3. Dynamic Modulus Test

The dynamic modulus test was performed by utilizing an Asphalt Mixture Performance Tester (AMPT) and following the test procedure provided in AASHTO: TP−79

(2010) in load-controlled uniaxial compression mode. The test loading waveform was a sinusoidal wave and the loading amplitude kept the specimen's max strain between 75 and 125 uε. The max strain range cannot cause any plasticity or damage to the specimen. Tests were carried out at six temperatures (5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C) and nine frequencies (25, 20, 10, 5, 2, 1, 0.5, 0.2, and 0.1 Hz). All of the SBS-modified asphalt mixture and PU mixture specimens were tested under the same test temperatures and loading frequencies to obtain the dynamic modulus data information. The dynamic modulus and phase angle results used in this study were the average value of four replicates for each mixture.

2.4. Master Curve Fitting

For fitting the master curve, five master curve models and five shift factor equations were used in this study, the master curve models utilized included the Standard Logistic Sigmoid (SLS) model [49], Generalized Logistic Sigmoidal (GLS) model [50], Christensen Anderson and Marasteanu (CAM) model [11,51], Modified CAM model [11,51], and Sigmoidal CAM Model (SCM) [52]. All of the five mentioned master curve models were originally designed for dynamic modulus data. The master curve models for the phase angle data were obtained from the corresponding dynamic modulus based on the approximate K−K relations [53]. The shift factor equations included the log-linear equation [54], polynomial equation [55], Arrhenius equation [56], Williams–Landel–Ferry equation (WLF) [57], and Kaelble equation.

The fitting procedure is in order to minimize the error between the predicted data and measured data; four parameters were used to evaluate the fitting degree. The R^2 value represents the fitting degree, the Se and Sy represent the standard error of estimate and standard error of deviation, the $Error^2$ represents the square of the difference between the measured and predicted data, and the Sum of Squares Error (SSE) is the relative error between the predicted and experimental measured data. The R^2 (>0.99) was used as the main constraint, and the Se/Sy (<0.05), $Error^2$ (<0.05), and SSE (<0.05) were used as the additional constraints during the fitting procedure.

The fitting procedure followed the steps by the shift factor equations were incorporated into the master curve model by Equation (1), then the error minimization method was used to regress the parameters in the master curve model and shift factor equation until the error between the predicted and measured data reached the settled constraints.

$$\log(f_r) = \log(f) + \log(\alpha_T), \tag{1}$$

where $\log(f)$ is the frequency in experiment temperature, $\log(f_r)$ is the reduced frequency in reference temperature, and $\log(\alpha_T)$ is the shift factor.

3. Results

3.1. Comparing Dynamic Modulus between the SBS-Modified Asphalt and PU Mixtures

The graphical representations of the dynamic modulus of the SBS-modified asphalt and PU mixtures under different temperatures were separately plotted in Figure 2 in order to analyze the influence of temperature and loading frequency. For further analysis of the effect of temperature on the dynamic modulus of different mixtures, the dynamic moduluses of the SBS-modified asphalt and PU mixture at the same temperatures were plotted together. In the following plots, the "Asphalt" in the legends represents the SBS-modified asphalt mixture, the "PU" in the legends represents the PU mixture, the $x-$axis represents the loading frequency, and the $y-$axis represents the dynamic modulus.

3.2. Comparing Phase Angle between the SBS-Modified Asphalt and PU Mixtures

The variations of the phase angle of the SBS-modified asphalt and PU mixture at various temperatures and loading frequencies were separately plotted in Figure 3. The $y-$axis represents the phase angle and the $x-$axis represents the loading frequency. The phase angles of the SBS-modified asphalt and PU mixtures at different temperatures were plotted in every single plot in order to compare the effect of temperature on the phase angle of both the SBS-modified asphalt and PU mixtures.

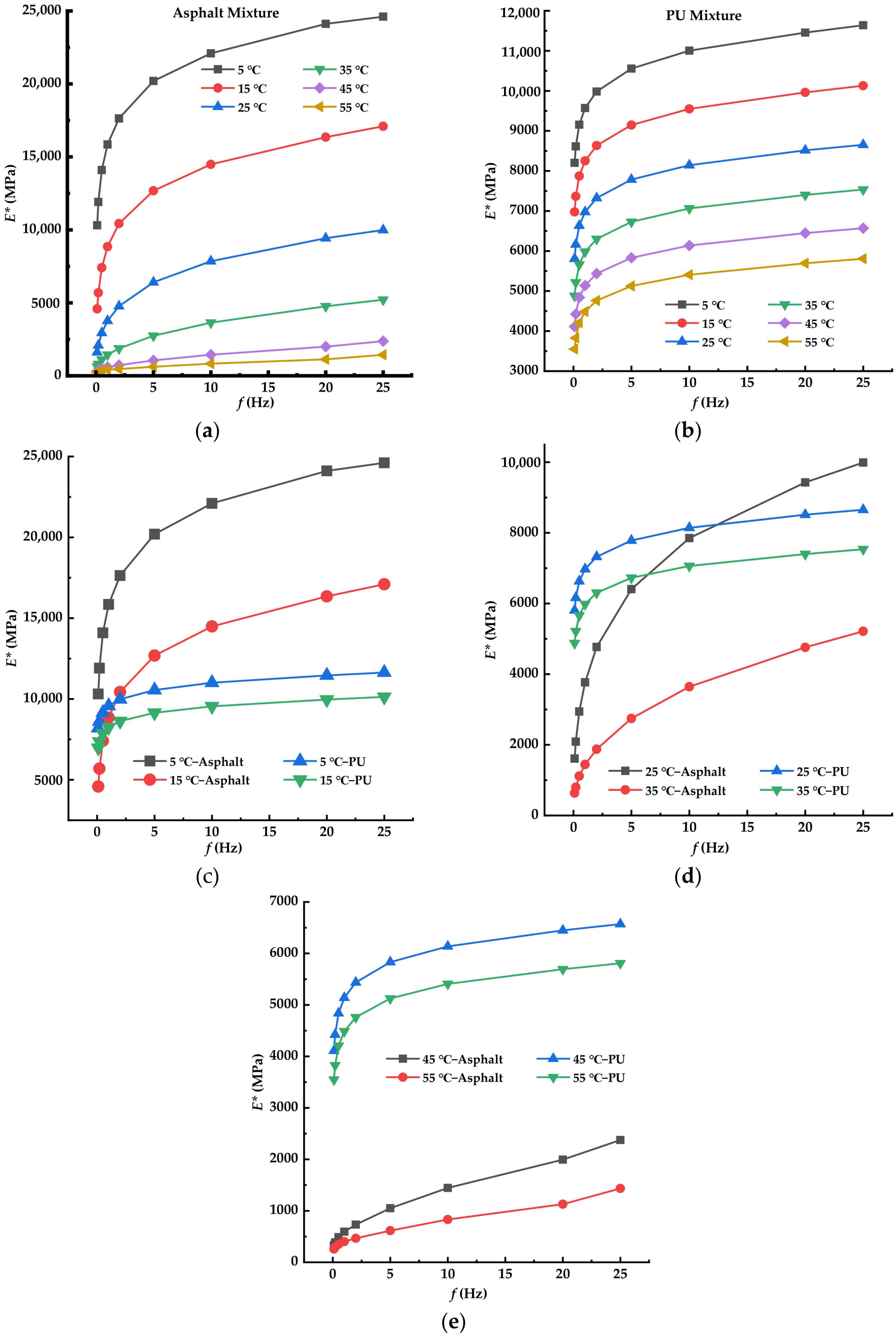


Figure 2. The dynamic modulus (E^*) of SBS-modified asphalt and PU mixtures. (**a**) Dynamic modulus of SBS-modified asphalt mixture; (**b**) dynamic modulus of PU mixture; (**c**) dynamic modulus of mixtures under 5 °C and 15 °C; (**d**) dynamic modulus of mixtures under 25 °C and 35 °C; (**e**) dynamic modulus of mixtures under 45 °C and 55 °C.

3.3. Comparing the Stiffness Parameters ($E^*/sin(\delta)$) of the SBS-Modified Asphalt and PU Mixtures

The stiffness parameters ($E^*/sin(\delta)$) of the SBS-modified asphalt and PU mixtures are shown in Figure 4. The stiffness parameters ($E^*/sin(\delta)$) of the SBS-modified asphalt and PU mixtures under the same temperatures were plotted in every single plot. In Figure 4, the $x-$axis represents the loading frequency and the $y-$axis represents the stiffness parameters.

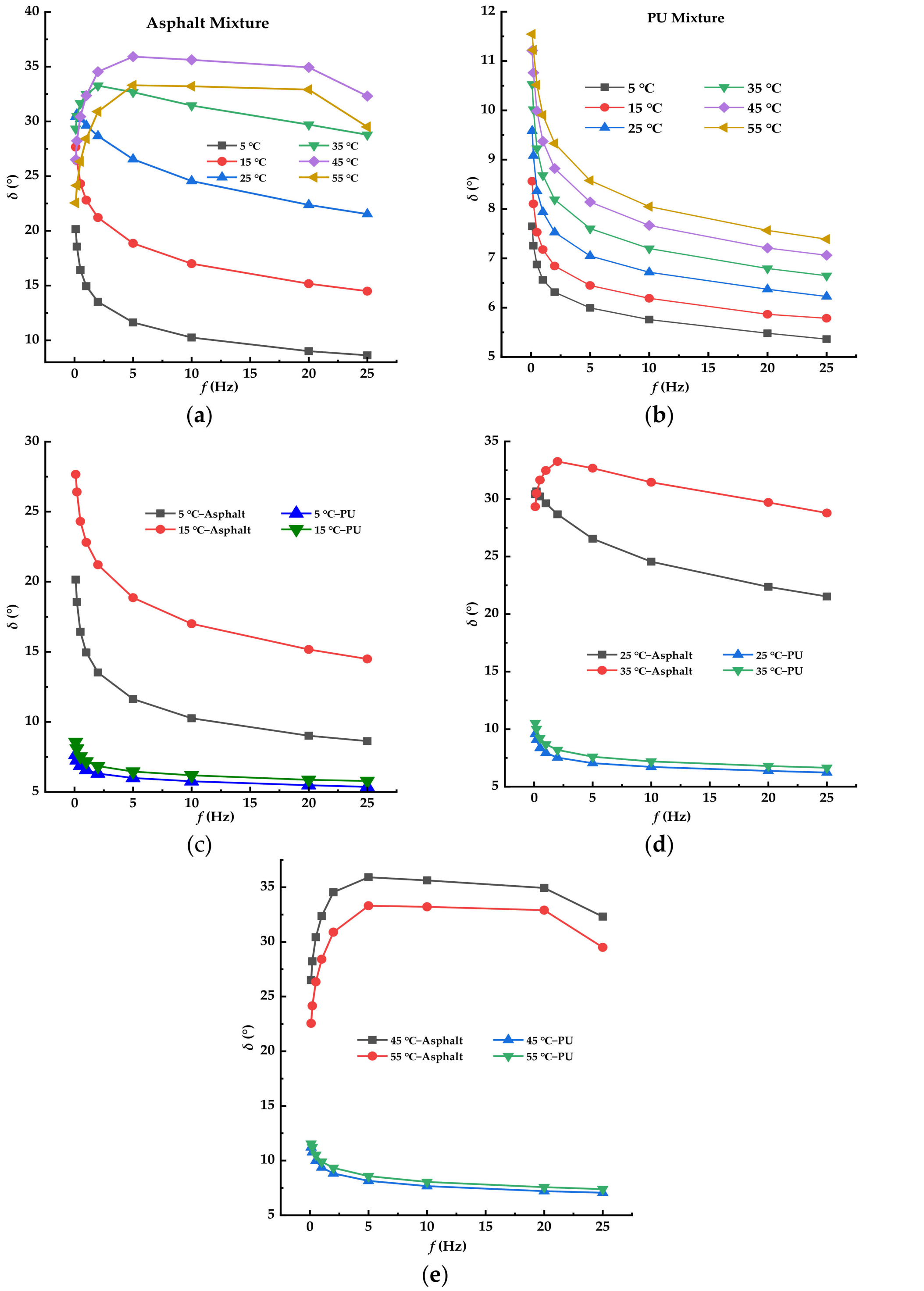


Figure 3. The phase angle (δ) of SBS-modified asphalt and PU mixtures. (**a**) Phase angle of SBS-modified asphalt mixture; (**b**) phase angle of PU mixture; (**c**) phase angle of mixtures under 5 °C and 15 °C; (**d**) phase angle of mixtures under 25 °C and 35 °C; (**e**) phase angle of mixtures under 45 °C and 55 °C.

