Research of recyclable epoxy asphalt regeneration approach

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ABSTRACT: The present study serves as an extension of the recyclable epoxy asphalt regeneration process, providing additional details on the rejuvenator proportion employed. Specifically, a comprehensive analysis of the rejuvenator proportion is conducted based on the rheological performance of the asphalt phase in recyclable epoxy asphalt. Through dynamic shear rheometer and bending beam rheometer experiments, it has been determined that an optimal proportion of 8% rejuvenator effectively restores the rheological performance of aged asphalt phase in recyclable epoxy asphalt. Following regeneration, a significant recovery in complex modulus is observed compared to the aged sample, thereby demonstrating the efficacy of this regeneration approach.

1 INTRODUCTION

Epoxy asphalt serves as a fundamental construction material, extensively utilized in the orthotropic steel deck systems of long-span bridges. The commercial epoxy asphalt products exhibit exceptional tensile strength, long-lasting durability, and high-quality pavement performance. However, the regeneration of epoxy asphalt poses a formidable engineering challenge due to the formation of irreversible covalent crosslinks. The regeneration of epoxy asphalt not only enables significant epoxy-based resource conservation but also maximizes the protection of the ecological environment, aligning with the fundamental national policy on sustainable development in transportation. Therefore, it is imperative to address this technical challenge in order to achieve epoxy asphalt regeneration.

Relevant research has been conducted thus far, with a specific focus on addressing this issue. Alamri et al. employed the epoxy asphalt mixture after milling as the aggregate to produce the asphalt mixture (Alamri et al., 2020). The implementation of this disposal method proves to be an effective approach in mitigating the accumulation of aged epoxy asphalt in landfills. Jing et al. discovered that the incorporation of a soft bituminous recycling agent positively impacted the aged epoxy asphalt, particularly in terms of its rheological properties (Jing et al., 2021; Jing et al., 2023), being a remarkable attempt to regenerate epoxy asphalt.

In our previous study, we developed a novel approach for regenerating epoxy asphalt by incorporating dynamic covalent bonds to render the irreversible covalent crosslinks reversible, while simultaneously rejuvenating the aged asphalt phase through the addition of a rejuvenator during recycling (Yi et al., 2023; Zhou et al., 2022). Thus far, a synthesis strategy and regeneration validation for recyclable epoxy asphalt embedded with the Diels-Alder reaction have been proposed, along with an optimization design. It is necessary to clarify more details on the regeneration process of recyclable epoxy asphalt. This study aims to further evaluate the impact of the regeneration process, particularly the proportion of rejuvenator, on the rheological performance of recyclable epoxy asphalt.

2 EXPERIMENTAL DETAILS

2.1 *Recyclable epoxy asphalt preparation and regeneration*

Figure 1 provides a summary of the preparation process for recyclable epoxy asphalt, where MA denotes maleic anhydride, FGE stands for furfuryl glycidyl ether, and BDMA refers to benzyldimethylamine. When used in combination with MA as the curing agent, the cured FGE can be recycled at 120 °C, facilitating the activation of the reverse Diels–Alder reaction. The material composition was determined using the surface response method, with the asphalt mass ratio set at 54%, the FGE mass ratio at 15%, and the MA mass ratio at 31%.

According to the standard of JTG E20-2011, the aging of recyclable epoxy asphalt can be simulated by subjecting it to oven heating at a temperature of 85 °C for a duration of 120 h. This process can be considered as representing a service life ranging from 5 to 7 years. Subsequently, in the regeneration process, the aged samples are initially placed in an oven at a temperature of 120 °C for a duration of 1

h. Following this step, the samples are combined with the rejuvenator and heated at 120 °C for a period of 10 min. Finally, the samples undergo a reheating process lasting for 24 h at a temperature of 70 °C.

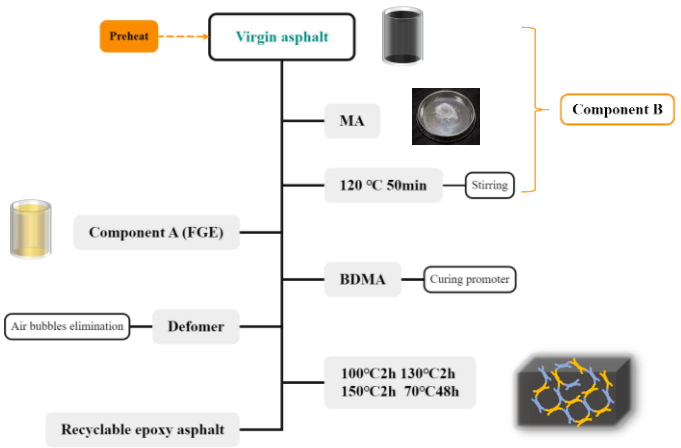

Figure 1. Preparation process of recyclable epoxy asphalt.

