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Predicting Dynamic Properties and Fatigue Performance of Aged and Regenerated Asphalt Using Time–Temperature–Aging and Time–Temperature–Regenerator Superposition Principles

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Abstract: Reclaimed asphalt pavement (RAP) reduces energy consumption and enhances economic benefits by recycling road materials, making it an effective approach for the sustainable use of solid waste resources. The performance of reclaimed asphalt pavement is significantly affected not only by the degradation of asphalt binders due to aging but also by the dosage of the rejuvenator used. The master curve of the complex shear modulus is widely recognized as a valuable tool for characterizing the rheological properties of asphalt binders. First, a virgin asphalt binder with a grade of SK70 was subjected to varying degrees of aging, followed by the rejuvenation of the aged asphalt using different dosages of the rejuvenator. Second, frequency sweeps were conducted on the aged and rejuvenated asphalt binders at various temperatures. Complex modulus master curves were constructed, and the CAM model was applied to fit these curves. The viscoelastic properties of asphalt at different aging levels and rejuvenator dosages were then analyzed based on the CAM parameters. Next, by applying a curve-shifting technique based on the least squares method to a reference state, both the time–temperature–aging (TTA) and time–temperature–regenerator (TTR) master curves of the complex modulus were constructed. The relationships between aging shift factors and aging times, as well as between regenerator shift factors and dosages, were established to predict the complex moduli of both aged and rejuvenated asphalt. Finally, the shear stress–strain relationships and material integrity of aged and rejuvenated asphalt were evaluated to assess their fatigue performance. The results indicated that aging significantly increases the complex modulus of asphalt, with TFOT (Thin Film Oven Test) aging having a more pronounced impact than PAV (Pressurized Aging Vessel) aging, resulting in reduced viscous deformation and an increased risk of cracking. Rejuvenator dosage reduces the complex modulus, with a 6% dosage effectively restoring mechanical properties and enhancing low-temperature performance. The TTA master curve demonstrates a strong linear correlation between aging shift factors and time, allowing for accurate predictions of the complex modulus of aged asphalt. Similarly, the TTR master curve reveals a linear relationship between regenerator dosage and shift factor, offering high predictive accuracy for optimizing regenerator dosages in engineering applications. The study further explores how varying levels of aging and rejuvenator dosage affect fatigue life under different strain conditions, uncovering complex behaviors influenced by these aging and regeneration processes.

Keywords: reclaimed asphalt pavement (RAP); aged asphalt; rejuvenated asphalt; complex modulus; time–temperature–aging (TTA); time–temperature–regenerator (TTR); fatigue

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1. Introduction

Asphalt pavement is commonly used on highways due to its superior performance. However, it is prone to wear and aging under high temperatures and ultraviolet radiation, leading to performance deterioration and a shortened service life [1,2]. This results in increased repair and maintenance of asphalt pavement, generating a significant amount of solid waste [3]. According to the Environmental Protection Agency (EPA), nearly 600 million tons of reclaimed asphalt pavement (RAP) are generated annually [4]. RAP consists of aged asphalt and aggregates of varying particle sizes, and its utilization helps reduce environmental pollution and costs and conserves natural resources. However, compared to original asphalt, RAP becomes more rigid and brittle when used in regenerated asphalt pavements. Additionally, according to the migration theory of components, oxidation occurs during the mixing, transportation, paving, and maintenance of asphalt pavements. This oxidation results in the loss of light components and an increase in heavy components, leading to low-temperature cracking and reduced fatigue life [5]. As a result, researchers are increasingly using regenerators to restore the performance of aged asphalt pavements [6,7].

A rejuvenator has a chemical composition similar to the lighter components of asphalt; it consists of engineered products made from various organic compounds and exhibits a specific polarity and molecular structure [8,9]. The addition of a rejuvenator can restore the performance of asphalt. Studies have shown that rejuvenators can reduce the complex modulus of aged asphalt and increase its phase angle [10]. Sharma et al. evaluated the potential use of RAP as a replacement material for asphalt binders and found that binders incorporating 40% RAP exhibited superior rheological properties [11].

Asphalt pavement aging is influenced by traffic loads and natural factors, with aging being proportional to time, temperature, and load. Since aging occurs over an extended period, real-time measurement of asphalt performance is challenging. Therefore, indoor accelerated aging tests are commonly employed to better predict the performance of aged asphalt. Anjali et al. proposed a time–temperature superposition approach to predict the complex modulus of asphalt under various dosage conditions [12]. This approach employs a consistent dose rate to construct a CA model for predicting the complex modulus of asphalt binders. Liu et al. developed a method based on a time–aging superposition approach to construct an aging master curve for the complex modulus and phase angle [13]. Rad et al. utilized the NCHRP09-54 and GAS models to predict asphalt binder properties under thermal–oxidative aging, using the viscosity index as a key metric. They found that the NCHRP09-54 model demonstrates high accuracy in predicting aging performance. Additionally, Saleh et al. used the complex modulus to predict the aging process of asphalt binders by decoupling the time–temperature and time–aging superposition effects [14]. Chen et al. employed frequency sweeps and the time–temperature superposition principle (TTSP) to construct complex modulus master curves and a black diagram, evaluating the effect of modifiers on the aging sensitivity and rheological behavior of asphalt during the aging process [15].

Over the past decades, research has verified that asphalt materials within the linear viscoelastic (LVE) domain are thermos-rheological simple, allowing their behavior in this undamaged state to be characterized using the TTSP. Building upon this theory, Chen et al. established a master curve for asphalt aging time and thoroughly examined the long-term aging performance of various modified asphalts [16]. Qin et al. explored changes in asphalt pavement performance under real aging conditions using rheological indicators, proposing a relationship between asphalt structure and these indicators to predict the rheological properties of aging asphalt binders [17]. Using the time–aging superposition principle, Wang et al. established an aging time master curve to accurately predict asphalt's dynamic modulus index under various aging conditions [18]. Wen et al. performed a series of monotonic constant shear strain-rate tests on asphalt binders at various temperatures and loading rates, subsequently constructing master curves for failure stress and failure energy [19]. Based on the above studies, adopting models to predict the performance of aging and regenerated asphalt binders is crucial for optimizing the use of reclaimed asphalt pavement (RAP) in modern infrastructure projects. As asphalt binders age, they undergo chemical and physical changes that affect their rheological properties, including increased stiffness and a higher susceptibility to cracking. Regeneration of these aged binders with rejuvenators helps restore their flexibility and resistance to deformation. However, predicting the performance of both aged and regenerated binders requires a robust modeling approach to ensure pavement durability and longevity.

