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Article

Interface Interaction of Waste Rubber–Asphalt System

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Abstract: Asphalt pavement construction is a large-volume project, with the ability to recycle the industrial waste and reduce carbon emissions. Rubber-modified asphalt is a carbon-neutralized asphalt-based material, facilitating the recycling of waste rubber materials and improving the road performance of the asphalt mixture. To evaluate the interface interaction of the rubber–asphalt system and its effect on the viscosity characteristics of rubber-modified asphalt, the contact properties of rubber particles in asphalt were analyzed on a microscopic level. Rubber swelling tests and solvent elution tests were conducted on the rubber–asphalt system under different preparation conditions. The swelling ratio, degradation ratio, and swelling–degradation ratio were proposed to evaluate the interface interaction. The results show that the interface interaction of the rubber–asphalt system can be divided into the following three stages: swelling, effective degradation, and over-degradation. The degree of swelling is mainly affected by the content and size of the rubber particles and it is physically condensed, while the degradation is mainly affected by the preparation temperature and preparation time. The effective interface interaction greatly affects the viscosity with the building of the stable three-dimensional network structure. The stronger the interface interaction, the greater the viscosity of the rubber-modified asphalt, except for the 25% content of rubber particles. The gel film will be generated on the surface of the rubber particles throughout the swelling and effective degradation, increasing the viscosity of the rubber-modified asphalt.

Keywords: rubber–asphalt system; interfacial interaction; particle contact properties; three-dimensional net microstructure; viscosity characteristics

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1. Introduction

Energy shortages and environmental pollution are prominent issues of the 21st century [1]. The recycling of waste materials represents an effective approach to address both of these challenges and to reduce carbon emissions. With the advancement of the automotive industry, the rapid accumulation of waste rubber tires has become a global issue, commonly referred to as "black pollution". Additionally, the road performance of asphalt mixtures needs to be improved [2,3]. The utilization of waste rubber powder as a modifier to prepare rubber-modified asphalt, which is a carbon-neutralized asphalt-based material, harnessing the elastic and flexible properties of rubber to enhance asphalt performance, has emerged as a carbon emission reduction and resource-efficient solution [4]. This waste rubber recycling technology has found increasing applications in the field of road construction [5]. Ilyin et al. [6] analyzed the effect of rubber particles on the rheological properties of asphalt. The study found that the addition of rubber particles improved the rutting resistance of road binders. Xiao et al. [7] reported that the addition of rubber particles can increase the Voids in Mineral Aggregates (VMAs) and improve the resistance to rutting in asphalt mixtures. Mashaan et al. [8] focused on the influence of tire rubber particles on the performance of Stone Mastic Asphalt (SMA) mixtures. Mull et al. [9] found that the crack resistance of rubber-modified asphalt pavements surpasses that of base pavements. Chen and Li [10] employed the Discrete Element Method (DEM) for a microstructural analysis of rubber particle-modified asphalt mixtures. Tan et al. [11] explored the production process of rubber-modified asphalt concrete. Huang et al. [12] investigated the fatigue properties of rubber-modified asphalt mixtures. Cao et al. [13] analyzed the road performance of rubber-modified asphalt mixtures utilizing various activation and modification methods. Yu and Wu [14] studied the design method of rubber-modified asphalt mixtures. Wang [15] analyzed the influence of particle size and the content of rubber powder on the high-temperature rheological properties of asphalt mixtures. Tang et al. [16] examined the impact of mineral powder on the road performance of rubber-modified asphalt mixtures.

Due to the steric effect of rubber particles and the interface adhesive effect between rubber particles and asphalt, rubber-modified asphalt exhibits a higher viscosity and more complex viscoelastic, lubrication, and rheological properties [17]. Investigating the interactions between rubber particles and asphalt aids in understanding the modification mechanisms of rubber-modified asphalt, facilitating the development of asphalt with an improved performance and, in turn, enhancing the service performance of road surfaces. Guo et al. [18,19], through the establishment of molecular models for the components of rubber particles and asphalt, demonstrated the compatibility between rubber and asphalt. The study found that the rubber particles' content significantly influenced the storage stability of rubber-modified asphalt. Liseane et al. [20] proposed that the digestion time determined the elastic properties of rubber particles and its solubility in asphalt. Dong et al. [21] simulated the swelling process of rubber powder in asphalt and discovered that rubber particles only absorb the lighter components of asphalt, with swelling rates initially increasing rapidly and then stabilizing. Frantzis et al. [22] analyzed the impact of particle swelling on the storage stability of rubber-modified asphalt and proposed asphalt diffusion coefficients and dissolution parameters. Ni et al. [23] examined the relationship between rubber particles' swelling degree and asphalt components, discussing the devulcanization during the rubber swelling process. Bradley et al. [24] explored the interaction of rubber particles with asphalt and the particle effects. Wang et al. [25] investigated the microstructure of rubber particles and the interface properties between rubber particles and the base asphalt. Frédérique et al. [26] employed a wetting dynamics approach to calculate the surface energies between rubber particles and asphalt, explaining the compatibility between rubber particles and asphalt.