2.2 *Rejuvenator*

The rejuvenator utilized for enhancing the performance of aged asphalt phase consists of self-developed diffusion materials, comprising petroleum light components and bio-oil components. The related properties of rejuvenator are recorded in Table 1.

Table 1. Technical properties of the rejuvenator.

Technical indexes	Test result	Criteria
Flash point / 25 °C	230	⩾200
Saturated content / %	13.2	⩽30
Aromatics content / %	79.6	⩾60
Mass change / %	0.5	-4~4

2.3 *Rheological performance test*

The rejuvenator plays a crucial role in the recovery of aged asphalt phase during the regeneration process of recyclable epoxy asphalt. Therefore, the proportion of rejuvenator is determined based on the rheological performance of aged asphalt combined with varying concentrations of rejuvenator. To replicate the aging conditions of recyclable epoxy asphalt, virgin asphalt underwent a 120 h aging process in an oven maintained at 85 °C. Subsequently, the rejuvenator was thoroughly mixed with the aged asphalt using specific mass ratios of asphalt (6%, 7%, 8%, and 9% respectively).

The study involved conducting Frequency Sweep (FS) measurements, Linear Amplitude Sweep (LAS) tests, Multiple Stress Creep and Recovery (MSCR) tests, and Bending Beam Rheometer (BBR) experiments. All the procedures were performed in accordance with the AASHTO standard methods. The optimal proportion of rejuvenator will ultimately be determined through a comprehensive analysis of rheological properties.

3 RESULTS AND DISCUSSION

3.1 *Complex modulus*

The complex modulus of aged asphalt phase combined with different proportions were characterized with the FS test. Master curves at a reference temperature of 20 °C are determined based on the principle of time-temperature superposition, and the results are shown in Figure 2.

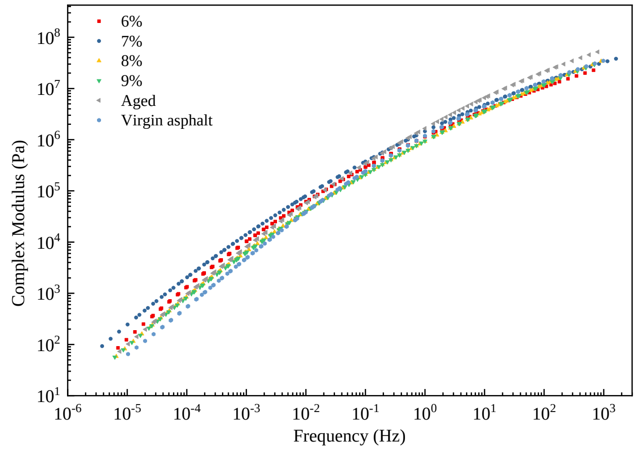

Figure 2. Master curves of complex modulus for aged asphalt.

The complex modulus of asphalt is observed to increase following a 120 h aging period. The addition of rejuvenator has an apparent influence on the complex modulus of aged asphalt. The complex modulus of the aged asphalt mixed with 6% and 7% proportions of rejuvenator is higher at lower frequencies compared to that of the aged asphalt, whereas the addition of 8% and 9% rejuvenator has minimal influence on the complex modulus of aged asphalt. At higher frequencies, the rejuvenator exerts a discernible downward influence on the complex modulus of aged asphalt, closely approximating its virgin state. The rheological performance of aged asphalt can be effectively restored by both 8% and 9% proportions of rejuvenator. Considering economic considerations, the optimal proportion for complex modulus recovery of aged asphalt is selected as 8%.

3.2 *Fatigue life*

The relationship between stress and strain was evaluated based on the LAS test, as shown in Figure 3. The stress-strain behavior of aged asphalt encompasses that of the virgin material, with consistent observation of a descending trend in stress-strain curves as the proportion of rejuvenator increases. What's more, the stress-strain curves of recycled asphalt are lower than that of the virgin asphalt.