Aging not only alters the dynamic mechanical properties of asphalt but also reduces its fatigue life. Since the addition of a regenerating agent also affects the fatigue life of aged asphalt, it is essential to examine the fatigue performance of both aged and regenerated asphalt. Numerous studies have shown that the fatigue characteristics of asphalt binders decline with age [20–22]. Yang et al. evaluated the fatigue characteristics of asphalt at different aging times using the Simplified Viscoelastic Continuum Damage (S-VECD) model, finding that as aging time increased, fatigue resistance declined [23]. Researchers have also tested the fatigue characteristics of aged asphalt binders using regenerators. Jacobs et al. used the linear amplitude sweep (LAS) test to measure the fatigue characteristics of reclaimed asphalt pavement and found that the rejuvenator improved the fatigue life of regenerated asphalt binders without compromising their high-temperature performance [24]. Cao et al. studied the effects of bio-oil regenerants on the fatigue performance of asphalt binders aged for different durations and found that longer aging resulted in lower fatigue life [25]. Understanding the fatigue behavior of both aged and regenerated asphalt is crucial for ensuring the long-term durability and sustainability of pavement structures. Since aging diminishes the binder's resistance to fatigue cracking, proper evaluation helps in optimizing the dosage of rejuvenators, ensuring that the mechanical properties are restored while maintaining structural integrity. This is essential for enhancing pavement life, especially with the growing focus on recycling asphalt and reducing environmental impacts.

Existing research has investigated the aging and regeneration processes of asphalt pavements, particularly focusing on the effectiveness of rejuvenators in restoring the performance of aged asphalt. Various models and methods, such as the time–temperature superposition principle (TTSP), by shifting the complex modulus curves at different aging times, can be used to construct a time–temperature–aging (TTA) equivalent master curve for predicting asphalt performance. The previously discussed research methods, while valuable, have certain limitations that need to be addressed for a more comprehensive understanding of asphalt behavior. Specifically, these methods fail to clearly delineate the relationships between different modes of asphalt aging, the duration of aging, and the corresponding shift factor that is often used to predict material behavior under varying conditions. This gap in the methodology creates uncertainty in accurately modeling how asphalt will perform over time as it ages. Moreover, when considering the rejuvenation of aged asphalt, the connection between the shift factor and the quantity of rejuvenator used is not well defined. This lack of clarity impedes our ability to establish a reliable framework for predicting the dynamic mechanical properties of rejuvenated asphalt. Without a better understanding of these relationships, it becomes challenging to forecast how both aged and rejuvenated asphalt will behave under different loading and environmental conditions, which is critical for the effective design and maintenance of asphalt pavements. Therefore, further research is needed to elucidate these relationships and enhance the predictive accuracy of asphalt performance models. This study predicted the dynamic mechanical properties and fatigue life of aged–rejuvenated asphalt using complex modulus aging and rejuvenation master curves, along with the S-VECD model, under various aging conditions and rejuvenator admixtures. The aim of this study is to predict the dynamic properties of aged and rejuvenated asphalt binders, focusing on the effects of aging and rejuvenator dosage on the material's rheological and fatigue performance. By subjecting virgin asphalt to varying degrees of aging and rejuvenating the aged binder with different rejuvenator dosages, this research seeks to elucidate how these factors influence the complex modulus of asphalt. The study employs the master curve of the complex shear modulus, using the CAM model and curve-shifting techniques, to construct time–temperature–aging (TTA) and time–temperature–regenerator (TTR) master curves for accurate predictions of the asphalt's performance. Additionally, the research evaluates the fatigue performance and material integrity of both aged and rejuvenated asphalt under different strain conditions, aiming to provide valuable insights for optimizing the use of reclaimed asphalt pavement (RAP) in sustainable road construction.

2. Materials

2.1. Asphalt Binders

The virgin asphalt used in this study is SK70 matrix asphalt. Its essential performance properties were tested according to the (JTG E20-2011) [26], and test results are presented in Table 1.

Table 1. Physical properties of matrix asphalt.

Property	SK70	Test Method
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	57.3	T0604
Ductility (5 cm/min, 10 °C)	77.3	T0605
Softening point (°)	46.9	T0606
Viscosity (135°, Pa·s)	0.37	T0625

2.2. Rejuvenator

A generic rejuvenator was adopted in this study, and its properties are presented in Table 2.

Table 2. Essential properties of rejuvenator.

Property	Test Result	Technical Specifications	Test Method
Viscosity (60 °C, mm^2/s)	55	≥50	T0619
Flash point (°C)	234	≥220	T0611
RTFOT Viscosity ratio	1.02	≤3	T0619
RTFOT Mass Change (%)	−0.32	≤±4	T0609
Saturation content (%)	11.31	≤30	TLC-FID
Aromatic content (%)	78.8	-	TLC-FID

2.3. Specimen Preparation

As the actual aging station could be simulated in a laboratory aging process based on Kim and Saleh et al.'s study [14], this study prepared asphalt binders at three aging stages: original SK70 asphalt, short-term-aged asphalt binders at different aging times, and long-term-aged asphalt binders at different aging times. The short-term-aged asphalt binders were prepared using the Thin Film Oven Test (TFOT) at a temperature of 163 °C, with five aging durations: 5, 10, 20, 30, and 40 h, to simulate thermal–oxidative aging. The long-term-aged asphalt binders were prepared using the Pressurized Aging Vessel (PAV) at 100 °C and 2.1 MPa, with two aging durations: 20 and 40 h on TFOT-aged asphalt binders (5 h). The rejuvenation procedure was as follows: the aged asphalt (PAV: 20 h) was heated to 135 °C, and the rejuvenator was added. The mixture was then blended for 20 min at 3000 rpm in a mixer.

3. Experimental Methods

3.1. Design of Experiments

An AR2000 dynamic shear rheometer (DSR) by TA Instruments (New Castle, DE, USA) was employed to measure the rheological performance of asphalt binders. The temperature–frequency and LAS tests were conducted using plates with diameters of 8 mm and 25 mm, following AASHTO T315 standards [27]. Temperature–frequency sweep tests were performed at six temperatures: 20 °C, 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C, across frequencies ranging from 0.1 to 15.9 Hz. To ensure the test results were within the linear viscoelastic (LVE) range of the asphalt binder, a linear amplitude sweep (LAS) was applied with a strain amplitude of 1% across all test frequencies and temperatures. The LAS tests included a frequency sweep within the LVE range and an oscillatory strain amplitude sweep, following AASHTO TP 101 [28].