3.4. Black Space Diagram Analyzing

The experimental data of the phase angle versus dynamic modulus were plotted in Figure 5 together: (1) comparing the distinction between the SBS-modified asphalt and PU mixtures; (2) detecting the occurrence of inconsistencies in rheological data caused by testing irregularities and distinctive material properties.

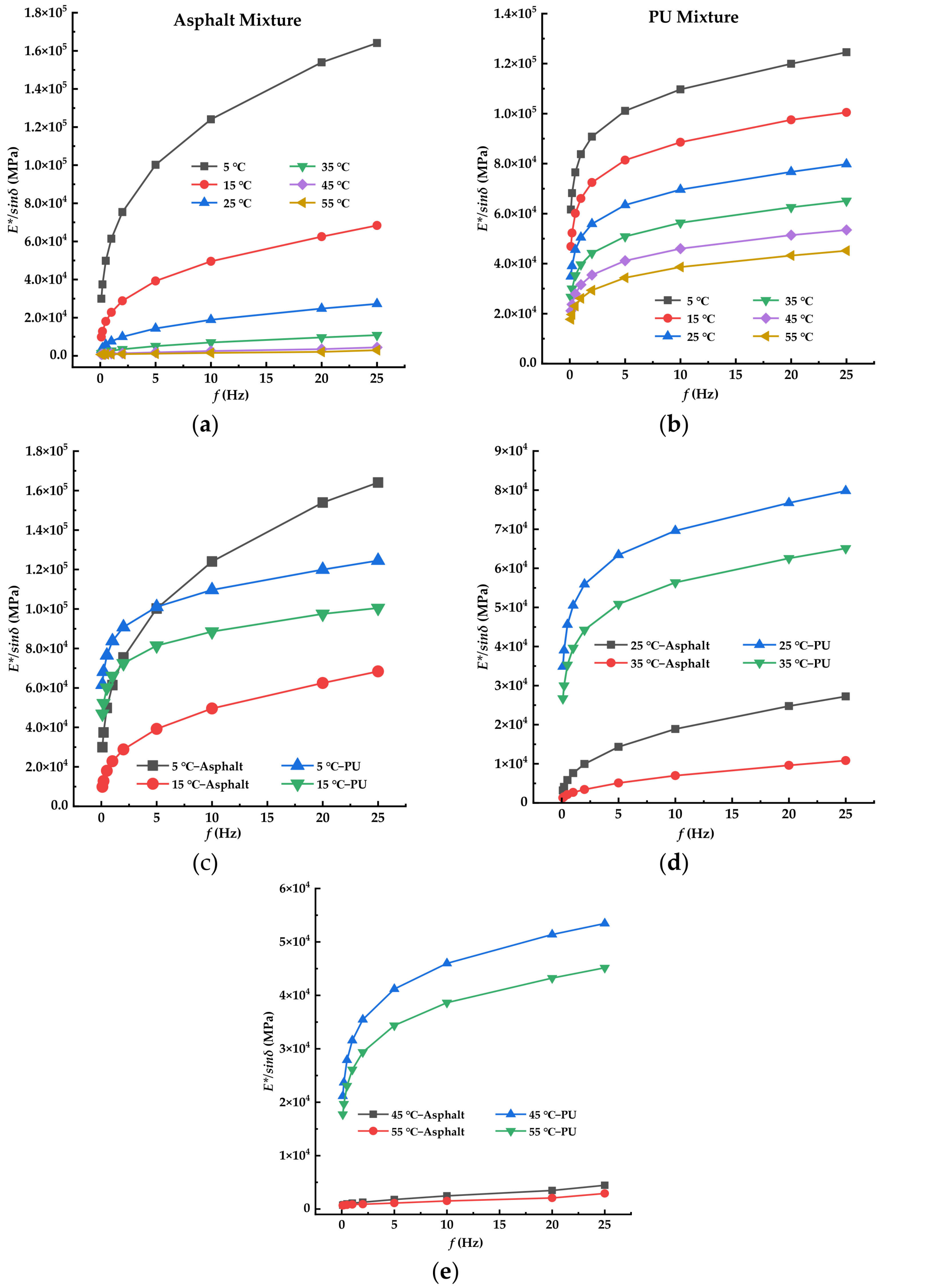


Figure 4. The stiffness parameters ($E^*/sin(\delta)$) of the SBS-modified asphalt and PU mixtures. (**a**) $E^*/sin(\delta)$ of SBS-modified asphalt mixture; (**b**) $E^*/sin(\delta)$ of PU mixture; (**c**) $E^*/sin(\delta)$ of mixtures under 5 °C and 15 °C; (**d**) $E^*/sin(\delta)$ of mixtures under 25 °C and 35 °C; (**e**) $E^*/sin(\delta)$ of mixtures under 45 °C and 55 °C.

3.5. The Master Curves of the SBS-Modified Asphalt and PU Mixtures

3.5.1. Dynamic Modulus Master Curves of the SBS-Modified Asphalt and PU Mixtures

The dynamic moduluses of the SBS-modified asphalt mixture and PU mixture were fitted by five different models and equations to construct the master curve, shown in Figure 6a–e and Table 3. The equations under different models with the best-fitting results are plotted in Figure 6f, and the master curve fitting results are listed in Table 4. In Figure 6, the $x-$axis represents the loading frequency in logarithmic form and the $y-$axis represents the dynamic modulus in logarithmic form.

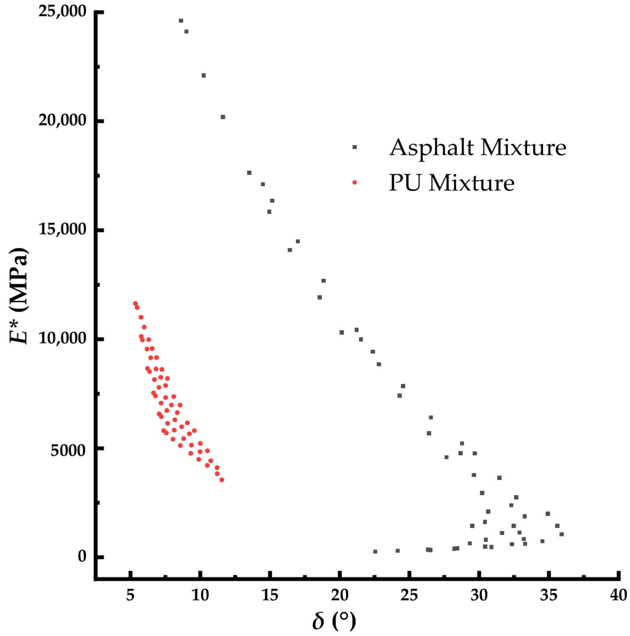


Figure 5. The black space diagram of the SBS-modified asphalt and PU mixtures.

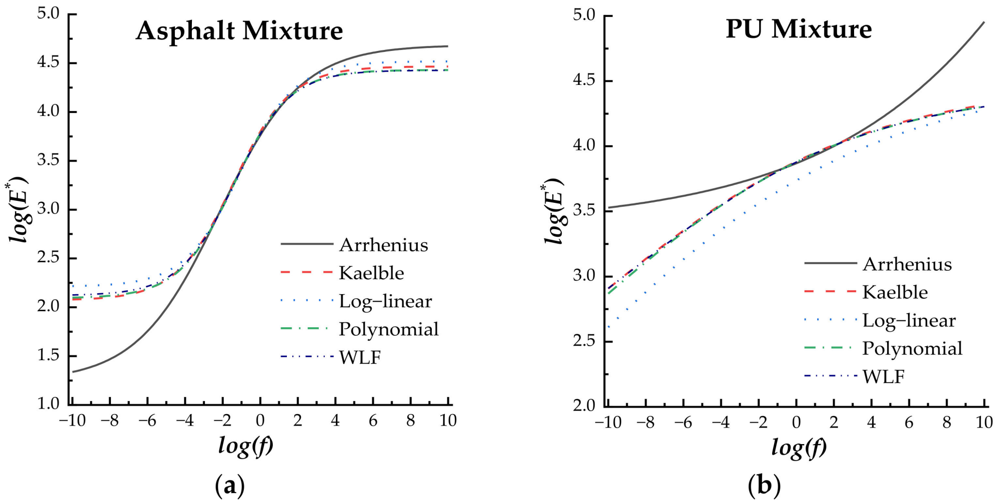
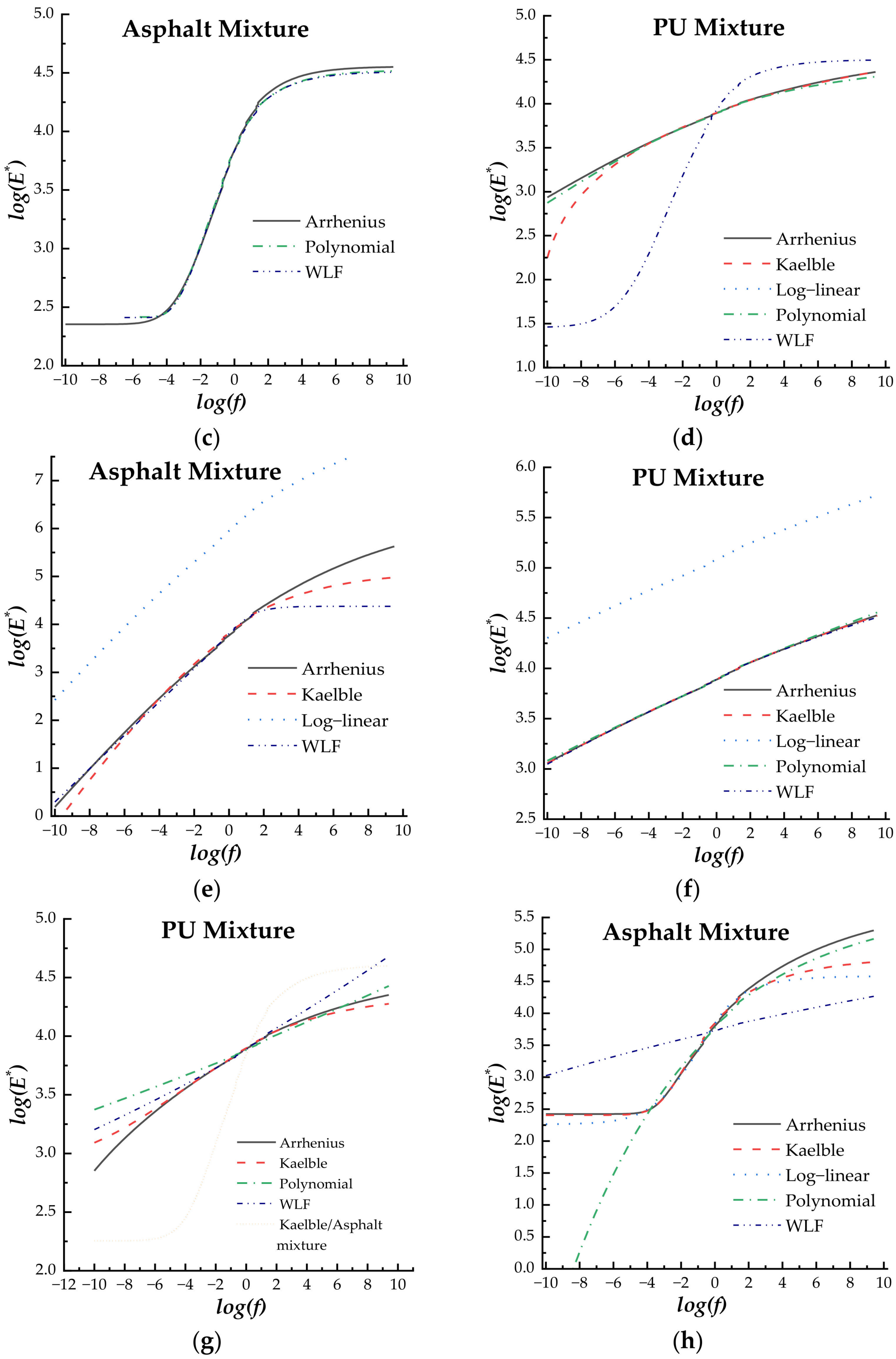