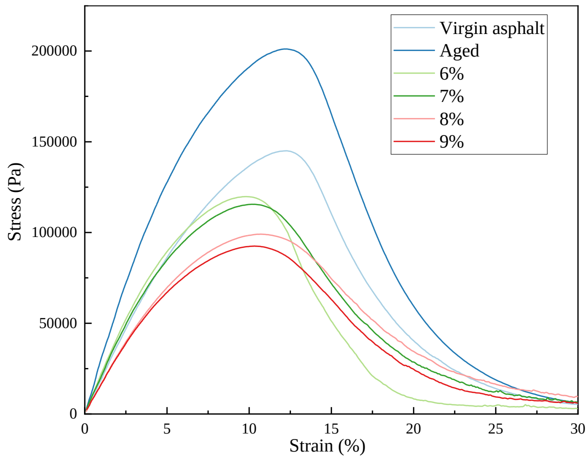

Figure 3. Stress-strain response of aged asphalt.

Then the fatigue behavior evolution of recyclable epoxy asphalt was investigated based on the stress-strain response, employing a viscoelastic continuous damage model (S-VECD). The fatigue life prediction for the aged asphalt under various strain levels is presented in Table 2. The aging process has marginally enhanced the fatigue life of asphalt under higher strain levels. However, when a rejuvenator is added, the fatigue life of aged asphalt decreases significantly compared to both its virgin state and the aged condition. The proportion of 8% has the apparent improvement on the fatigue performance.

Table 2. Fatigue life prediction for aged asphalt.

Strain / Sample	Fatigue life		
	2%	4%	6%
Virgin asphalt	70333	7603	2069
Aged	46285	7257	2455
6%	37761	4249	1184
7%	24171	3785	1279
8%	28546	4645	1606
9%	23842	3769	1281

3.3 *Rutting resistance ability*

The results of the MSCR tests conducted on aged asphalt are illustrated in Figure 4. The experimental temperature is set to be 46 °C. The MSCR test employs the average recovery percentage *R* and non-recoverable creep compliance J_{nr} as assessment indicators for evaluating rutting resistance capability.

The creep recovery percentage *R* demonstrates a slight increase following the aging process. Upon the addition of rejuvenator, *R* exhibits an upward trend in comparison to both the virgin and aged samples. The proportion of the 8% sample exhibits an obvious decrease in the recovery percentage *R* at a stress level of 3.2 kPa, closely resembling both the virgin and aged states.

The non-recoverable creep compliance J_{nr} characterizes the unrecoverable creep compliance of asphalt. After aging, the value of J_{nr} decreases at the stress level of 0.1 kPa. The incorporation of a lower amount of rejuvenator results in a reduced J_{nr} compared to the virgin and aged asphalt, indicating an improvement in elasticity and a decrease in permanent deformation. Until the proportion exceeds 8%, the aged asphalt samples demonstrate a partial yet incomplete recovery of the non-recoverable creep compliance. At the stress level of 0.1 kPa, the rutting resistance is similar to the aged samples, albeit still remaining better than that of the virgin material.

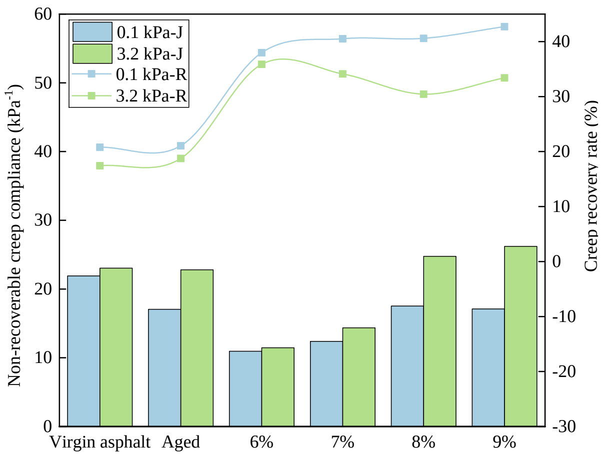

Figure 4. MSCR test results of aged asphalt.

3.4 *Low-temperature cracking resistance*

The stiffness *S* and the creep rate *m*-value can be determined through the BBR test, enabling an assessment of low-temperature cracking resistance. The BBR test was conducted at temperatures of -6 °C, -12 °C, and -18 °C, respectively. The results are recorded in Table 3.

Table 3. Stiffness and *m*-value of aged asphalt.