3.2. Christensen–Anderson–Marasteanu (CAM) Model

Based upon the time–temperature superposition principle, the master curve of the asphalt binder's dynamic shear modulus was established by multiple temperature and frequency sweep test results, and the CAM model was applied to fitting the complex modulus master curve [29,30]. Yusoff et al. demonstrated that the CAM model provides a better fit for the complex modulus master curve compared to the CA model [31]. Therefore, this study employs the CAM model to fit the complex modulus master curve of asphalt binders under different aging and regenerating conditions. The fitting of the CAM model is shown in Figure 1, and the shape parameter can be described in Equation (1).

$$|G^*| = \frac{G_g^*}{\left[1+f_c/(f)^k\right]^{m/k}} \tag{1}$$

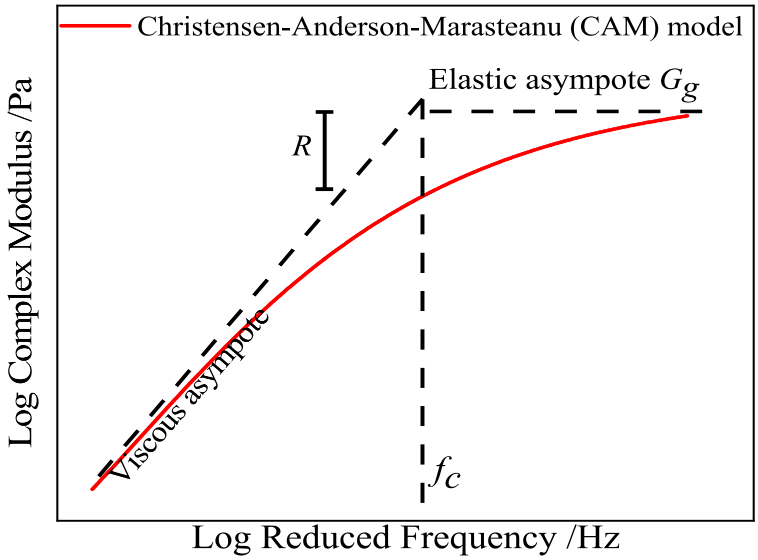

Figure 1. Fitting the complex modulus master curve for the CAM model.

Here, G_g^* is the glassy complex modulus, f is actual loading frequency, f_c is the cross frequency, and m and k are the master curve fitting parameters. The shape parameter, m, represents the slope of the third asymptote of the complex modulus's primary curve. A smaller slope of the asymptotic line indicates that the asphalt is less sensitive to frequency, suggesting better viscoelastic performance at both high and low temperatures. The parameter k determines how rapidly the complex modulus master curve converges with the two asymptotes as the frequency approaches zero or infinity.

3.3. Simplified Viscoelastic Continuum Damage Model

The viscoelastic continuum damage (VECD) model is based on Schapery's mechanical theory. It was applied to predict the fatigue life of asphalt materials of different scales. In the library, the relation of modulus and strain obtained from the LAS test was selected to calculate the fatigue life of asphalt according to the VEDC model [16]. However, the calculation process is quite complex. To reduce the calculation process, Underwood et al. simplified the VECD model to make it more effective and predict the fatigue life of asphalt successfully. In the S-VECD model, the peak pseudostrain in any loading cycle is defined as shown in Equation (2):

$$\gamma_P^R = \frac{1}{G_R}(\gamma_P |G^*|_{LVE}) \tag{2}$$

In which γ_P is the peak pseudostrain in the loading cycle, $|G^*|_{LVE}$ is the complex modulus of the material in the linear viscoelastic range, and G_R is the reference modulus, which was set to 1.

At the beginning of the amplitude sweep process, the material exhibits linear viscoelasticity, while the pseudostrain value decreases as the material's damage level increases. Therefore, the pseudostrain value can be calculated to analyze the damage evolution characteristics of the material, referred to as the material integrity coefficient, $C^*(S)$, and the DMR is the dynamic modulus ratio, shown in Equations (3) and (4).

$$C^*(S) = \frac{\tau_P}{\gamma_P^R \times DMR} \tag{3}$$

$$DMR = \frac{|G^*|_{Fingerprint}}{|G^*|_{LVE}} \tag{4}$$

In which τ_P is effective peak shear stress, and $|G^*|_{Fingerprint}$ is the initial complex modulus measured.

To calculate the nonlinear viscoelastic properties of the material during loading, the nonlinear viscoelastic complex modulus, $|G^*|_{NLVE}$, is substituted for the linear viscoelastic complex modulus, $|G^*|_{LVE}$, during the strain sweep, and the internal damage evolution variable $S(t)$ is shown in Equations (5)–(7).

$$\gamma_P^R NLVE = \frac{1}{G_R}(\gamma_P |G^*|_{NLVE}) \tag{5}$$

$$S(t) = \sum_{i=1}^{n} \left[\frac{DMR}{2} (\gamma_{P,i}^R)^2 (C_{i-1}^* - C_i^*) \right]^{\frac{\alpha}{\alpha+1}} (t_{Ri} - t_{Ri-1})^{\frac{1}{\alpha+1}} \tag{6}$$

$$t_R = \frac{t_i}{\alpha_T} \tag{7}$$

In which t_R is the reduced time, i is the cycle number, α is a non-damaged material constant, m is the fitting slope parameter of the linear viscoelastic dynamic shear modulus master curve, and n is the maximum load time. When the damage characteristic curve, $S(t)$, is independent of loading duration and temperature, the test results can predict the damage evolution in a material subjected to a given loading duration.

As fatigue damage accumulates within the asphalt material, fatigue breakdown occurs when a critical damage state is reached, which destroys material cohesion, and reduces the asphalt mixture's fatigue life. This paper evaluates the fatigue life of aged and regenerated asphalt using the pseudostrain energy release rate, G^R, and fatigue life, N_f, to predict fatigue performance more scientifically. The pseudostrain energy released, W_r^R, represents the difference between the total pseudostrain energy and the stored pseudostrain energy, and the mean pseudostrain energy release rate, G^R, is shown in Equations (8) and (9).

$$W_r^R = \frac{1}{2}(1 - C^*)(\gamma_p^R)^2 \tag{8}$$

$$G^R = \frac{\overline{W_r^R}}{N_f} = \frac{TRPSE}{{N_f}^2} \tag{9}$$

In which $TRPSE$ is the area of the curve before the point of damage and $\overline{W_r^R}$ is the mean virtual strain energy released. The relation between the mean virtual strain energy release rate, G^R, and the fatigue life constitutes the damage criterion of the material, and the relation formula is shown in Equation (10).

$$G^R = a{N_f}^b \tag{10}$$

The relation between the material's final fatigue life, N_f, and the strain, γ_p, is shown in Equation (11).

$$N_f = \left(\frac{A}{a}\gamma_p^{2+2\alpha C_2/K}\right)^{\frac{1}{b+1-C_2/K}} \quad (11)$$

In which C_1 and C_2 are optimized fitting parameters that are also the change rate parameters of the strength damage evolution associated with $C^*(S)$, A and K are calculated parameters, and a and b are material failure criterion parameters.

4. Results and Discussion

4.1. Impact of Aging on the Complex Modulus and Viscoelastic Behavior of Asphalt Binders

The complex modulus master curves of asphalt binders under different aging conditions were constructed using the least squares method, with T_{ref} taken at 40 °C. The CAM model was then applied to fit the master curve of the complex modulus, as shown in Figure 2. Compared to the original asphalt, the complex shear modulus of aged asphalt significantly increases with the extension of aging time. Comparing the effects of TFOT and PAV aging on asphalt over the same duration (Figure 2a,b) revealed that the TFOT aging has a more pronounced effect on the complex modulus of asphalt than that of PAV aging. Meanwhile, Figure 2 indicates that the differences in the complex modulus of asphalt with various aging times are more pronounced at a low frequency than that at a high frequency. According to free volume theory of polymers, asphalt binders exhibit the same time–temperature dependence as polymer materials. That means an increase in temperature causes the volume within the asphalt binders to expand, the free space between molecules to increase, and the restriction on molecular movement to decrease, resulting in a decrease in the complex modulus at high temperatures and low frequencies.