Figure 6. *Cont.*



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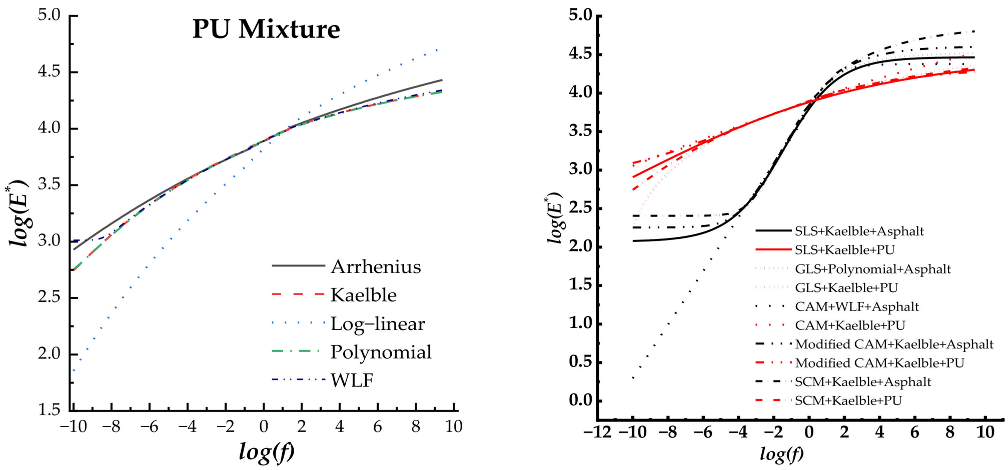


(**i**) (**j**)

Figure 6. The dynamic modulus master curves of SBS-modified asphalt and PU mixtures. (**a**) SLS model master curves of the SBS-modified asphalt mixture; (**b**) SLS model master curves of the PU mixture; (**c**) GLS model master curves of the SBS-modified asphalt mixture; (**d**) GLS model master curves of the PU mixture; (**e**) CAM model master curves of the SBS-modified asphalt mixture; (**f**) CAM model master curves of the PU mixture; (**g**) modified CAM model master curves of the SBS-modified asphalt and PU mixtures; (**h**) SCM model master curves of the SBS-modified asphalt mixture; (**i**) SCM master curves of the PU mixture; (**j**) dynamic modulus master curves recommended.

Table 3. Dynamic modulus fitting results of SBS-modified asphalt mixture.

Equation	SLS Model	GLS Model	CAM Model	Modified CAM Model	SCM Model
Arrhenius	Yes	Yes	Yes	NO	Yes
Kaelble	Yes	NO	Yes	Yes	Yes
Log-Linear	Yes	NO	Yes	NO	Yes
Polynomial	Yes	Yes	NO	NO	Yes
WLF Equation	Yes	Yes	Yes	NO	Yes

Table 4. Dynamic modulus master curve fitting parameters.

	SLS + Kaelble + Asphalt	SLS + Kaelble + PU	GLS + Polyno-mial + PU	GLS + Kaelble + PU	CAM + WLF + Asphalt	CAM + Kaelble + PU	Modified CAM + Kaelble + Asphalt	Modified CAM + Kaelble + PU	SCM + Kaelble + Asphalt	SCM + Kaelble + PU
R^2	0.99999932	1	0.999999325	1	0.999992347	1	0.999999484	1	0.999999517	1
Se/Sy	0.00240	0.00031	0.00239	0.00025	0.00806	0.00088	0.00209	0.00034	0.00202	0.00025
$Error^2$	0.04600	0.00080	0.03697	0.00069	0.14656	0.00258	0.04988	0.00102	0.03637	0.00079
SSE	0.24056	0.00420	0.19175	0.00364	0.75111	0.01358	0.25918	0.00534	0.19340	0.00413

3.5.2. Phase Angle Master Curve of the SBS-Modified Asphalt and PU Mixtures

Five master curve models and shift factor equations were used to fit and construct the experimentally measured phase angle data of the SBS-modified asphalt mixture and PU mixture, and the fitting results are plotted in Figure 7 and Table 5. In Figure 7, the x−axis represents the loading frequency in logarithmic form and the y−axis represents the phase angle in arithmetic scale.

3.5.3. Shift Factors of the SBS-Modified Asphalt and PU Mixtures

The shift factors of the SBS-modified asphalt mixture and PU mixture obtained from the master curve fitting were plotted in a single picture for comparison, and all the results are shown in Figure 8. The difference in the shift factors between the SBS-modified asphalt mixture and the PU mixture can be obtained from a graphical comparison.

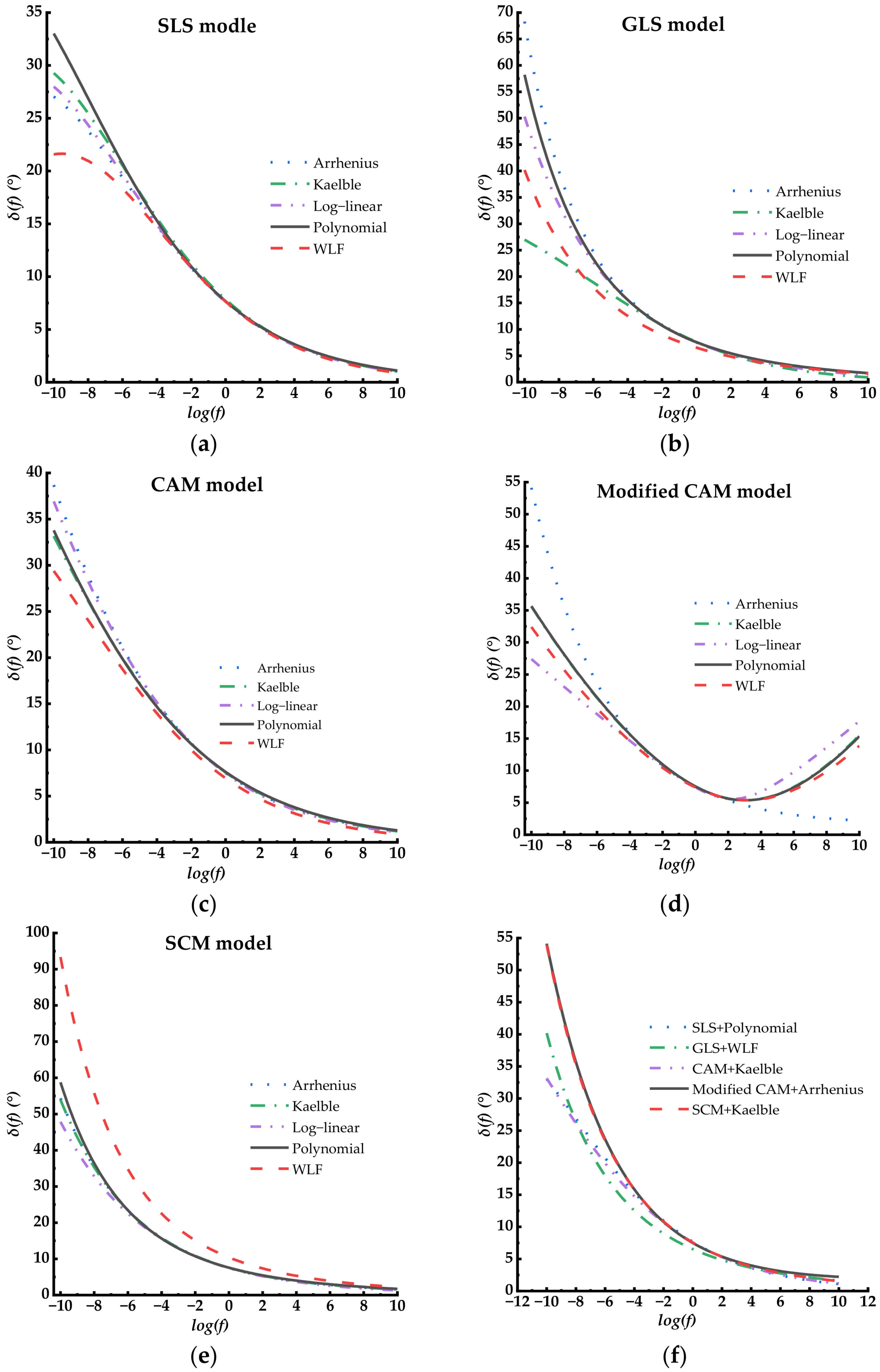


Figure 7. The phase angle master curves of PU mixtures. (**a**) SLS model master curves; (**b**) GLS model master curves; (**c**) CAM model master curves; (**d**) Modified CAM model master curves; (**e**) SCM model master curves; (**f**) phase angle master curves recommended.

Table 5. Phase angle master curve fitting parameters.

	SLS + Polynomial	GLS + WLF	CAM + Kaelble	Modified CAM + Kaelble	SCM + Kaelble
R^2	0.9985	0.9970	0.9976	0.9990	0.9981
Se/Sy	0.0161	−1.4934	0.0200	−1.4279	−1.4308
$Error^2$	1.1595	0.0226	1.5164	0.0130	0.0176
SSE	0.0332	1.3939	0.0290	0.5409	0.9639

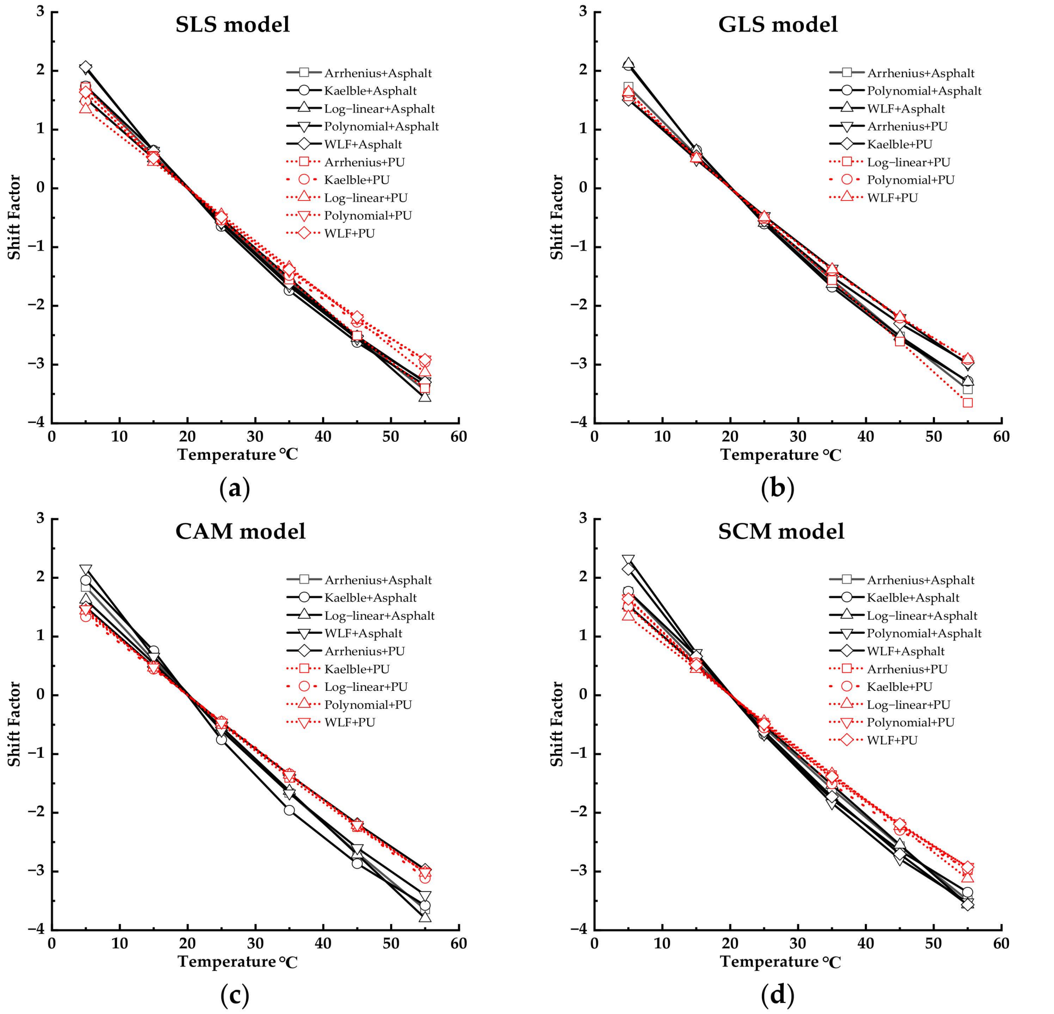
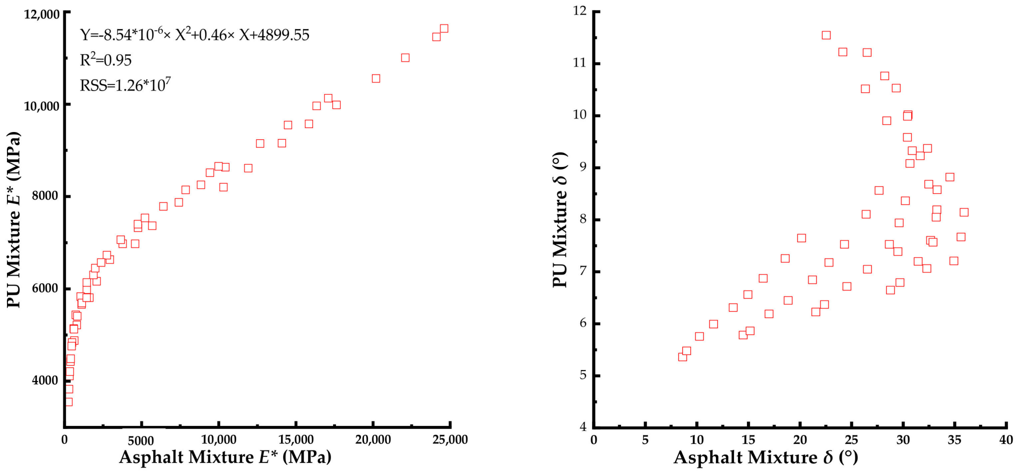