The rubber particles absorb the saturated and aromatic components of asphalt, leading to an increase in volume during the preparation process of rubber-modified asphalt. This absorption triggers the degradation of rubber powder, releasing small molecules such as styrene and butadiene, thus facilitating the exchange of substances between rubber particles and asphalt [27]. Based on these observations, this investigation designed rubber powder swelling tests and solvent elution experiments and proposed swelling rate and degradation rate as parameters to evaluate the physicochemical behavior of rubber powder during the preparation of rubber-modified asphalt.

In this investigation, the rubber-modified asphalt was considered as a rubber–asphalt system. The research delved into the movement characteristics of rubber particles at a microscopic level and introduced swelling and degradation rates to characterize the interface interactions within the rubber–asphalt system. These findings will contribute to the exploration of the relation of the interface interaction and viscosity of rubber-modified asphalt, providing a theoretical foundation for the development of the sustainable rubber-based asphalt material and an analysis of the composition mechanism of rubber-modified asphalt.

2. Materials and Preparation Methods of Rubber-Modified Asphalt

2.1. Base Asphalt

SK 90# asphalt was selected as the base asphalt, and the relevant testing was conducted in accordance with the requirements of the Standard Test Method of Bitumen and Bituminous Mixtures for Highway Engineering (JTG-E20 2011) [28]. The property parameters for the asphalt are presented in Table 1.

Table 1. The properties of asphalt.

Properties		Standard Requirement	Test Results	Method
Penetration (25 °C, 5 s, 100 g)/0.1 mm		80~100	88.6	T0604
Penetration index, PI		−1.0~+1.0	−0.6	T0604
Ductility (5 cm/min, 10 °C)/cm		≥25	79.5	T0605
Ductility (5 cm/min,15 °C)/cm		≥100	>100	T0605
Softening point (ring and ball method)/°C		≥45	46	T0606
Flash point (open bottle method)/°C		≥245	292	T0611
Solubility (trichloroethylene)/%		≥99.5	99.88	T0607
Density (15 °C) g/cm^3		≥1.01	1.034	T0603
RTFOT(163 °C, 85 min)	Mass change/%, no more than	±0.8	−0.065	T0609
	Residual penetration ratio (25 °C)/%	≥57	61.2	T0604
	Residual ductility (10 °C)/cm	≥8	10	T0605
	Residual ductility (15 °C)/cm	≥8	47.3	T0605

2.2. Rubber Powder

The rubber powder utilized in the experiments was a product of Huayi Rubber Company, located in Dujiangyan. This rubber powder was available in various particle sizes, specifically 20 mesh, 40 mesh, 60 mesh, 80 mesh, and 100 mesh. It exhibited a black color and did not contain any visible particles perceptible to the naked eye, as shown in Figure 1.

Figure 1. The rubber powder before mixing with asphalt.

According to the relevant requirements of the Ground Vulcanized Rubber of Scrap Tires for Highway Engineering (JT/J 797-2011) [29], the physicochemical properties of the rubber powder were tested with the test indicators presented in Table 2.

Table 2. The physicochemical properties of rubber.

Properties	Test Results	Standard Requirement
Density/(g·cm^{-3})	1.19	1.10~1.30
Moisture content/%	0.47	<1
Metal content/%	0.028	<0.05
Fiber content/%	0.49	<1
Ash content/%	5.3	≤8
Acetone extract/%	14.7	≤22
Carbon black content/%	31	≥28

2.3. Preparation Method

Preliminary research in the project indicated that the optimal conditions for preparing rubber-modified asphalt using a stirring method at a rotational speed of 500 r/min were as follows: a rubber size of 20 mesh, a rubber content of 20% asphalt mass, a preparation temperature of 180 °C, and a preparation time of 90 min [30]. To investigate the interface interactions within the rubber–asphalt system and their mechanistic impact on viscosity, this investigation adopted a control variate method. The preparation parameters for rubber-modified asphalt are presented in Table 3.