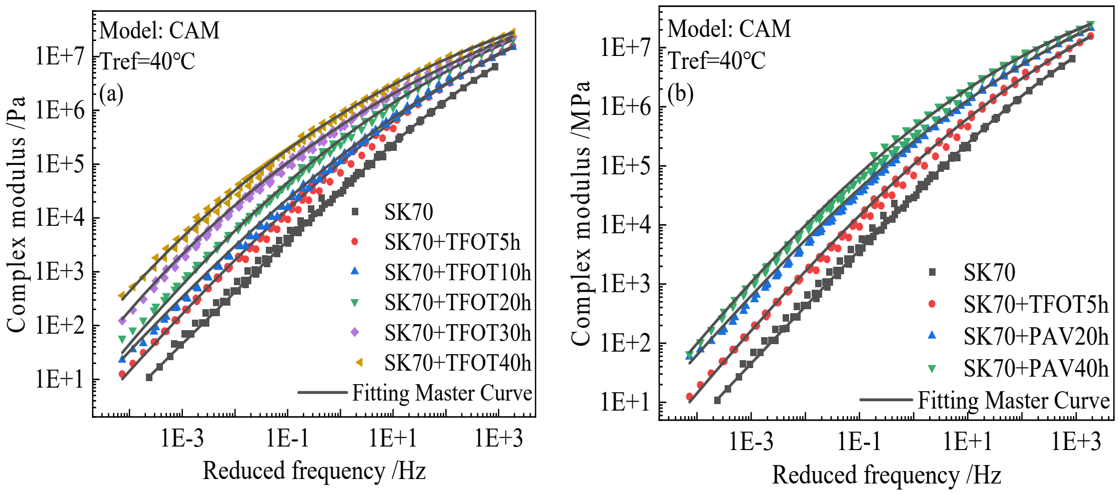

Figure 2. Evolution of complex modulus with different aging times (**a**) TFOT; (**b**) PAV.

Table 3 presents the CAM fitting parameters for both original and aged asphalt binders. The values of the fitted correlation coefficients, R^2, indicate that the CAM model can effectively fit the complex modulus master curve of the asphalt binders with varying degrees of aging. Therefore, the model parameters can be applied to analyze the impact of aging on the performance of bitumen.

Table 3. CAM model parameters for unaged and aged asphalt binders.

Aging Methods	f_c/Hz	k	m_e	R^2
SK70	4.02×10^{3}	0.955	0.976	0.9999
SK70 + TFOT5h	1.69×10^{2}	2.012	1.204	0.9990
SK70 + TFOT10h	2.46×10^{1}	2.365	1.278	0.9986
SK70 + TFOT20h	2.70×10^{-1}	2.943	1.598	0.9991
SK70 + TFOT30h	3.35×10^{-8}	3.556	3.182	0.9990
SK70 + TFOT40h	3.98×10^{-17}	4.451	8.848	0.9993
SK70 + PAV20h	4.90×10^{1}	1.924	1.162	0.9990
SK70 + PAV40h	6.55	1.987	1.353	0.9994

According to the changes observed in the frequency division parameter f_c, it is evident that as the aging time increases, the f_c value gradually decreases. This phenomenon indicates that, during the aging process of asphalt, the viscous deformation region of the material gradually diminishes, while the elastic deformation region relatively increases. This implies that aging induces more elastic behavior in the asphalt material, reducing its capacity for viscous deformation. This change may be attributed to the evaporation of light components in the asphalt, oxidative reactions, and other chemical changes during the aging process, which result in a more rigid internal structure of the asphalt. Consequently, its viscous properties decrease, and its elastic properties are enhanced. Such changes in characteristics have implications for the long-term performance of asphalt pavements, as an increase in elastic deformation may lead to a greater likelihood of cracks or other forms of damage under external loading conditions. m_e is defined as the slope of the third asymptote of the complex modulus master curve, a parameter that quantifies the material's sensitivity to variations in temperature and frequency. This parameter is crucial in characterizing the viscoelastic behavior of asphalt binders, under different thermal and loading conditions. A higher m_e value indicates that the material exhibits greater sensitivity to changes in temperature and frequency, implying that its mechanical properties, including stiffness and deformation characteristics, are more susceptible to alterations under varying environmental conditions. Table 3 shows that the m_e value tends to increase with prolonged aging of asphalt materials. This trend suggests that the aging process, which may involve oxidative hardening, loss of volatile components, and other chemical or physical changes, enhances the material's sensitivity to temperature and frequency fluctuations. As a result, aged asphalt becomes more prone to performance issues such as cracking at low temperatures, indicating a degradation in its low-temperature flexibility.

4.2. Impact of Rejuvenator on the Complex Modulus and Viscoelastic Properties of Aged Asphalt Binders

The complex modulus master curves of asphalt binders under different rejuvenator dosages were constructed using the least squares method at 40 °C, followed by the application of the CAM model to fit the master curves, as shown in Figure 3. With the increasing dosage of the rejuvenator, the complex modulus of the aged asphalt binder progressively diminishes. Notably, when the rejuvenator dosage reaches 6%, the complex modulus of the regenerated asphalt becomes comparable to that of the original asphalt. This indicates that the addition of 6% rejuvenator is sufficient to restore the mechanical properties of the aged asphalt to a level similar to that of the original material. The fitting parameters of the CAM model for the complex modulus master curve of the regenerated asphalt binder are presented in Table 4. The CAM model's fitting correlation coefficients (R^2) for the complex modulus master curves of the regenerated asphalt binders are all above 0.998, demonstrating that the CAM model is highly effective in fitting the complex modulus master curves of regenerated asphalt binders. As the rejuvenator dosage increased, the f_c value of the regenerated asphalt increased gradually, while the m_e value decreased gradually, indicating that rejuvenator can improve the low-temperature performance and temperature sensitivity of aged asphalt binders. Composed primarily of low-molecular-weight aromatic oils, the rejuvenator exhibits a viscous flow state within the test temperature range of 20 to 70 °C, along with excellent low-temperature ductility and temperature sensitivity. These characteristics enable the rejuvenator to restore the flexibility and resilience of aged asphalt, thereby enhancing its resistance to low-temperature cracking and reducing its sensitivity to temperature fluctuations. Consequently, the addition of a rejuvenator significantly improves the low-temperature crack resistance and temperature stability of the regenerated asphalt binder, making it more durable under varying environmental conditions.