Figure 8. Shift factors of the SBS-modified asphalt and PU mixtures. (**a**) SLS model; (**b**) GLS model; (**c**) CAM model; (**d**) SCM model.

3.6. Correlation Study between the SBS-Modified Asphalt and PU Mixtures

The dynamic modulus experimental data of the SBS-modified asphalt mixture and PU mixture were plotted together in order to compare the correlation between these two series of data, and the comparison results were plotted in Figure 9. The residual sum of squares (RSS) is the parameter in the linear correlation fitting to describe the accuracy. Pearson correlation analysis was used to analyze the correlation between the SBS-modified asphalt mixture and the PU mixture, and the results are listed in Table 6. The red squares in Figure 9 represent the measured data point of the asphalt and PU mixtures at the same temperatures and loading frequencies.



(**a**) (**b**)

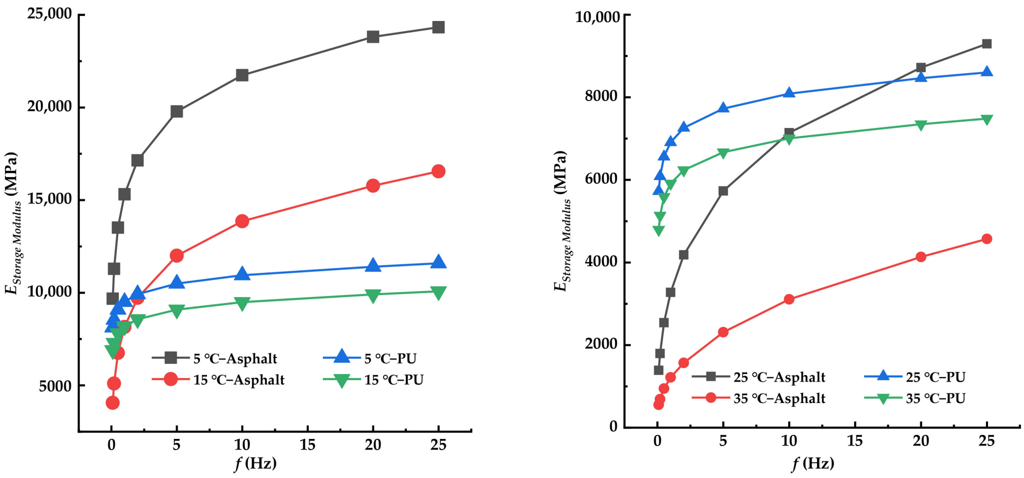
Figure 9. The experimental data comparison of the SBS-modified asphalt and PU mixtures. (**a**) Dynamic modulus comparison; (**b**) phase angle comparison.

Table 6. Correlation comparing results.

	Index	PU Mixture	
		Dynamic Modulus	**Phase Angle**
Asphalt Mixture	Pearson Correlation	0.954	0.544
	Significance (Double Tail)	0	0
	Covariance	13,747,253.34	6.523

3.7. Storage Modulus and Loss Modulus Analyzing

The storage modulus and loss modulus of the SBS-modified asphalt and PU mixtures under different temperatures were plotted in a single plot, seen in Figure 10, in order to compare the difference between elastic and viscous components.



(**a**) (**b**)

Figure 10. *Cont.*

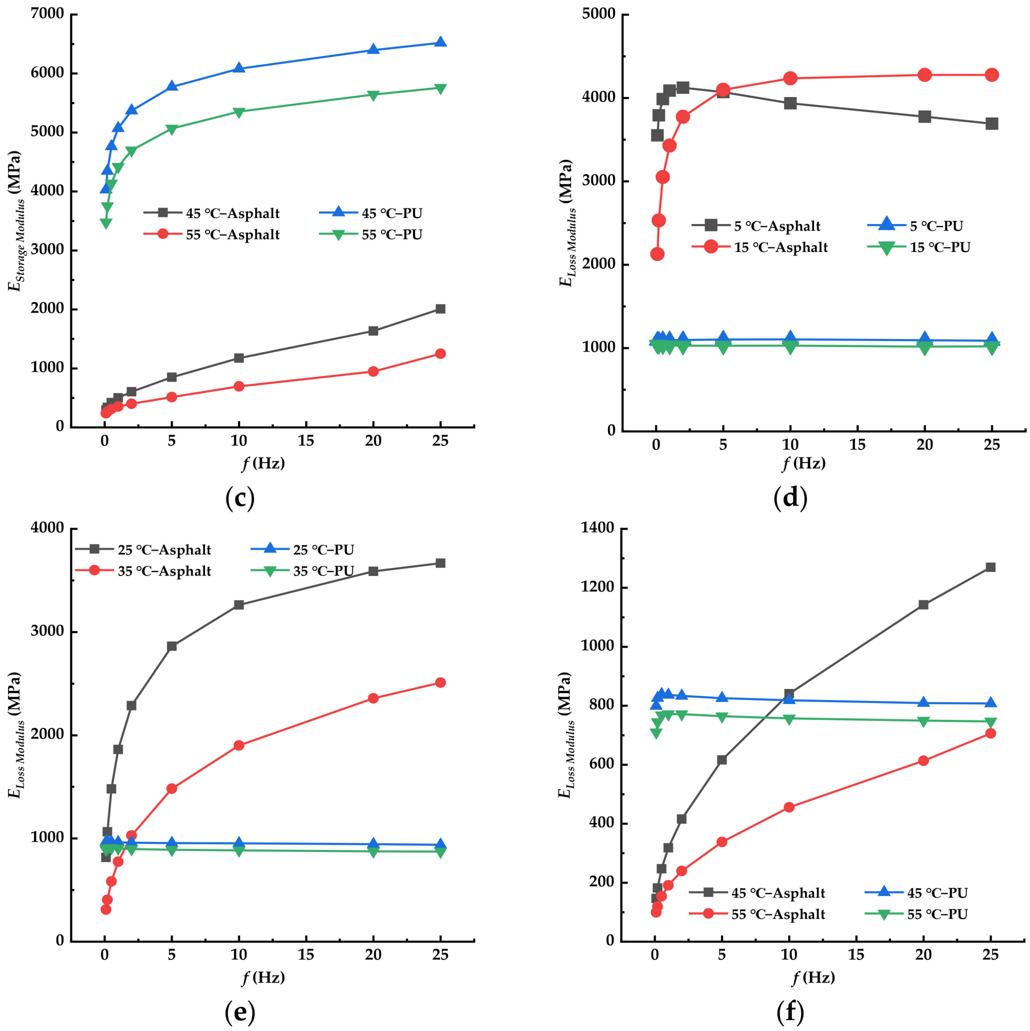


Figure 10. The storage and loss modulus of the SBS-modified asphalt and PU mixtures. (**a**) Storage modulus under 5 °C and 15 °C; (**b**) storage modulus under 25 °C and 35 °C; (**c**) storage modulus under 45 °C and 55 °C; (**d**) loss modulus under 5 °C and 15 °C; (**e**) loss modulus under 25 °C and 35 °C; (**f**) loss modulus under 45 °C and 55 °C.

4. Discussion

4.1. Comparing the Dynamic Modulus of the SBS-Modified Asphalt and PU Mixtures

The dynamic modulus is one of the fundamental mechanical parameters of the pavement material, and could be combined with the phase angle to represent its viscoelastic property. The fact that dynamic modulus could be significantly affected by temperatures and loading frequency is proven by many studies [58,59]. From Figure 2a,b, it could be concluded that the dynamic modulus of the SBS-modified asphalt and PU mixture followed a similar changing trend in that: (1) under the same temperature, the dynamic moduluses would both grow as the loading frequencies increase; (2) under the same loading frequency, the dynamic moduluses would both reduce as the temperatures increase. When the loading frequency is raised from 0.1 Hz to 25 Hz, the increment of the dynamic modulus of the SBS-modified asphalt mixture ranged from 138.7% to 720.8% as the temperatures rose from 5 °C to 55 °C, and the biggest increment was at 35 °C; for the PU mixture, the increment of dynamic modulus gradually increased from 41.9% to 63.7% as the loading frequency was raised from 0.1 Hz to 25 Hz. Therefore, the influence of loading frequency on the dynamic modulus rose as the temperature increased. The loading frequency had a considerably greater influence on the dynamic modulus of the SBS-modified asphalt mixture than on that of the PU mixture. When the temperatures rose from 5 °C to 55 °C, the SBS-modified asphalt mixture's dynamic modulus reduced by about 94%–98% under different loading frequencies, and approach a value of unbound granular material. The PU mixture's dynamic modulus would decrease by about 50%–57% under different loading frequencies, and the residual dynamic modulus of the PU mixture was still 3549 MPa at 55 °C and 0.1 Hz, while the SBS-modified asphalt mixture's dynamic modulus dropped to 258 MPa. The decreased magnitudes under different loading frequencies had a slight difference. The temperature had an extremely great impact on the dynamic modulus of the SBS-modified asphalt mixture compared to the PU mixture. In other words, the temperature sensitivity or high-temperature stability of the PU mixture was superior to that of the SBS-modified asphalt mixture. The PU mixture could remain in a good mechanical state at higher temperatures.

It could be discovered from Figure 2c–e that at temperatures of 5 °C and 15 °C, the dynamic modulus of the SBS-modified asphalt mixture was notably bigger than that of the PU mixture; when the temperature rose to 25 °C and 35 °C, the PU mixture's dynamic modulus was greater than the SBS-modified asphalt mixture, except at a higher frequency at 25 °C; the PU mixture's dynamic modulus was remarkably bigger than the SBS-modified asphalt mixture at 45 °C and 55 °C. This finding proves the conclusion mentioned above: that the PU mixture's temperature sensitivity was much smaller than the SBS-modified asphalt mixture's. At lower loading frequencies (0.5 Hz−0.1 Hz) or lower vehicle speed, the dynamic modulus of the PU mixture was higher than that of the SBS-modified asphalt mixture, except at 5 °C. This indicates that the PU mixture was stiffer than the SBS-modified asphalt mixture, and could resist the rutting damage caused by slow-speed traffic. Thus, the PU mixture is suitable for such situations as bus stations, long upslope lanes, and docks. When the loading frequencies are reduced from 25 Hz to 0.1 Hz, the ratio of dynamic modulus between the PU mixture and SBS-modified asphalt mixture ranged from 47.3% to 79.5% at 5 °C, 59.2% to 152.2% at 15 °C, 86.6% to 360.4% at 25 °C, 144.5% to 767.6% at 35 °C, 276.6% to 1252% at 45 °C, and 404.7% to 1369% at 55 °C.