Sample		Temperature/ °C		
		-6	-12	-18
Virgin asphalt	*S*/MPa	13.97	54.26	153.18
	m	0.58	0.46	0.36
Aged	*S*/MPa	19.35	60.62	212.75
	m	0.53	0.43	0.34
6%	*S*/MPa	13.26	41.80	114.80
	m	0.49	0.41	0.34
7%	*S*/MPa	13.91	43.27	114.14
	m	0.49	0.41	0.33
8%	*S*/MPa	12.42	42.22	112.88
	m	0.50	0.42	0.35
9%	*S*/MPa	10.71	35.35	102.49
	m	0.50	0.42	0.34

Following the aging period, the aged asphalt demonstrates a noticeable increase in stiffness, while concurrently exhibiting a decrease in *m*-values. The results suggest the presence of a slightly slower relaxation of stress. The aged asphalt exhibits reduced resistance to low temperature performance. The stiffness has fully recovered to the virgin state after regeneration, even exhibiting a lower level. However, *m*-values solely correspond to the virgin asphalt with a higher proportion of rejuvenator; nevertheless, there remains a noticeable disparity.

3.5 *Regeneration implementation*

The rejuvenation of aged recyclable epoxy asphalt was achieved by selecting a proportion of 8% rejuvenator, taking into account the rheological performance of recycled asphalt. Ultimately, the rheological performance of aged recyclable epoxy asphalt and regenerated recyclable epoxy asphalt was compared to that of virgin recyclable epoxy asphalt in order to assess the effectiveness of regeneration.

Using the complex modulus as an illustrative example to elucidate the matter in this study. The results of complex modulus are shown in Figure 5. After aging, the recyclable epoxy asphalt displays raised stiffness over the all frequencies. Combined with the regeneration process, the complex modulus of recyclable epoxy asphalt descends to even lower values than those of virgin materials. The utilization of an 8% rejuvenator can indeed result in a superior deduction of the complex modulus of recyclable epoxy asphalt.

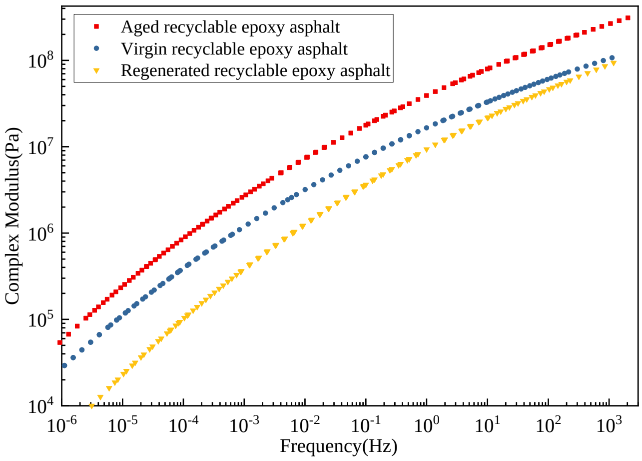

Figure 5. Master curves of complex modulus for recyclable epoxy asphalt.

To further analyze the results of complex modulus, the cross modulus at a temperature of 20 °C was derived, as shown in Figure 6.

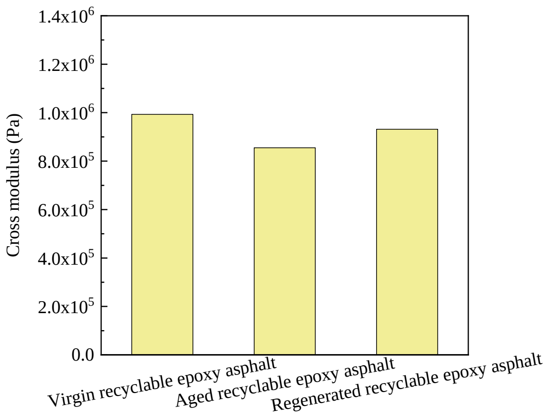

Figure 6. Cross modulus of recyclable epoxy asphalt.

After regeneration, the cross modulus exhibits an increase and approaches its initial level closely. The regenerative process demonstrates a clear ability to restore the virgin properties. The enhanced cross modulus accelerates the dynamic response of recyclable epoxy asphalt, enabling it to promptly react to external forces and facilitate relaxation.

4 CONCLUSIONS

(1) The optimal proportion of 8% rejuvenator is selected to regenerate the recyclable epoxy asphalt from the perspective of the asphalt phase.

(2) The regeneration has restored the capacity to elicit a dynamic response of recyclable epoxy asphalt.

(3) Rejuvenator proportions can be further adjusted in the future, taking into account the complex modulus requirements.

5 REFERENCE

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