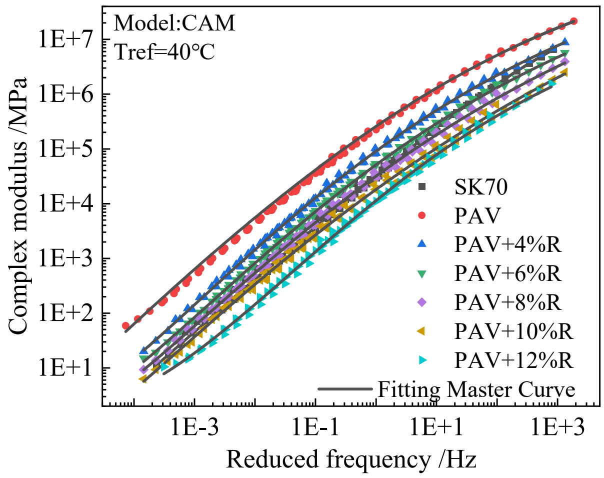

Figure 3. Temperature master curves at different regenerator dosages.

Table 4. CAM model parameters for regenerated asphalt binders.

Regeneration	f_c/Hz	k	m_e	R^2
SK70	4.02×10^3	0.955	0.976	0.9999
SK70 + PAV20h	4.90×10^1	1.924	1.162	0.9990
PAV + 4%R	4.54×10^3	1.895	0.905	0.9989
PAV + 6%R	4.95×10^4	1.803	0.849	0.9994
PAV + 8%R	2.58×10^6	1.252	0.816	0.9990
PAV + 10%R	1.62×10^7	0.061	0.737	0.9980
PAV + 12%R	1.33×10^8	0.002	0.674	0.9982

4.3. Construction and Prediction of Asphalt Complex Modulus Master Curve Based on Time–Temperature–Aging (TTA) Superposition Principle

The observation of master curves of the asphalt complex modulus at different aging times reveals that the master curves are essentially parallel. This pattern is similar to the curves obtained from frequency sweeps at different temperatures. The influence of aging time on the complex modulus of asphalt can be addressed by referencing the time–temperature superposition principle. The time–temperature superposition principle is an important method in the study of asphalt material behavior, demonstrating that within a certain range, the effects of temperature and time on the material's mechanical properties are equivalent. Therefore, the material response at different temperatures can be normalized into a single master curve through time shifting. Similarly, for the effect of aging time on the asphalt complex modulus, if the master curves at different aging times are found to be essentially parallel, the time–temperature superposition principle can be analogized. By shifting the complex modulus curves at different aging times, a time–temperature–aging (TTA) equivalent master curve can be constructed. Specifically, the steps to construct such an equivalent master curve may include the following:

(1) Determine a reference state: first, select a reference aging time and temperature as the baseline for constructing the master curve.

(2) Curve shifting: by appropriately shifting the curves (along the time or frequency axis), align the complex modulus curves at other aging times or temperatures with the master curve at the reference state.
(3) Construct the equivalent curve: after completing the curve shifts, integrate all the data points to form the time–temperature–aging equivalent complex modulus master curve.

This method treats aging as a factor similar to temperature, and by applying appropriate shifts, achieves equivalence between aging, time, and temperature. The TTA superposition principle provides an effective tool for studying the mechanical properties of asphalt materials under different aging times and temperature conditions, aiding in a better understanding of the long-term performance of asphalt [32]. In this study, the original asphalt (0 h) was applied as the reference state and the least squares method was employed to shift the complex modulus master curves at different aging times to the reference state, thereby constructing the time–temperature–aging master curve (Figure 4). During this process, the shift factors corresponding to the master curves at each aging level were also obtained. By analyzing the relationship between the shift factors and aging time, it is possible to accurately predict the complex modulus of asphalt at different aging times. The aging shift factors obtained at different aging times using the time–temperature–aging superposition method are shown in Figure 5. Aging shift factors for different aging methods (TFOT and PAV) significantly increase with aging time. A strong linear correlation is observed between the aging shift factors and aging time, with correlation coefficients greater than 0.975. Therefore, it can be concluded that the relationship between aging shift factors and aging time can be used to accurately predict the complex modulus of asphalt under different aging methods and times.

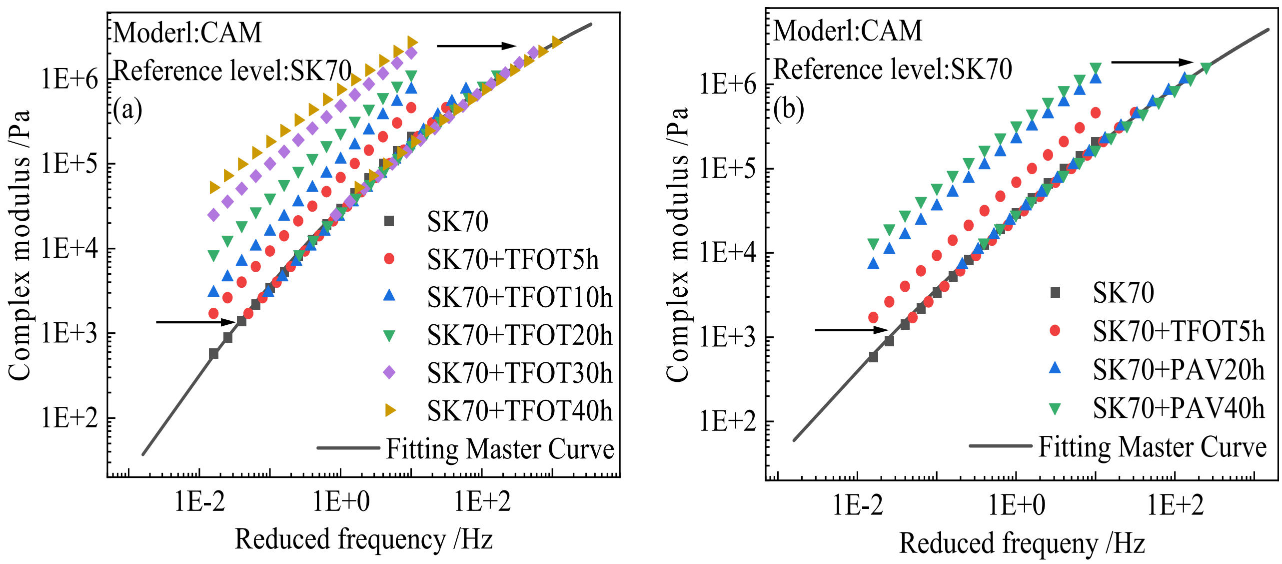

Figure 4. TTA master curves of complex modulus for asphalt binders with different aging times: (**a**) TFOT; (**b**) PAV.

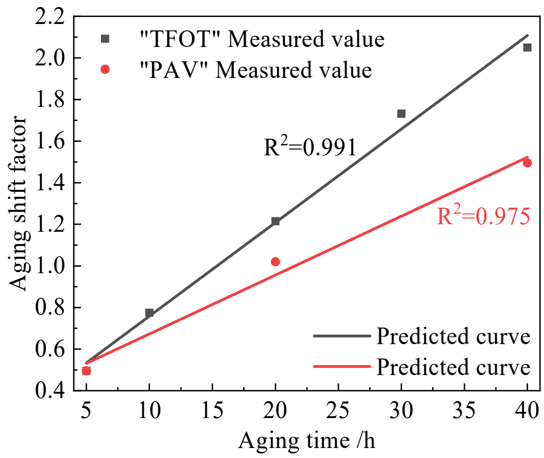

Figure 5. Relations between aging shift factors and aging time at the different aging times.