The dynamic modulus reflects the stiffness of a mixture or material under different loading frequencies and temperatures. The greater the dynamic modulus value, the greater the mixture's resistance to rutting (permanent deformation). Compared with the PU asphalt mixture, the SBS-modified asphalt mixture had a notably higher dynamic modulus at a lower temperature, which means that the stiffness of the SBS-modified asphalt mixture was notably greater than that of the PU mixture. This phenomenon demonstrates that the SBS-modified asphalt mixture would be more prone to cracking at lower temperatures, in contrast to the PU mixture. The dynamic modulus of the SBS-modified asphalt mixture was remarkably smaller than that of the PU mixture at higher temperatures (≥35 °C). This finding indicates that the stiffness of the PU mixture was greater than that of the SBS-modified asphalt mixture and the PU mixture could resist high-temperature deformation, compared with the SBS-modified asphalt mixture. When the loading frequency was low, the stiffness of the SBS-modified asphalt mixture decreased at a larger magnitude than that of the PU mixture. Based on the time-temperature superposition principle (TTSP), a short time or a high frequency is equivalent to a low temperature and vice versa. This indicates that permanent deformation (rutting) occurs frequently on sections of steep slopes, intersections, bus stations, etc., where vehicles are at slow speed, frequently braking, and there is a long contact time between the tires and the road surface.

The dynamic modulus correlated to the mixture's load spreading capacity [60] and the mixture with a higher dynamic modulus would distribute the loading over a wide area. Thus. the SBS-modified asphalt mixture's structure cannot distribute the loading effectively at higher temperatures with lower dynamic modulus values. The load would concentrate on the SBS-modified asphalt mixture structure, which would lead to rutting disease. The dynamic modulus is one of the most essential parameters for mechanical analysis, design, and structural evaluation of flexible pavement [61], and is one of the main reasons for the differences in pavement design worldwide. A pavement structure with higher dynamic modulus would need less thickness to withstand external force and to resist the damage caused by the vehicles and climate. For most pavement design methods, the dynamic modulus, or other modulus when the temperatures are under 15 °C, the pavement structure designed by these parameters with reasonable thickness could exhibit enough performance for most conditions, but cannot provide enough stiffness at higher temperatures because the asphalt mixture has little dynamic modulus at higher temperatures. Therefore, it is unreasonable to use the parameters at lower temperatures for new flexible pavement design and in-service pavement life assessment. The PU mixture with a bigger dynamic modulus at a higher temperature would be an excellent material for flexible pavement design with improved high temperatures, and the appropriate pavement thickness of the PU mixture should be determined at a higher temperature so that the pavement will not fail prematurely during its design life.

4.2. Comparing the Phase Angles of the SBS-Modified Asphalt and PU Mixtures

The SBS-modified asphalt mixture's phase angle reduced as the loading frequency increased when the temperature was lower than 25 °C; when the temperature was higher than 25 °C, the SBS-modified asphalt mixture's phase angle initially grew as the loading frequency increased to the highest point and then started to reduce as the loading frequency further increased, due to the temperature sensitivity of the SBS-modified asphalt. This means that the SBS-modified asphalt mixture exhibited some viscous properties as the temperature increased. For the PU mixture, the phase angle gradually decreased with the increase of the loading frequency. This phenomenon demonstrates that the PU mixture displays elastic properties all the time, and the viscosity of the PU mixture acted gradually and was not in a dominant phase. When the loading frequency is raised from 0.1 Hz to 25 Hz, the SBS-modified asphalt mixture's phase angle is reduced by about 57.2% to 29.2%, with the temperature ranging from 5 °C to 25 °C; at a temperature of 35 °C, the phase angle changed slightly; at temperatures of 45 °C and 55 °C, this translated into about a 21.9% and 30.8% increase on average in phase angle, with the frequency raised from 0.1 Hz to 25 Hz. For the PU mixture, the phase decreased by about 29.9% to 36% when the frequency was raised from 0.1 Hz to 25 Hz, and the decreased magnitude increased with the increase in temperature. This indicates that the influence of temperature on the phase angle of the PU mixture enhanced as the temperatures increased.

Under the same loading frequencies, the phase angle of the SBS-modified asphalt mixture initially grew, and then reduced when the temperature was higher than 45 °C. The increasing magnitudes were about 12% to 265% when the loading frequency was raised from 0.1 Hz to 25 Hz. These results could be explained by the fact that when the temperature was low, the SBS-modified asphalt binder was in elastic status and tended to behave mechanically with significant elastic properties. The SBS-modified asphalt mixture was subjected to the asphalt binder, and the SBS-modified asphalt mixture's behavior was dominated by the asphalt property, so the phase angle was small. The SBS-modified asphalt binder became soft and turned viscous as the temperature increased. The viscoelastic property of the SBS-modified asphalt mixture is dominated by the viscous characteristic, so the phase angle would increase. When the SBS-modified asphalt binder tended to lose stiffness and could not withstand the stress alone in a viscous state, the aggregate skeleton would start to take up the stress together with the SBS-modified asphalt binder, and the SBS-modified asphalt mixture's behavior transitioned from being dominated by the SBS-modified asphalt binder to the aggregate skeleton [62], and the phase angle would decrease. The dominant factor in the viscoelastic behavior of the SBS-modified asphalt mixture altered within this temperature range. The SBS-modified asphalt mixture displayed more viscous properties at higher temperatures. Therefore, the SBS-modified asphalt mixture would be damaged by rutting disease at high temperatures. When the loading frequencies decreased from 25 Hz to 0.1 Hz, the ratio of the phase angle between the PU mixture and SBS-modified asphalt mixture ranged from 62.2% to 38% at 5 °C, 39.9% to 31% at 15 °C, 31.5% to 26.3% at 25 °C, 23.1% to 35.9% at 35 °C, 20.6% to 42.3% at 45 °C, and 23% to 51.5% at 55 °C.

Under the same loading frequencies, the phase angle of the PU mixture steadily grew as the temperature increased. The increases magnitudes were 38%–55% when the loading frequency was reduced from 25 Hz to 0.1 Hz. At higher loading frequencies, the increase in magnitude was smaller. The phase angles of the PU mixture at 55 °C ranged from 7° to 12°, which indicates that the PU mixture would still be in elastic status at 55 °C. Therefore, the PU mixture would be subjected to the PU binder at 55 °C and the aggregate skeleton did not exhibit obvious effort to withstand the stress. The dominant factor in the viscoelastic behavior of the PU mixture did not change in this temperature range. The PU mixture could resist rutting damage at higher temperatures, compared with the SBS-modified asphalt mixture.

Figure 3c shows that the phase angles of the SBS-modified asphalt mixture were higher than those of the PU mixture at all test temperatures, and the gap became bigger as the temperatures increased. The phase angles of the PU mixture at 55 °C were still smaller than those of the SBS-modified asphalt mixture at 5 °C, which indicated that the PU mixture's temperature sensitivity was a great deal smaller than the SBS-modified asphalt mixture. In other words, the SBS-modified asphalt mixture had a significant viscosity when compared to the PU mixture. Therefore, the PU mixture has outstanding high-temperature stability and maintains good elasticity at high temperatures, which was the disadvantage of the asphalt mixture.

From the viscosity standpoint, the phase angle describes the mixture's capacity to resist deformation under the applied load [63], which depicts the actual force and dynamic behavior of pavement [64]. When the viscoelastic material is loaded, the strain response lags behind the applied stress and the phase lagging is represented by the phase angle. The phase angle is between 0−90° [65,66]; a larger phase angle manifests more viscous and less elastic behavior. The pavement structure's internal stress will progressively dissipate as time progresses as a result of temperature and vehicle load, which is known as stress relaxation [67].

When the phase angle is close to zero, the material is pure elastic and there is no time lag between the stress and strain, which means that the structure with pure elastic material would immediately recover after unloading the stress. When the phase angle is close to 90 °, the material is pure viscous and there is a big lag between the stress and strain, which means that the structure with pure viscous material would take a longer time to recover after unloading the stress. Therefore, the bigger the phase angle is, the longer the relaxation time the structure takes to recover after unloading the stress. Comparing the phase angle data, the phase angle of the SBS-modified asphalt mixture was much higher than that of the PU mixture under the same temperatures and loading frequencies, which means the SBS-modified asphalt mixture structure would take a longer time to recover from strain after unloading stress, compared with the PU mixture. This means that the SBS-modified asphalt mixture would tend to incur permanent deformation, compared with the PU mixture. This could explain why rutting damage occurs in the slow-speed vehicle section for asphalt mixture pavements. The PU mixture with a smaller phase angle produces less permanent deformation and improves rutting resistance.

4.3. Comparing the Stiffness Parameters ($E^*/sin(\delta)$) of the SBS-Modified Asphalt and PU Mixtures

The dynamic modulus correlates well with the field permanent deformation behavior suggested by the NCHRP report 513 and incorporates the Superpave system for performance evaluation. It is important to recognize that rutting was rated as the most significant hot mixed asphalt mixture problem in current practice. According to one reference [68], there is an excellent correlation between the rutting resistance of asphalt pavement and the stiffness parameter ($E^*/sin(\delta)$) of the asphalt mixture, and the stiffness parameter of the asphalt mixture can more precisely reflect its resistance to rutting at comprehensively high service temperatures. Generally, the greater the stiffness parameter value, the greater the asphalt mixture's resistance to rutting (permanent deformation).

Based on the experimental data of dynamic modulus and phase angle of the SBS-modified asphalt mixture, the stiffness parameter would decrease as the temperatures increase, and increase as the loading frequency increases. Under the same temperature, the stiffness parameter would increase sharply at a lower temperature and the increase rate would slow down. When the temperature rose above 25 °C, the increased speed would be very small. This means that the loading frequency had a bigger influence on the stiffness parameter at lower temperatures, and the loading frequency could be ignored at higher temperatures. At the same loading frequency, the stiffness parameter would decrease sharply with the increase in temperature. The stiffness parameter at 15 °C would be much smaller at one order of magnitude than that at 5 °C. When the temperatures rose to 35 °C, 45 °C, and 55 °C, the stiffness parameter would decrease by about 47%–57%, 57%–66%, and 63%–72%, separately. Therefore, the temperature could greatly affect the stiffness parameter of the SBS-modified asphalt mixture, and the SBS-modified asphalt mixture cannot resist high-temperature deformation, which is the insurmountable drawback of the SBS-modified asphalt mixture.

For the PU mixture, the stiffness parameter would also increase as the loading frequency increased, and decrease as the temperature increased. However, the changing rate was much smaller than that of the SBS-modified asphalt mixture. At the same temperature, the stiffness parameter would gradually increase as the loading frequency increased, and the increasing rate would steadily decrease as the temperature increased. Under the same loading frequency, the stiffness parameter would gradually decrease as the temperature increased, and the increase rate would decrease as the temperature increased. Therefore, the loading frequency and temperature had a certain effect on the stiffness parameter of the PU mixture.

The stiffness parameter of the SBS-modified asphalt mixture at 5 °C was bigger at higher loading frequencies and smaller at lower loading frequencies, compared with that of the PU mixture. The stiffness parameter of the SBS-modified asphalt mixture would become smaller than that of the PU mixture at 15 °C. At temperatures of 25 °C and 35 °C, the stiffness parameters of the PU mixture were all bigger than those of the SBS-modified asphalt mixture; when the temperature rose to 45 °C and 55 °C, the difference became bigger. This demonstrates that the PU mixture had higher stiffness parameters than the SBS-modified asphalt mixture, and the PU mixture could resist high-temperature deformation or rutting. This could be explained by the fact that the PU mixture would produce little thermal rheological deformation at high temperatures, and the PU mixture's temperature sensitivity was much smaller than the SBS-modified asphalt mixture. The PU mixture is applicable for replacement of the SBS-modified asphalt mixture in order to resist high-temperature deformation. The SBS-modified asphalt mixture cannot solve the rutting problem.

4.4. Black Space Diagram Analyzing

The black space diagram [69] is an effective way to compare and evaluate the asphalt binder's rheological properties and asphalt mixture's performance [21,70], and estimate the mixtures' stiffness and relaxation capability from a dynamic modulus versus phase angle plot [71]. If the black space curve shifts to the right or the inflection point is on the right, the material or the mixture would exhibit a more viscous property. Due to the interaction of the asphalt binder with aggregate, the black space plot of the asphalt mixture exhibits a peak phase angle value at moderate stiffness [72]. Owing to the asphalt binder's low stiffness and viscous flow at high temperatures, the aggregate structure starts to take control of behavior, whereas at lower temperatures the asphalt mixture's volumetrics and binder stiffness are in charge.