Table 3. Preparation parameters of rubber-modified asphalt.

Preparation Conditions	Values
Rubber size/Mesh number	20, 40, 60, 80
Rubber content/%	5, 10, 15, 20, 25
Preparation temperature/°C	150, 160, 170, 180, 190
Preparation time/min	30, 60, 90, 120, 150

Firstly, the SK90# base asphalt was heated in an oven to 160 °C and was then transferred into an oil bath. The temperature was rapidly increased on a heating plate to reach the designated preparation temperature. To mitigate the adverse effects of asphalt aging, it is important that the heating temperature in the oven does not exceed 160 °C, and the heating time in the oil bath does not exceed 20 min. Secondly, the stirring machine was activated, and the rotational speed was set at 500 r/min. Finally, the pre-weighed rubber powder was added in five equal portions to the base asphalt, and rubber-modified asphalt was prepared under the specified conditions.

3. Experimental Method

The interface interaction between rubber particles and asphalt is a process involving the swelling, devulcanization, and degradation of rubber powder, and the combined effects of these processes impacts the properties of rubber-modified asphalt. The degree of swelling and degradation is related to the rubber content, rubber size, preparation temperature, and preparation time. Rubber powder absorbs the light components of asphalt, leading to an initial mild swelling effect. However, as swelling reaches a certain level, the degradation process accelerates, resulting in the disintegration of rubber particles and the breaking of molecular chains. The development of swelling and degradation determines the extent to which the interface interaction between rubber particles and asphalt affects viscosity. To quantitatively characterize the interface interaction between rubber particles and asphalt, the swelling tests and degradation tests designed are employed for this investigation [31].

3.1. Swelling Test of Rubber Powder

In preparation for the experiment, a sieve with a mesh number of 120 was selected along with a corresponding support base. Approximately 100 g of the prepared rubber-modified asphalt was poured onto the sieve. The sieve and its support base were then placed inside an oven preheated to 160 °C, where they were maintained for approximately one hour. The rubber-modified asphalt exhibited a liquid state under high-temperature environments, with the base asphalt flowing into the support base, while rubber particles were retained on the sieve.

A small quantity of rubber particles from the sieve was placed onto glass slides to prepare the test specimens. These specimens were then subjected to observation under an optical microscope to measure the size of the rubber particles. The optical microscope used is the ZOOM-2860 microscope produced by Shanghai Yuguang Instrument Company, the magnification can be expanded from 2× to 180×, and the maximum distance can reach 280 mm. The separation process of the rubber particles and asphalt is illustrated in Figure 2.

To reduce the experimental error, the size of fifty rubber particles was measured for each set of specimens, and the average size was calculated.


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

Figure 2. The separation of rubber and modified asphalt. (**a**) Before separation. (**b**) After separation.

3.2. Solvent Elution Test

Firstly, the rubber-modified asphalt with a weight of 4 g was placed within a pre-folded filter paper. Subsequently, the filter paper was folded to seal the top end, ensuring that the rubber powder would not leak from the filter paper. The folded filter paper was then inserted into a prepared Soxhlet extractor. In a 250 mL volumetric flask, trichloroethylene was added to approximately two-thirds of the volume. Finally, the flask was heated and the extraction process was repeated until the liquid in the extractor turned colorless. To minimize error, five parallel experiments were conducted. Rubber is an inert material, which is difficult to solubilize in trichloroethylene. To verify the accuracy of the research, three blank samples were prepared to test the solubility of rubber particles in the trichloroethylene, and only 1 g rubber particles were placed in the blank sample. The filter paper that wraps the rubber particles was placed in trichloroethylene, and was then weighed and dried. The experimental process and the rubber powder after elution are depicted in Figures 3 and 4, respectively.