4.4. Prediction Regenerated Asphalt Complex Modulus Master Curve Based on Time–Temperature–Regenerator (TTR) Superposition Principle

Based on the parallel relationship observed between the complex modulus master curves of regenerated asphalt at different regenerator dosages and the original asphalt complex modulus master curve, this study further employs the least squares method to construct the TTR complex modulus master curve of regenerated asphalt. In this process, the complex modulus master curve of asphalt aged for 20 h was used as the reference state, and the complex modulus master curves of regenerated asphalt with varying regenerator dosages were shifted to the left to construct the time–temperature–regenerator complex modulus master curve (Figure 6). Simultaneously, shift factors associated with the regenerator dosage were extracted. Figure 7 illustrates the regenerator dosage shift factors determined using this method. The results indicate that as the regenerator dosage increases, the shift factor exhibits a decreasing trend. This phenomenon suggests a significant linear relationship between the regenerator dosage and the shift factor. Furthermore, by comparing the calculated regenerator shift factor curve with the predicted curve, it is evident that the error between the two is minimal, indicating that this method possesses a high degree of predictive accuracy. Consequently, the regenerator dosage shift factor can serve as an effective tool for predicting the complex modulus of regenerated asphalt under various regenerator dosage conditions. This method not only provides a theoretical foundation for predicting the performance of regenerated asphalt but also offers practical guidance for optimizing regenerator dosages in engineering applications.

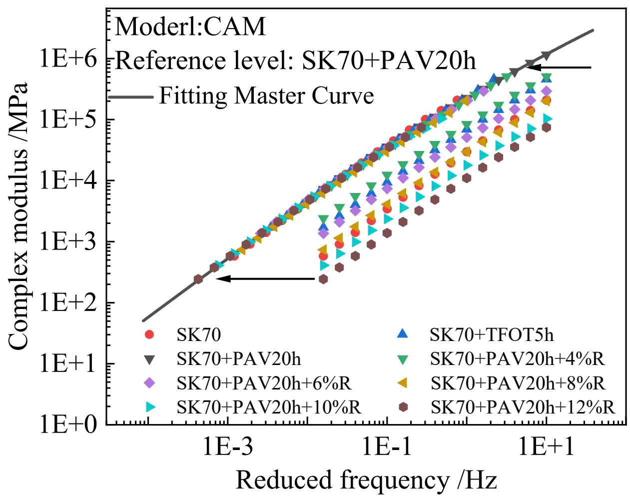

Figure 6. TTR master curve with different rejuvenator dosages.

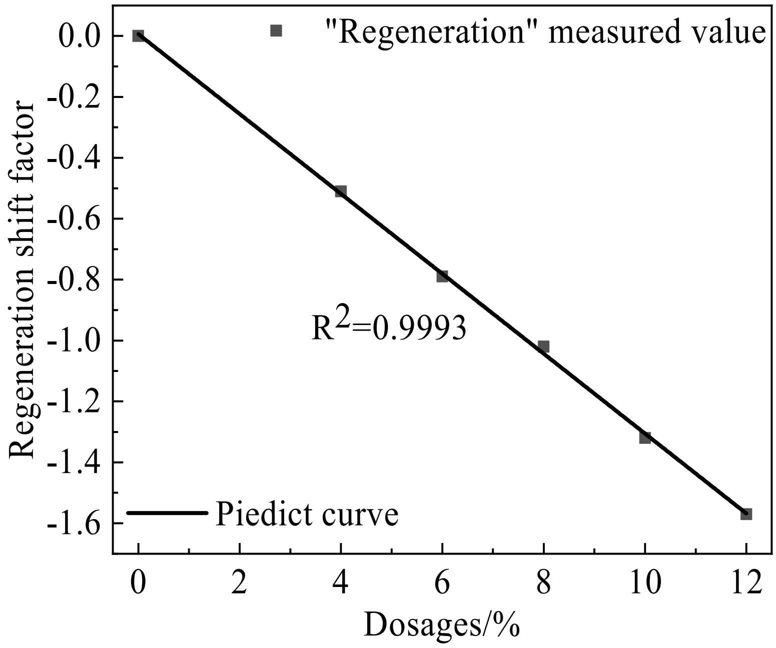

Figure 7. Relation between regeneration shift factors and rejuvenator dosages.

4.5. Material Integrity Analysis of Aged and Regenerated Asphalt Fatigue Performance

LAS test shear stress–strain curves for various levels of aged and regenerated asphalt are illustrated in Figure 8. These curves are employed to determine the breakdown strain of asphalt and to analyze the strain dependence of the material's properties. The width of the curve at its peak is indicative of the material's strain dependence. The analysis presented in Figure 8 demonstrates that aging narrows the peak width of the asphalt binder's LAS stress–strain curve, signifying an increased dependence on stress and strain as the aging level rises. Conversely, the inclusion of the regenerant causes the peak width of the stress–strain curve for the regenerated asphalt to broaden, indicating that the regenerant mitigates the stress dependence of the asphalt binder. Aging leads to an increase in the rigidity and brittleness of the asphalt binder. As the binder undergoes aging, like under TFOT and PAV conditions, its molecular structure becomes more cross-linked, and the material loses its original flexibility. This narrowing of the peak width reflects an increased strain dependence, meaning that the material becomes more sensitive to changes in stress and strain. The asphalt binder's ability to deform elastically is reduced, leading to a more pronounced stress–strain response in a narrower range of strains. The addition of a regenerant (rejuvenator), on the other hand, restores some of the flexibility and viscoelastic properties of the aged asphalt binder. Regenerants work by reintroducing light oils or maltenes that help to soften the asphalt, reducing the cross-linking that occurs during aging and improving its ability to deform under stress. The broadened peak width seen in the stress–strain curve of the regenerated asphalt indicates a reduced strain dependence, meaning that the material becomes more resilient and less sensitive to changes in stress and strain over a wider range. The regenerant helps to mitigate the material's brittleness, improving the ductility and fatigue resistance of the asphalt by increasing its ability to deform more uniformly under stress.