From Figure 5, it is seen that the black space curves of the dynamic modulus versus phase angle of the SBS-modified asphalt mixture show an obvious curve shape and have an inflection point. The black space diagram could be utilized to compare the difference in rheological characteristics of asphalt binder or asphalt mixture with different additions or additives. If the material possesses typical rheological properties, the black space curves have obvious curve shapes and inflection points. The SBS-modified asphalt mixture confirmed this conclusion. However, for the PU mixture, the black space spots of dynamic modulus versus phase angle did not show a curve shape and were all on the left side of the black space diagram, which indicates the PU mixture shifted to a stiffer and elastic condition. The black space spots were scattered together, which means that the temperature and loading frequency had a relatively smaller influence on the dynamic modulus of the PU mixture. This indicates that the PU mixture does not exhibit rheological properties at the test temperature range, and the PU mixture would still be in elastic status even at 55 °C. This result confirms the findings concluded above.

4.5. The Master Curves of the SBS-Modified Asphalt and PU Mixtures

4.5.1. Dynamic Modulus Master Curve of the SBS-Modified Asphalt and PU Mixtures

Based on the theoretical premise of TTSP, a master curve could be developed by shifting the experimental data acquired at various temperatures and loading frequencies. This is an effective tool for representing and analyzing the dynamic mechanical properties of the asphalt mixture. The master curve could reflect the loading-rate dependency of the mixture. In this study, the reference temperature was set as 20 °C.

Five master curve models were adopted to construct the dynamic modulus master curve, which were the SLS, GLS, CAM, modified CAM, and SCM models. The shift factor equations based on the TTSP are needed to shift the experimental data at different temperatures and loading frequencies to form a smooth master curve. The log-linear, polynomial, Arrhenius, WLF, and Kaelble equations were used for constructing the master curves. The error minimization method, based on nonlinear least squares regression analysis, was used to evaluate the five dynamic modulus models' fitting divergence and diminish the difference between the predicted and measured dynamic modulus.

There were 25 kinds of master curve models and shift factor equation combinations that needed to be evaluated. For the PU mixture, only the combination of the modified CAM model and log-linear equation did not produce acceptable fitting results, therefore, the experimental data of the PU mixture had relatively small diversity and could be better fitted by the mathematical models. The fitting results of the SBS-modified asphalt mixture for 25 combinations were listed in Table 3. Seven combinations did not produce acceptable fitting results, and only the Kaelble equation could produce acceptable, fitting results for the modified CAM model. This indicated that the dynamic modulus results of the SBS-modified asphalt mixture under different temperatures had significant differences, which could influence the fitting procedure and result. The Sy of the dynamic modulus of the SBS-modified asphalt mixture (0.6034) is considerably greater than that of the PU mixture (0.1295).

According to previous research, the dynamic modulus master curve of the asphalt mixture shows the "S" shape and tends to be the ultimate value at extremely high or low loading frequencies (temperature). At lower temperatures (higher frequency), the asphalt mixture is subjected to asphalt binder, and the asphalt binder strength determines the ultimate value of dynamic modulus at lower temperatures. When the temperature rises, the binder becomes softer and could withstand the stress alone. The aggregate skeleton begins to bear the stress with the binder until the binder loses its capability to bear stress. Then, the aggregate skeleton would withstand the stress alone and the strength of the aggregate skeleton would determine the ultimate strength at higher temperatures. The SLS model, GLS model, modified CAM model, and part of the SCM model fitting master curves followed the traditional "S" shape, which could be depicted as the potential proper master curve model for the SBS-modified asphalt mixture. For the PU mixture, only the master curve of the combination of the GLS model and WLF equation followed the "S" shape. The other master curves gradually increased as the loading frequency increased and did not show an obvious ultimate value. This may be explained by the fact that the PU binder reacted with the chemical bond on the surface of the aggregates, and then the PU binder and aggregate reacted together to form the PU mixture, which was different from the asphalt mixture. The PU binder does not show obvious rheological properties at higher temperatures; its strength would be reduced as the temperature increased, but the PU binder would break under the outer stress with lower strength under higher temperatures, unlike the failure of the asphalt. Therefore, the PU mixture did not show an obvious ultimate dynamic modulus value as the asphalt mixture did.

The equation with the highest fitting accuracy was selected for comparison for each master curve model, and the best fitting results for the SBS-modified asphalt mixture and PU mixture were listed in Table 4 and Figure 6j. From Table 4, it could be concluded that the master curves of the PU mixture predict more accuracy than those of the SBS-modified asphalt mixture. The recommended combinations, except for the CAM model and WLF equation, for the SBS-modified asphalt mixture had similar shapes, and the curves converged together at the intermediate loading frequency (10^{-5} to 10^5 Hz).

4.5.2. Phase Angle Master Curve of the SBS-Modified Asphalt and PU Mixtures

The phase angle master curve models were acquired from the corresponding dynamic modulus master curve models, based on the terms of the approximate K-K relations [53,73]. There were also five master curve models, which were the SLS [49], GLS [51], CAM [52], modified CAM [74], and SCM models [51]. The shift factor equation and error minimization method adopted was the same as the dynamic modulus master curve fitting mentioned above.

The phase angle experimental data of the SBS-modified asphalt mixture had an extremely high standard deviation (7.455), and no acceptable fitting results could be obtained for the SBS-modified asphalt mixture. In Figure 7, for the PU mixture's phase angle master curve, all the phase angle master curves except the modified CAM model had similar shapes, and the curves decreased gradually as the loading frequency increased. The phase angle master curves of the modified CAM model initially reduced and then grew as the loading frequency increased. For some equations of the GLS and SCM model, the final values of the master curves at extremely low frequency (high temperature) were close to 90°, which represents that the PU mixture was in a viscous state. This PU binder would not turn to a viscous state after being cured, and the phase angle would not get close to 90°, so the GLS and SCM model with certain equations would not be applicable to the PU mixture. For the modified CAM model, the phase angle master curves were different from the others, there was a turning point at 100 Hz frequency, and the phase angle increased as the temperature decreased, which was not complying with the changing regularity of the material with a viscoelastic property. Therefore, the modified CAM model was not suitable for the phase angle master curve construction.

For each model, the equation with the best fitting results was plotted in Figure 7f and Table 5. The SCM model had extremely high values at a lower frequency and the shape of the modified model was different from the viscoelastic material. The other three models had similar shapes and values. According to Table 5, the SLS model with the polynomial equation had the best fitting results, e.g., R^2 (0.9985), Se/Sy (0.0161), SSE (0.032), which was recommended for the phase angle master curve construction.

The typical phase angle master curve of the asphalt mixture displays a "bell" shape, whereas, the shape of the phase angle master curve of the PU mixture was different. The phase angle of the asphalt mixture rose as the loading frequency increased and then fell as the frequency continued to rise. The phase angle master curve shape of the asphalt mixture complied with the viscoelastic property of the asphalt binder, e.g., the asphalt binder exhibited elastic properties at a reduced temperature (or higher loading frequency), and exhibited viscous properties at a higher temperature (or lower loading frequency). The PU binder did not exhibit obvious viscous properties at higher temperatures (or lower loading frequency). Therefore, the shape of the phase angle master curve is a smooth decreasing curve.

4.5.3. Shift Factor of the SBS-Modified Asphalt and PU Mixtures

The shift factor in the function of temperature represents the translation of the modulus curve at each temperature into the master curve, and the translation quantity reflects the correlation between frequency and temperature [48]. The shift factor describes the degree to which the mixture is temperature dependent at a given temperature; a larger shift factor indicates a stronger temperature dependence [75]. The larger the activation energy, the more challenging it is to shift the curve with reference temperature. Activation energy is a measure of the energy barrier that must be overcome. Additionally, the shift factor agrees with activation energy [76].

The dynamic modulus of the SBS-modified asphalt mixture could only get an acceptable fitting result based on the Kaelble equation, and the shift factor of the SBS-modified asphalt mixture was smaller than that of the PU mixture. From Figure 8, it is evident that under all master curve models and shift factor equations, the value or absolute value of the shift factors of the SBS-modified asphalt mixture were all bigger than that of the PU mixture. This indicated that the PU mixture would consume less activation energy to shift the curves to the reference, compared with the SBS-modified asphalt mixture. In other words, the temperature sensitivity of the PU mixture was relatively low. The PU mixture was resistant to permanent deformation, fatigue, and low-temperature cracking.

4.6. Correlation Study between the SBS-Modified Asphalt and PU Mixtures

For comparing the dynamic modulus experimental data of the SBS-modified asphalt mixture and PU mixture, the dynamic modulus and phase angle of the SBS-modified asphalt mixture and PU mixture were compiled into a single plot. From Figure 9a, it could be concluded that the dynamic modulus plots did not show linear trending, but the plots follow an obvious curve shape and show little dispersion. Nonlinear regression was used to fit the power model form of dynamic modulus of the SBS-modified asphalt mixture and PU mixture, the power model form was $Y = -8.54 \times 10^{-6} \times X^2 + 0.46 \times X + 4899.55$, R^2 was 0.94, and the residual sum of squares (RSS) was 1.26×10^7. A two-sided F-test was used to evaluate the correlation based on Pearson correlation analysis and a 99% significance level was adopted. The analyzing results are listed in Table 6, and indicate that the dynamic modulus of the SBS-modified asphalt mixture had a good relationship with that of the PU mixture, as the Pearson correlation was 0.954. The double tail result (0.0) was smaller than 0.1, which was the 99% significance level. This indicates that the dynamic modulus of the SBS-modified asphalt mixture was statistically significantly different from that of the PU mixture. Therefore, the binder had a substantial impact on the dynamic modulus of the asphalt mixture or PU mixture.

Figure 9b compared the experimental data for the SBS-modified asphalt mixture and the PU mixture for the phase angle. It was clear from Figure 9b that the spots did not show obvious curves and were scattered at a certain range. The linear and polynomial fitting methods were used to fit the phase angles between the SBS-modified asphalt mixture and the PU mixture, and there were no acceptable results after the fitting procedure. The Pearson correlation results are listed in Table 6. The Pearson correlation (0.54) was smaller than that of the dynamic modulus data, which means that the correlation of the phase angle was weaker than that of the dynamic modulus and the phase angle had more variability. The double tail result (0.0) was also smaller than 0.1, which was the 99% significance level. This means that the phase angle between the SBS-modified asphalt and the PU mixture had a certain correlation. The SBS-modified asphalt mixture and PU mixture had the same aggregate gradation, so the influence of aggregate type and gradation could be ignored. Therefore, the binder type is the only influence factor and had a substantial impact on phase angle data.

4.7. Storage Modulus and Loss Modulus Analyzing

The complex dynamic modulus (E^*) is composed of two components: storage modulus ($E_{Storage}$), and loss modulus (E_{Loss}). The storage modulus represents the elastic component of the mixture: the greater the value is, the more pronounced the elastic property. The loss modulus represents the viscous component of the mixture: the greater the value is, the stronger the viscosity. The storage modulus and the loss modulus can be calculated by Equations (2) and (3).

$$E_{Storage} = E^* \times \cos(\delta) \quad (2)$$

$$E_{Loss} = E^* \times \sin(\delta) \quad (3)$$

From Figure 10a–c, it could be discovered that the storage of the PU mixture was smaller than that of the SBS-modified asphalt mixture at lower temperatures (5 °C and 15 °C), and this could explain why the SBS-modified asphalt mixture is much stiffer than the PU mixture at lower temperatures. When the temperatures were in the intermediate range (25 °C and 35 °C), the PU mixture's storage modulus was bigger than that of the SBS-modified asphalt mixture at the same temperature, but the SBS-modified asphalt mixture's storage modulus at 25 °C was bigger than that of the PU mixture at 35 °C. At higher temperatures (45 °C and 55 °C), the storage modulus of the PU mixture was bigger than that of the SBS-modified asphalt mixture. The storage modulus of the SBS-modified asphalt mixture sharply decreased with the increase of the temperatures, and the decreased magnitude of the storage modulus of the PU mixture was much smaller than that of the SBS-modified asphalt mixture. This could be explained by the fact that the PU mixture's temperature sensitivity was much lower than that of the SBS-modified asphalt mixture, and the elastic component of the PU mixture would decrease much more slowly than that of the SBS-modified asphalt mixture. The PU mixture would still exhibit higher elastic properties at higher temperatures to resist the elastic deformation.