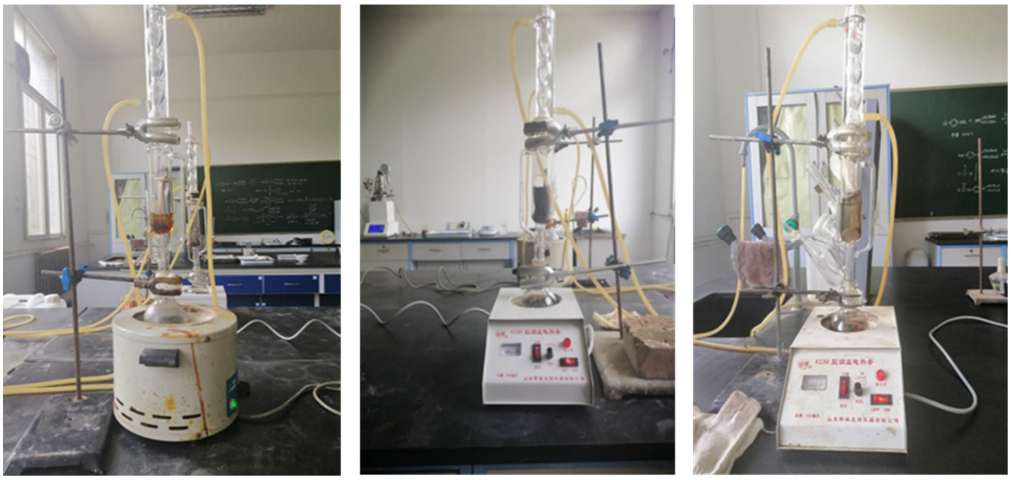

(1) Before elution (2) During elution (3) After elution

Figure 3. Process of elution.

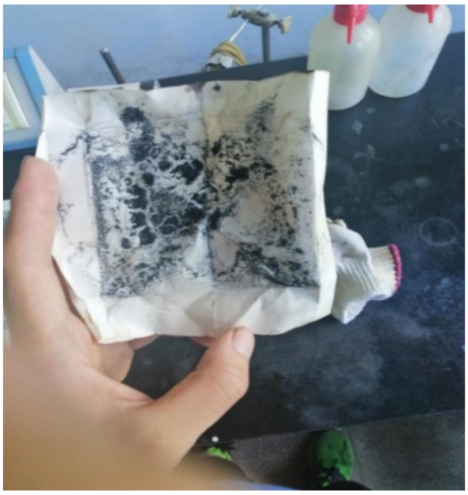


Figure 4. The rubber after elution.

3.3. Evaluation Indices

The swelling ratio V_R was proposed to characterize the increased extent of volume in the rubber particles. Assuming that the rubber particles are approximate spheres, the calculation method for the swelling ratio is expressed in Equation (1):

$$V_R = \frac{R_1^3 - R_2^3}{R_2^3} \tag{1}$$

where R_1 is the average diameter of rubber after swelling, in um; R_2 is the average diameter of rubber before swelling, in um.

The degree of the degradation rate, T, was proposed to evaluate the reduction degree of the mass of the rubber powder, expressed in Equation (2):

$$T = \frac{M \cdot a - m}{M \cdot a} \tag{2}$$

where M is mass of the rubber-modified asphalt before elution, in g; m is mass of the rubber powder after elution, in g; and a is the content of the rubber powder.

The volume expansion of rubber particles occurs due to their absorption of the light components from the asphalt, leading to an increase in the steric effect within these particles. Throughout the degradation process, there is a continual precipitation of smaller molecular substances, enhancing the connections between rubber particles and asphalt, as well as among different rubber particles. However, as the extent of degradation becomes more substantial, the rubber particles undergo disintegration, nearly dissolving within the asphalt. To quantitatively evaluate the interface interaction within the rubber–asphalt system, the swelling–degradation rate φ was proposed, as expressed in Equation (3):

$$\varphi = V_R + T \tag{3}$$

4. Interface Interaction of Rubber–Asphalt System

As depicted in Figure 5, the swelling ratio initially showed an increase in preparation time and then decreased, reaching its maximum value at 90 min. Rubber powder, being an inert high-molecular-weight material, finds it challenging to achieve complete molecular integration with asphalt to form a stable modified asphalt. Consequently, numerous free-standing rubber particles disperse within the base asphalt. Upon the addition of rubber powder to asphalt and subsequent heating and stirring, the lighter components within the asphalt permeate and diffuse into the rubber particles, leading to the swelling of these rubber particles. Concurrently, chemical changes such as the degradation of rubber polymer chains occur.