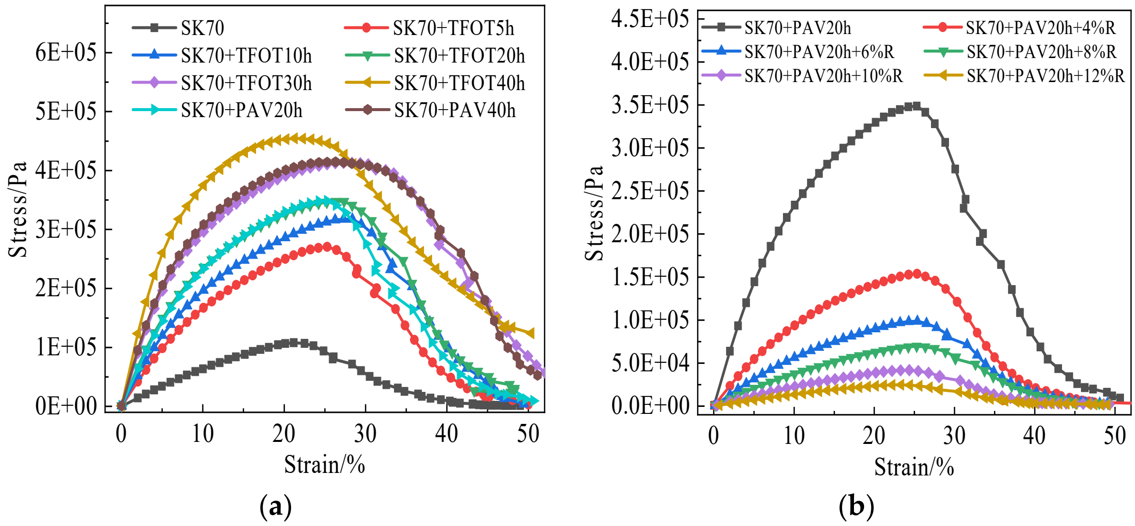

Figure 8. The LAS test strain–stress curves for aged (**a**) and regenerated asphalt binders (**b**).

Figure 9 illustrates the relationship between the material integrity factor $C^*(S)$ and the strength damage parameter $S(\mathrm{t})$ for various levels of aged and regenerated asphalt. As the aging time increased, the material integrity values at failure indicated a gradual decrease in the material's resistance to damage, ultimately impacting the asphalt's fatigue life. However, the addition of the regenerant resulted in a lower integrity value factor at failure, which enhanced the material's resistance to damage and subsequently improved the fatigue performance of the aged asphalt. The fitting parameters α and β were derived from the nonlinear fitting of the S-VECD model data, with the corresponding curve fitting parameters and slopes detailed in Table 5. α is a damage parameter used to characterize and model the extent of damage within the material. In this study, α was utilized to fit the energy storage modulus for various levels of aging and regeneration. As the aging time increased, α decreased due to a reduction in the material's maximum relaxation rate, which corresponds with higher levels of aging. Conversely, when different dosages of regenerant were introduced to the aged asphalt, α also decreased. This reduction occurred because the regenerant enhanced the material's maximum relaxation rate and increased the viscosity of the regenerated asphalt.

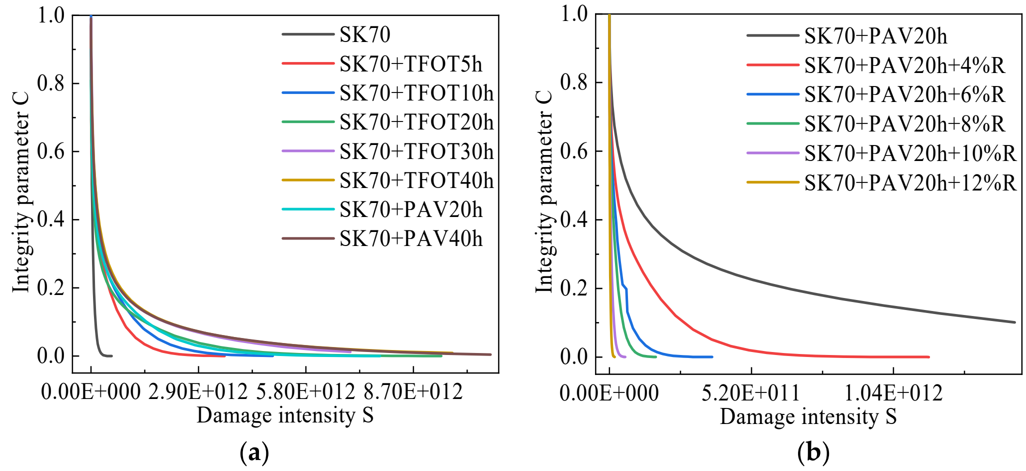

Figure 9. Damage characteristic curves of aged (**a**) and regenerated asphalt (**b**).

Table 5. Slope and damage parameters of aged and regenerated asphalt.

Asphalt	α	C_1	C_2	R^2
SK70	2.054156	0.000167	0.329662	0.9979
SK70 + TFOT5h	2.271325	0.000189	0.306717	0.9951
SK70 + TFOT10h	2.369731	0.000253	0.292416	0.9946
SK70 + TFOT20h	2.470602	0.007556	0.242607	0.9935
SK70 + TFOT30h	2.650436	0.001405	0.168638	0.991
SK70 + TFOT40h	2.892544	7.63×10^{-5}	0.223471	0.9985
SK70 + PAV20h	2.38692	0.001642	0.273924	0.9943
SK70 + PAV40h	2.584196	0.000152	0.223331	0.9967
SK70 + PAV20h + 4%R	2.283139	3.96×10^{-5}	0.286903	0.9973
SK70 + PAV20h + 6%R	2.222211	0.000431	0.349668	0.9924
SK70 + PAV20h + 8%R	2.187286	0.000143	0.350461	0.9914
SK70 + PAV20h + 10%R	2.142417	0.00021	0.390778	0.9928
SK70 + PAV20h + 12%R	2.127048	0.00015	0.441002	0.9911

The failure criterion, based on damage characterization within the S-VECD model, is employed to evaluate and predict the fatigue performance of asphalt materials. This criterion demonstrates a stronger correlation within the relationship model developed by Sabouri and Kim [33]. Figure 10 illustrates the relationship between the fatigue failure criterion and various levels of aging and regenerated asphalt, which can be utilized to estimate fatigue life under different loading conditions. The figure shows that aging caused the $G^R - N_f$ fitting curve to shift upward, with the most pronounced shift occurring after a TFOT of 5 h aging, indicating that short-term aging has a significant impact on fatigue life. Conversely, the addition of the regenerator caused the $G^R - N_f$ curve to shift downward, suggesting that the regenerator reduced the rate of damage accumulation during fatigue testing and significantly enhanced the fatigue life of the regenerated asphalt. Figure 11 presents the fatigue life under varying strain conditions for different levels of regeneration and aging. The figure illustrates that the fatigue equation, which relates N_f to strain, provides a strong fit, with the slope of the equation indicating the material's sensitivity to N_f under strain. At lower strain levels, the fatigue life of aged asphalt increased with longer aging times, and it was observed that TFOT aging had a more pronounced effect on fatigue life than PAV aging for the same duration. Conversely, under high strain conditions, the traditional view holds true: the longer the aging period, the shorter the fatigue life of the asphalt. The relationship between the fatigue life and strain of regenerated asphalt exhibited a markedly different trend compared to that of aged asphalt when varying dosages of rejuvenator were added. Under low strain conditions, the fatigue performance of regenerated asphalt gradually approached that of the original asphalt as the dosage of rejuvenator increased. In contrast, under high strain conditions, the higher the dosage of rejuvenator, the greater the fatigue life of the regenerated asphalt. The underlying reasons for this behavior remain unclear and may be linked to the complex mechanisms involved in the aging and regeneration processes, as suggested by some studies [16,20,34].