From Figure 10d–f, at temperatures of 5 °C and 15 °C, the loss modulus of the PU mixture was much smaller than that of the SBS-modified asphalt mixture, which indicated that the viscous component of the PU mixture was much smaller. When the temperature rose to 25 °C and 35 °C, the loss modulus of the PU mixture changed very little. This shows that the temperature did not have as much of an effect on the viscous component of the PU mixture compared with the SBS-modified asphalt mixture. At 45 °C and 55 °C, the loss modulus of the PU mixture was much bigger than that of the SBS-modified asphalt mixture. This could be explained by the fact that the dynamic modulus of the SBS-modified asphalt mixture decreased sharply at high temperatures. Furthermore, the loss modulus of the PU mixture at high temperatures decreased little, which indicates that temperature had little effect on the viscous component of the PU mixture, and the PU mixture would exhibit insignificant viscous properties at higher temperatures. Therefore, a PU mixture could produce little thermal rheological deformation at high temperatures. The loss modulus of the SBS-modified asphalt mixture would also sharply decrease with the increase in temperatures. This means that the viscous component of the SBS-modified asphalt mixture would decrease at higher temperatures, and the SBS-modified asphalt mixture would lose the ability to bond the aggregates and resist the stress.

5. Conclusions

In this paper, an SBS-modified asphalt mixture and a PU mixture with the same aggregate type, gradation, and binder content were compared to the influence of binder type on dynamic property. The comparison method included a comparison between dynamic modulus, phase angle, stiffness parameter, storage and loss modulus, master curves, block diagram, and correlation analysis. According to the comparison and analysis, the following conclusion could be obtained.

(1) For the PU mixture at a constant loading frequency or temperature, the dynamic modulus would gradually grow as the loading frequency increased or temperature decreased. The phase angle exhibits the opposite trend, which is the expected behavior of a typical viscoelastic material; the PU mixture is a typical viscoelastic material when compared with the SBS-modified asphalt mixture.

(2) Compared with the SBS-modified asphalt mixture, the PU mixture with a smaller phase angle exhibited more notable elastic properties and did not even show viscous properties at higher temperatures (55 °C). Therefore, the PU mixture finds it easier to handle stress and recover from the deformation after unloading.
(3) The dynamic modulus of the PU mixture was smaller than that of the SBS-modified asphalt mixture at lower temperatures (e.g., 5 °C and 15 °C), but was higher than that of the SBS-modified asphalt mixture when temperatures were higher than 25 °C. The decline magnitude of the dynamic modulus for the PU mixtures was about 50%−57%, which was much smaller than that of the SBS-modified asphalt (about 94%−98%). The PU mixture had substantially higher temperature stability than the SBS-modified asphalt mixture. The dynamic modulus of the PU mixture at 45 °C and 10 Hz (6136.6 MPa) was a great deal higher than that of the high-modulus asphalt mixture (2500 MPa) recommended in the literature [77].
(4) The stiffness parameter, storage, and loss modulus analysis results also proved the conclusion that the PU mixture has higher stiffness to resist high-temperature deformation than the SBS-modified asphalt mixture.
(5) For the SBS-modified asphalt mixture, the phase angle and loading frequency are negatively correlated, whereas they are positively correlated for the PU mixture. The temperature is the dominant factor for the SBS-modified asphalt mixture, and the PU mixture's behavior was in a PU−dominated phase during the testing temperature or loading frequency range.
(6) The dynamic modulus between the SBS-modified asphalt and PU mixture had a high correlation with the R^2 value of 0.94, and there was no obvious correlation between the phase angle data of these two mixtures. This indicates that the chemical property of the SBS-modified asphalt was quite different from that of the PU binder. The black diagram analysis also proved this conclusion and demonstrated that the PU mixture was in an elastic state during the test temperature.
(7) The PU mixture's dynamic modulus under different temperatures was more stable than that of the SBS-modified asphalt mixture and could be better fitted by the mathematical models to represent its dynamic property. The PU mixture's dynamic modulus master curve rose with the increase of the loading frequency and did not follow the "S" shape, which was the traditional dynamic modulus master curve shape of the SBS-modified asphalt mixture. The master curve did not show ultimate values at extremely high or low frequencies.
(8) The phase angle data of the SBS-modified asphalt mixture exhibited high standard deviation values and could not be fitted by the mathematical models. The phase angle data of the PU mixture could be fitted acceptably by mathematical models, and the phase angle master curves of the PU mixture did not show the "bell" shape, which is the typical shape of the asphalt mixture. This proves that the viscoelastic property of the PU mixture was very different from that of the SBS-modified asphalt mixture.
(9) The thermal rheological property of the PU mixture is smaller than that of the SBS-modified asphalt mixture, and not obvious during the test temperature range.

As theoretically expected, the mixture should exhibit lower modulus or stiffness, which would decrease the crack risk for the ideal pavement mixture. Contrary to the requirements of a mixture at lower temperatures, the mixture should display higher modulus or stiffness at higher temperatures to resist rutting or deformation damage. The behavior of the SBS-modified asphalt mixture is contrary to the requirements: it would exhibit less elasticity at higher temperatures and more elasticity at lower temperatures due to the viscoelastic property of asphalt binder. Therefore, the SBS-modified asphalt mixture structure would tend to crack at lower temperatures and rut at higher temperatures. In comparison to the SBS-modified asphalt mixture, the PU mixture would exhibit lower modulus at lower temperatures and higher modulus at higher temperatures. Therefore, the PU mixture would decrease the cracking risk at lower temperatures and the rutting risk at higher temperatures.

The PU mixture could be considered as an ideal pavement mixture, which could resist the deformation of the pavement structure caused by the temperatures and loading.

This study attempted to compare the difference in the dynamic properties of SBS-modified asphalt and PU mixtures, and to analyze the PU mixture's viscoelastic properties, which produced these differences. This study could provide insight into understanding the characteristics of the PU mixture and designing the pavement structure. This could improve the advantage of the PU mixture, which is to resist high-temperature deformation. However, this paper only compared the dynamic properties. More aspects of road performance, e.g., high-temperature dynamic stability, low-temperature strain, and water stability, should be studied and compared for the SBS-modified asphalt and PU mixture to better understand the comprehensive properties and performance of the PU mixture.

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References

1. Tschoegl, N.W. *The Phenomenological Theory of Linear Viscoelastic Behavior: An Introduction*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
2. Enieb, M.; Diab, A. Characteristics of asphalt binder and mixture containing nanosilica. *Int. J. Pavement Res. Technol.* **2017**, *10*, 148–157. [CrossRef]
3. Sarnowski, M. Rheological properties of road bitumen binders modified with SBS polymer and polyphosphoric acid. *Roads Bridg. Drog. I Mosty* **2015**, *14*, 47–65. [CrossRef]
4. Fontes, L.P.; Trichês, G.; Pais, J.C.; Pereira, P.A. Evaluating permanent deformation in asphalt rubber mixtures. *Constr. Build. Mater.* **2010**, *24*, 1193–1200. [CrossRef]
5. Plewa, A. Asphalt mixtures with binders fluidized by addition of vegetable origin oil for applications as flexible anti-crack layers. *Roads Bridg. Drog. I Mosty* **2019**, *18*, 181–192. [CrossRef]
6. Sengul, C.E.; Oruc, S.; Iskender, E.; Aksoy, A. Evaluation of SBS modified stone mastic asphalt pavement performance. *Constr. Build. Mater.* **2013**, *41*, 777–783. [CrossRef]
7. Tayfur, S.; Ozen, H.; Aksoy, A. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. *Constr. Build. Mater.* **2007**, *21*, 328–337. [CrossRef]
8. Feiteira Dias, J.L.; Picado-Santos, L.G.; Capitão, S.D. Mechanical performance of dry process fine crumb rubber asphalt mixtures placed on the Portuguese road network. *Constr. Build. Mater.* **2014**, *73*, 247–254. [CrossRef]
9. Ilyin, S.; Arinina, M.; Mamulat, Y.S.; Malkin, A.Y.; Kulichikhin, V. Rheological properties of road bitumens modified with polymer and solid nanosized additives. *Colloid J.* **2014**, *76*, 425–434. [CrossRef]
10. Bahia, H. *Modeling of Asphalt Binder Rheology and Its Application to Modified Binders*; ASCE Press, McGraw-Hill Construction: New York, NY, USA, 2004; pp. 11–64.
11. Christensen, D. Analysis of creep data from indirect tension test on asphalt concrete. *J. Assoc. Asph. Paving Technol.* **1998**, *67*, 458–492.
12. Moon, K.H.; Marasteanu, M.; Turos, M. Comparison of thermal stresses calculated from asphalt binder and asphalt mixture creep tests. *J. Mater. Civ. Eng.* **2013**, *25*, 1059–1067. [CrossRef]
13. Airey, G.D.; Rahimzadeh, B. Combined bituminous binder and mixture linear rheological properties. *Constr. Build. Mater.* **2004**, *18*, 535–548. [CrossRef]
14. Huang, Y. *Pavement Analysis and Design*; Pearson Education, Inc.: Upper Saddle River, NJ, USA, 1993; p. 07458.