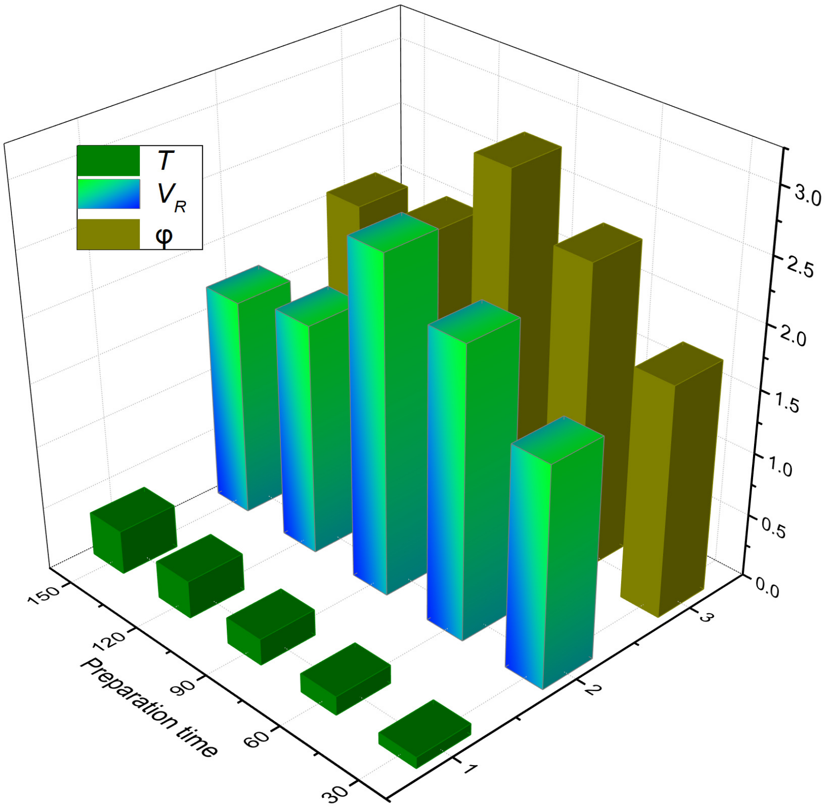
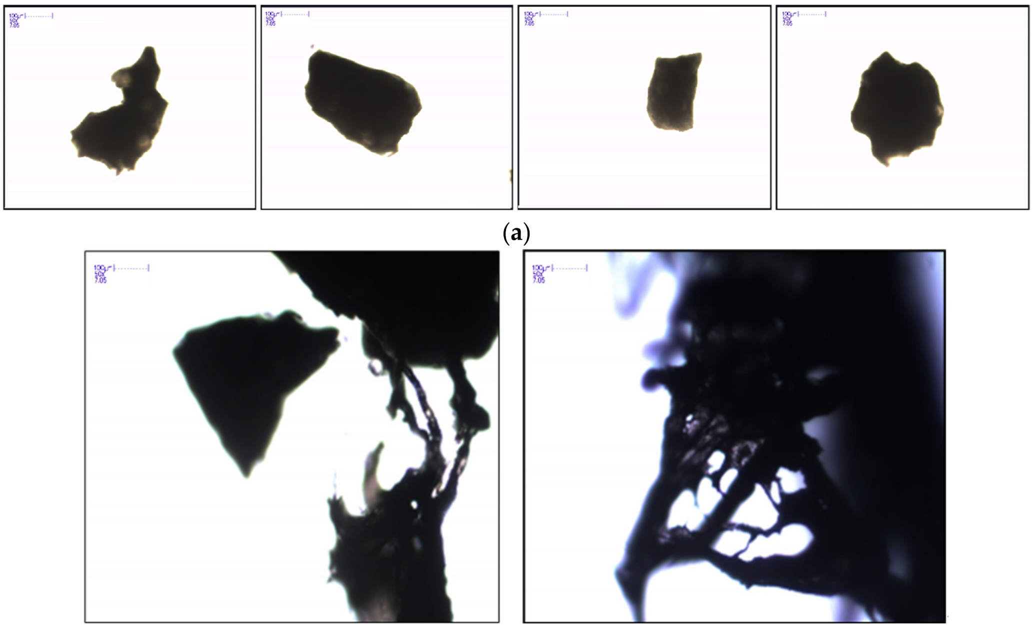


Figure 5. The change of interface interaction parameters with preparation time.

With the increase in preparation time, the volume of rubber particles continues to increase due to the swelling behaviors. However, when the preparation time exceeds 90 min, the swelling ratio notably decreases. The degradation of rubber powder not only diminishes the mass of the rubber particles, but also contributes to a decrease in their volume. During the initial stages of preparation, the degradation behavior of the rubber particles is relatively insignificant, exerting a slight influence on volume. From Figure 5, when the preparation time is prolonged, the extent of degradation of rubber powder significantly increases, promoting the generation of small molecules, ultimately leading to a reduction in the volume of rubber particles.