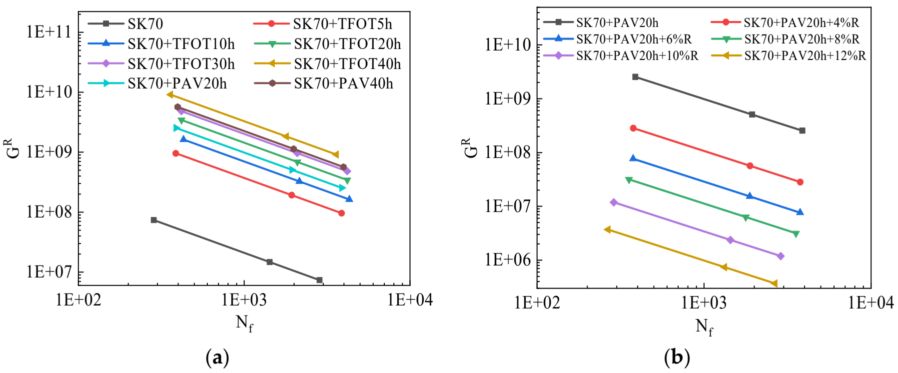

Figure 10. G^R and N_f curves of aged (**a**) and regenerated asphalt (**b**).

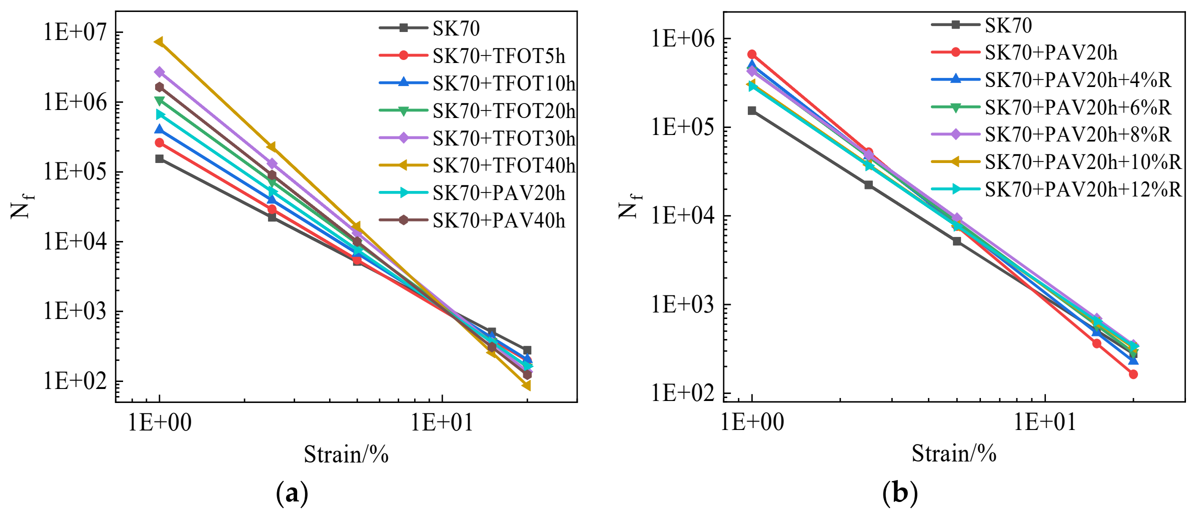

Figure 11. Aged (**a**) and regenerated (**b**) asphalt's fatigue life under various strain levels.

5. Conclusions

In this study, aging and regeneration master curves of the complex modulus for various asphalt binders were developed based on the time–temperature–aging–regeneration superposition principle. First, frequency sweep tests were conducted on aged and rejuvenated asphalt binders at various temperatures. Second, complex modulus master curves were constructed, and the CAM model was applied to fit these curves. The viscoelastic properties of asphalt at different aging levels and rejuvenator dosages were then analyzed based on the CAM parameters. Next, by applying a curve-shifting technique based on the least squares method to the reference state, both the time–temperature–aging (TTA) and time–temperature–regenerator (TTR) master curves of the complex modulus were constructed. Finally, the relationships between aging shift factors and aging times, as well as between regenerator shift factors and dosages, were established to predict the complex modulus of both aged and rejuvenated asphalt. The following conclusions can be drawn:

(1) Aging significantly increases the complex modulus, especially under TFOT aging compared to PAV aging. The CAM parameters can effectively explain the impact of aging on asphalt, revealing that aging reduces the viscous deformation and increases elastic behavior, making asphalt more prone to cracking under low-temperature conditions. Additionally, aging enhances the material's sensitivity to temperature and frequency changes.

(2) Increasing rejuvenator dosage reduces the complex modulus of aged asphalt, with 6% rejuvenator restoring its mechanical properties to near-original levels. As the rejuvenator dosage increases, the low-temperature performance and temperature sensitivity of the asphalt improve. Rejuvenators enhance flexibility, reduce temperature sensitivity, and improve resistance to low-temperature cracking, thereby enhancing the durability of regenerated asphalt under varying conditions.

(3) The master curves of the asphalt complex modulus with different aging times are essentially parallel, similar to the results observed in frequency sweeps at varying temperatures. With the original asphalt serving as the reference state and by curves shifting based on the least squares method, a time–temperature–aging equivalent master curve of the complex modulus was constructed, and aging shift factors were obtained. A strong linear correlation ($R^2 > 0.975$) between aging shift factors and aging time was observed, enabling accurate prediction of the asphalt complex modulus under different aging conditions.

(4) The time–temperature–regenerator complex modulus master curve of regenerated asphalt was constructed using the least squares method. By shifting the complex modulus master curves of regenerated asphalt with different regenerator dosages

to the reference state, shift factors were determined. Results show a significant linear relationship between regenerator dosage and shift factor, with the shift factor decreasing as dosage increases. The minimal error between calculated and predicted curves demonstrates high predictive accuracy, making this method a valuable tool for predicting the complex modulus and optimizing regenerator dosages in engineering applications.

(5) Aging narrows the stress–strain curve's peak, indicating increased stress dependence, while adding a regenerant broadens it, enhancing fatigue life. The study also explores how different levels of aging and regenerant dosage affect fatigue life under varying strain conditions, revealing complex behaviors influenced by the aging and regeneration processes.

The findings of this study provide practical guidance for improving the performance of both aged and rejuvenated asphalt in highway applications. By accurately predicting the effects of aging and rejuvenation on asphalt's dynamic properties, engineers can better design pavements that are both durable and sustainable, optimizing the use of recycled materials and enhancing the overall performance of road networks.

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