15. Caro, S.; Masad, E.; Bhasin, A.; Little, D.N. Moisture susceptibility of asphalt mixtures, Part 2: Characterisation and modelling. *Int. J. Pavement Eng.* **2008**, *9*, 99–114. [CrossRef]
16. Fonseca, O.; Witczak, M.W. A prediction methodology for the dynamic modulus of in-place aged asphalt mixtures (with discussion). *J. Assoc. Asph. Paving Technol.* **1996**, *65*, 532–572.
17. Marasteanu, M.; Velasquez, R.; Cannone Falchetto, A.; Zofka, A. Development of a simple test to determine the low temperature creep compliance of asphalt mixtures. *IDEA Program Final Rep. NCHRP* **2009**, *133*, 1–37.
18. Brown, E.R.; Kandhal, P.S.; Roberts, F.L.; Kim, Y.R.; Lee, D.-Y.; Kennedy, T.W. *Hot Mix Asphalt Materials, Mixture Design, and Construction*; NAPA Research and Education Foundation: Lanham, MD, USA, 2009.
19. Jin, H.-B.; Zhou, X.-Y.; Ju, Z.-C.; Shan, L.-Y. Study on Dynamic Modulus Dependence Model for Asphalt Mixture Based on Temperature and Strain Parameters. *J. Highw. Transp. Res. Dev.* **2020**, *14*, 70–77. [CrossRef]
20. Mitchell, M.R.; Link, R.E.; Li, X.; Christopher Williams, R. A Practical Dynamic Modulus Testing Protocol. *J. Test. Eval.* **2012**, *40*, 100–106. [CrossRef]
21. Nemati, R.; Dave, E.V. Nominal property based predictive models for asphalt mixture complex modulus (dynamic modulus and phase angle). *Constr. Build. Mater.* **2018**, *158*, 308–319. [CrossRef]
22. Apeagyei, A.K. Rutting as a Function of Dynamic Modulus and Gradation. *J. Mater. Civ. Eng.* **2011**, *23*, 1302–1310. [CrossRef]
23. Bayat, A.; Knight, M. Investigation of hot-mix asphalt dynamic modulus by means of field-measured pavement response. *Transp. Res. Rec.* **2010**, *2154*, 138–145. [CrossRef]
24. Zhou, F.; Scullion, T. Preliminary Field Validation of Simple Performance Tests for Permanent Deformation: Case Study. *Transp. Res. Rec. J. Transp. Res. Board* **2003**, *1832*, 209–216. [CrossRef]
25. Abed, A.; Thom, N.; Neves, L. Probabilistic prediction of asphalt pavement performance. *Road Mater. Pavement Des.* **2019**, *20*, S247–S264. [CrossRef]
26. Goh, S.W.; You, Z.; Williams, R.C.; Li, X. Preliminary dynamic modulus criteria of HMA for field rutting of asphalt pavements: Michigan's experience. *J. Transp. Eng.* **2011**, *137*, 37–45. [CrossRef]
27. Zhang, C.; Shen, S.; Jia, X. Modification of the Hirsch Dynamic Modulus Prediction Model for Asphalt Mixtures. *J. Mater. Civ. Eng.* **2017**, 29. [CrossRef]
28. Hou, H.; Wang, T.; Wu, S.; Xue, Y.; Tan, R.; Chen, J.; Zhou, M. Investigation on the pavement performance of asphalt mixture based on predicted dynamic modulus. *Constr. Build. Mater.* **2016**, *106*, 11–17. [CrossRef]
29. Solatifar, N.; Kavussi, A.; Abbasghorbani, M.; Katicha, S.W. Development of dynamic modulus master curves of in-service asphalt layers using MEPDG models. *Road Mater. Pavement Des.* **2017**, *20*, 225–243. [CrossRef]
30. Huo-ming, W.; Ru-Kai, L.; Xiu, W.; Tian-qing, L.; Gang, Z. Strength and road performance for porous polyurethane mixture. *China J. Highw. Transp.* **2014**, *27*, 24.
31. Lu, G.; Renken, L.; Li, T.; Wang, D.; Li, H.; Oeser, M. Experimental study on the polyurethane-bound pervious mixtures in the application of permeable pavements. *Constr. Build. Mater.* **2019**, *202*, 838–850. [CrossRef]
32. Sun, M. *Research on Performance of Polyurethane Porous Elastic Pavement Mixture*; Southeast University: Nanking, China, 2016.
33. Li, T.-S.; Lu, G.-Y.; Wang, D.-W.; Hong, B.; Tan, Y.-Q.; Oeser, M. Key properties of high-performance polyurethane bounded pervious mixture. *Zhongguo Gonglu Xuebao/China J. Highw. Transp.* **2019**, *32*, 158–169. [CrossRef]
34. Zhoucong, X.; Wang, H.; Rukai, L.; Chen, F. Control for Construction Technology and Quality of Permeable Pavement of Polyurethane Macadam Mixture. *Technol. Highw. Transp.* **2015**, *06*, 5–8.
35. Cong, L.; Wang, T.; Tan, L.; Yuan, J.; Shi, J. Laboratory evaluation on performance of porous polyurethane mixtures and OGFC. *Constr. Build. Mater.* **2018**, *169*, 436–442. [CrossRef]
36. Shi, J.; Cong, L.; Yang, F.; Wang, T.; Tan, L.; Yu, M. Comparative Study on the Early Stage of Skid Resistance Development between Polyurethane-Bound Porous Mixture and Asphalt Mixture. *J. Mater. Civ. Eng.* **2020**, *32*, 04020164. [CrossRef]
37. Chen, J.; Yin, X.; Wang, H.; Ding, Y. Evaluation of durability and functional performance of porous polyurethane mixture in porous pavement. *J. Clean. Prod.* **2018**, *188*, 12–19. [CrossRef]
38. Zhang, Q.; Wang, S.; Lv, R.; Wu, J.; Qi, H. Viscoelastic mechanical performance of dense polyurethane mixtures based on dynamic and static modulus testing and creep testing. *Constr. Build. Mater.* **2022**, *320*, 126207. [CrossRef]
39. Sun, M.; Bi, Y.; Zheng, M.; Wang, J.; Wang, L. Performance of Polyurethane Mixtures with Skeleton-Interlocking Structure. *J. Mater. Civ. Eng.* **2020**, *32*, 04019358. [CrossRef]
40. Wang, D.; Liu, P.; Leng, Z.; Leng, C.; Lu, G.; Buch, M.; Oeser, M. Suitability of PoroElastic Road Surface (PERS) for urban roads in cold regions: Mechanical and functional performance assessment. *J. Clean. Prod.* **2017**, *165*, 1340–1350. [CrossRef]
41. Chen, J.; Ma, X.; Wang, H.; Xie, P.; Huang, W. Experimental study on anti-icing and deicing performance of polyurethane concrete as road surface layer. *Constr. Build. Mater.* **2018**, *161*, 598–605. [CrossRef]
42. Jianbing, H. *Study on Compaction Characteristics of Polyurethane Mixture*; Beijing University of Civil Engineering and Architecture: Beijing, China, 2019.
43. Zhuang, W.; Bi, Y.; Liu, B.; Hou, D.; Jing, S.; Lu, X.; Sun, M. Mechanical Properties of Polyurethane Mixture and Load Response Behaviour of Polyurethane Composite Pavement. *Polymers* **2023**, *15*, 417. [CrossRef]
44. Guo, G.; Cong, L.; Yang, F. Analysis of Influencing Factors on Water Stability and Stripping Resistance of Paving Polyurethane Mixture. *J. Mater. Civ. Eng.* **2023**, *35*, 04022485. [CrossRef]

45. Venudharan, V.; Biligiri, K.P.; Das, N.C. Investigations on behavioral characteristics of asphalt binder with crumb rubber modification: Rheological and thermo-chemical approach. *Constr. Build. Mater.* **2018**, *181*, 455–464. [CrossRef]
46. Zhang, F.; Hu, C.; Zhuang, W. The research for low-temperature rheological properties and structural characteristics of high-viscosity modified asphalt. *J. Therm. Anal. Calorim.* **2017**, *131*, 1025–1034. [CrossRef]
47. Podolsky, J.H.; Williams, R.C.; Cochran, E. Effect of corn and soybean oil derived additives on polymer-modified HMA and WMA master curve construction and dynamic modulus performance. *Int. J. Pavement Res. Technol.* **2018**, *11*, 541–552. [CrossRef]
48. Qin, X.; Ma, L.; Wang, H. Comparison analysis of dynamic modulus of asphalt mixture: Indirect tension and uniaxial compression test. *Transp. A Transp. Sci.* **2018**, *15*, 165–178. [CrossRef]
49. Pellinen, T.K.; Witczak, M.W.; Bonaquist, R.F. Asphalt mix master curve construction using sigmoidal fitting function with non-linear least squares optimization. In *Recent Advances in Materials Characterization and Modeling of Pavement Systems*; Columbia University: New York, NY, USA, 2004; pp. 83–101.
50. Richards, F.J. A flexible growth function for empirical use. *J. Exp. Bot.* **1959**, *10*, 290–301. [CrossRef]
51. Booij, H.C.; Thoone, G.P.J.M. Generalization of Kramers-Kronig transforms and some approximations of relations between viscoelastic quantities. *Rheol. Acta* **1982**, *21*, 15–24. [CrossRef]
52. Marasteanu, M.; Anderson, D. Improved model for bitumen rheological characterization. In Proceedings of the Eurobitume Workshop on Performance Related Properties for Bituminous Binders, Brussels, Belgium, 3–6 May 1999.
53. Rouleau, L.; Deü, J.F.; Legay, A.; Le Lay, F. Application of Kramers–Kronig relations to time–temperature superposition for viscoelastic materials. *Mech. Mater.* **2013**, *65*, 66–75. [CrossRef]
54. Fan, B.; Kazmer, D.O. Low-temperature modeling of the time-temperature shift factor for polycarbonate. *Adv. Polym. Technol.* **2005**, *24*, 278–287. [CrossRef]
55. Yang, X.; You, Z. New Predictive Equations for Dynamic Modulus and Phase Angle Using a Nonlinear Least-Squares Regression Model. *J. Mater. Civ. Eng.* **2015**, *27*, 04014131. [CrossRef]
56. Coleman, M.M. *Fundamentals of Polymer Science: An Introductory Text*; Routledge: London, UK, 2019.
57. Yin, Y.; Huang, W.; Lv, J.; Ma, X.; Yan, J. Unified Construction of Dynamic Rheological Master Curve of Asphalts and Asphalt Mixtures. *Int. J. Civ. Eng.* **2017**, *16*, 1057–1067. [CrossRef]
58. Irfan, M.; Waraich, A.S.; Ahmed, S.; Ali, Y. Characterization of Various Plant-Produced Asphalt Concrete Mixtures Using Dynamic Modulus Test. *Adv. Mater. Sci. Eng.* **2016**, *2016*, 5618427. [CrossRef]
59. Cho, Y.-H.; Park, D.-W.; Hwang, S.-D. A predictive equation for dynamic modulus of asphalt mixtures used in Korea. *Constr. Build. Mater.* **2010**, *24*, 513–519. [CrossRef]
60. Kim, Y.; Lee, H.D.; Heitzman, M. Dynamic Modulus and Repeated Load Tests of Cold In-Place Recycling Mixtures Using Foamed Asphalt. *J. Mater. Civ. Eng.* **2009**, *21*, 279–285. [CrossRef]
61. Gong, H.; Sun, Y.; Hu, W.; Huang, B. Neural networks for fatigue cracking prediction using outputs from pavement mechanistic-empirical design. *Int. J. Pavement Eng.* **2019**, *22*, 162–172. [CrossRef]
62. Sias Daniel, J.; Gibson, N.; Tarbox, S.; Copeland, A.; Andriescu, A. Effect of long-term ageing on RAP mixtures: Laboratory evaluation of plant-produced mixtures. *Road Mater. Pavement Des.* **2013**, *14*, 173–192. [CrossRef]
63. Zhang, X. *Principle and Application of Viscoelastic Mechanics of Asphalt and Asphalt Mixture*; People's Communications Press: Bejing, China, 2006.
64. Li, P.; Jiang, X.; Guo, K.; Xue, Y.; Dong, H. Analysis of viscoelastic response and creep deformation mechanism of asphalt mixture. *Constr. Build. Mater.* **2018**, *171*, 22–32. [CrossRef]
65. Lu, X.; Isacsson, U. Rheological characterization of styrene-butadiene-styrene copolymer modified bitumens. *Constr. Build. Mater.* **1997**, *11*, 23–32. [CrossRef]
66. Di Benedetto, H.; Olard, F.; Sauzéat, C.; Delaporte, B. Linear viscoelastic behaviour of bituminous materials: From binders to mixes. *Road Mater. Pavement Des.* **2011**, *5*, 163–202. [CrossRef]
67. Krishnan, J.M.; Rajagopal, K. Triaxial testing and stress relaxation of asphalt concrete. *Mech. Mater.* **2004**, *36*, 849–864. [CrossRef]
68. Witzcak, M.W. *Simple Performance Test for Superpave Mix Design*; Transportation Research Board: Washington, DC, USA, 2002; Volume 465.
69. Airey, G.D. Use of Black Diagrams to Identify Inconsistencies in Rheological Data. *Road Mater. Pavement Des.* **2011**, *3*, 403–424. [CrossRef]
70. Mensching, D.J.; Rowe, G.M.; Sias Daniel, J. A mixture-based Black Space parameter for low-temperature performance of hot mix asphalt. *Road Mater. Pavement Des.* **2016**, *18*, 404–425. [CrossRef]
71. Oshone, M.; Dave, E.; Daniel, J.S.; Rowe, G.M. Prediction of phase angles from dynamic modulus data and implications for cracking performance evaluation. *Road Mater. Pavement Des.* **2017**, *18*, 491–513. [CrossRef]
72. Mensching, D.J.; Rowe, G.M.; Daniel, J.S.; Bennert, T. Exploring low-temperature performance in Black Space. *Road Mater. Pavement Des.* **2015**, *16*, 230–253. [CrossRef]
73. Chailleux, E.; Ramond, G.; Such, C.; de La Roche, C. A mathematical-based master-curve construction method applied to complex modulus of bituminous materials. *Road Mater. Pavement Des.* **2011**, *7*, 75–92. [CrossRef]
74. Zeng, M.; Bahia, H.U.; Zhai, H.; Anderson, M.R.; Turner, P. Rheological modeling of modified asphalt binders and mixtures (with discussion). *J. Assoc. Asph. Paving Technol.* **2001**, *70*, 403–441.

75. Arefin, M.S.; Quasem, T.; Nazzal, M.; Dessouky, S.; Abbas, A.R. Accuracy of MEPDG Dynamic Modulus Predictions for Short-Term and Long-Term Aged Asphalt Mixtures. *J. Transp. Eng. Part B Pavements* **2019**, *145*, 04019025. [CrossRef]
76. Ding, Z.; Su, J.; Li, P.; Bing, H. Mechanism of HCB-Modified Asphalt and Dynamic Properties of Mixtures. *Appl. Sci.* **2020**, *10*, 4971. [CrossRef]
77. Guo, L.; Xu, Q.; Zeng, G.; Wu, W.; Zhou, M.; Yan, X.; Zhang, X.; Wei, J. Comparative Study on Complex Modulus and Dynamic Modulus of High-Modulus Asphalt Mixture. *Coatings* **2021**, *11*, 1502. [CrossRef]

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