Rubber-modified asphalt is a multiphase dispersion rubber–asphalt system resulting from complex physicochemical interactions between rubber particles and asphalt. The rubber–asphalt system comprises rubber particles, an interface viscous phase, and the liquid asphalt phase. The swelling and degradation behaviors of the rubber particles within the base asphalt are the sources of the interface interactions of the rubber–asphalt system. When rubber particles were enveloped by the asphalt, the lighter components were absorbed, causing an expansion in the volume of the rubber particles. Simultaneously, as the volume expands, the polymer chains experience fragmentation, giving rise to the generation of small molecular substances that dissolve into the asphalt. As Figure 6 illustrates, compared with the original rubber powder, the rubber particles undergo swelling and degradation, transferring and exchanging substances within the base asphalt. Consequently, this process leads to an interconnection among rubber–asphalt–rubber and the formation of a three-dimensional network structure.


(**a**)

(**b**)

Figure 6. Microscopic characteristic at the optimal preparation conditions. (**a**) Original rubber particles [27]; (**b**) Rubber–asphalt system.

The pattern of change in the swelling–degradation rate is consistent with that of the swelling rate, indicating that the interface interactions in the rubber–asphalt system are the strongest at a preparation time of 90 min.

As demonstrated in Figure 7, it can be observed that the swelling rate of rubber-modified asphalt increases first and then decreases as the size of the rubber powder particles increases, reaching its maximum value at a size of 60 mesh. On the one hand, as the size of rubber powder particles increases, there are fewer pores and cracks on the surface of the rubber powder [32], making it more difficult for the light components in asphalt to penetrate the interior of the rubber powder. On the other hand, larger particle sizes result in a lower quantity of rubber powder, with a rubber powder content of 20%. During the preparation process, larger rubber particles have fewer opportunities for contact and collision, weakening its ability to absorb the light components from the asphalt.

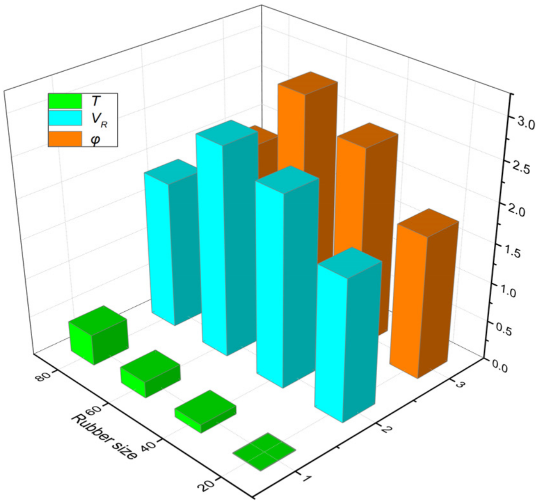


Figure 7. The change of interface interaction parameters with size of rubber.

Based on Figure 7, it is evident that the degradation rate of rubber particles increases with an increase in particle size. When the preparation time and preparation temperature remain constant, the extent of the degradation of the rubber powder is contingent upon both the mass of the rubber powder and the degree of individual rubber particle swelling. A smaller rubber powder particle size yields a more porous structure and a larger specific surface area, thereby leading to a greater degree of degradation at the same preparation temperature and preparation time. As the lightweight components are absorbed by rubber particles, the volume of rubber particles increases and degradation gradually initiates during the swelling process, indicating that degradation is contingent upon the swelling process.

At the point where the particle size reaches 80 mesh, a reduction in swelling rate becomes evident. Normally, decreasing the particle size of the rubber powder can enhance its capability to absorb lightweight components. Hence, it can be deduced that this phenomenon is a result of the degradation behavior of rubber powder, resulting in a more significant reduction in its volume compared to the increase in volume caused by the absorption of lightweight components. This phenomenon is herein defined as "excessive degradation".

The swelling–degradation rate of rubber powder follows the same trend as the swelling rate, indicating that the interface interaction within the rubber–asphalt system is at its strongest intensity when the rubber powder particle size is 60 mesh.

5. The Effect of Interface Interaction on the Viscosity of Rubber-Modified Asphalt

A comprehensive analysis of Figures 8 and 9 elucidates that the viscosity of rubber-modified asphalt exhibits a consistent trend with the degradation rate of rubber powder, and this relationship follows a highly significant quadratic function with a correlation coefficient as high as 0.998. This indicates that the interface interactions of the rubber–asphalt system constitute the primary source of variation in viscosity of rubber-modified asphalt. Notably, the interface interactions between rubber particles and asphalt are at their strongest at a temperature of 180 °C, leading to the formation of the most stable three-dimensional network structure and consequently yielding the highest viscosity.

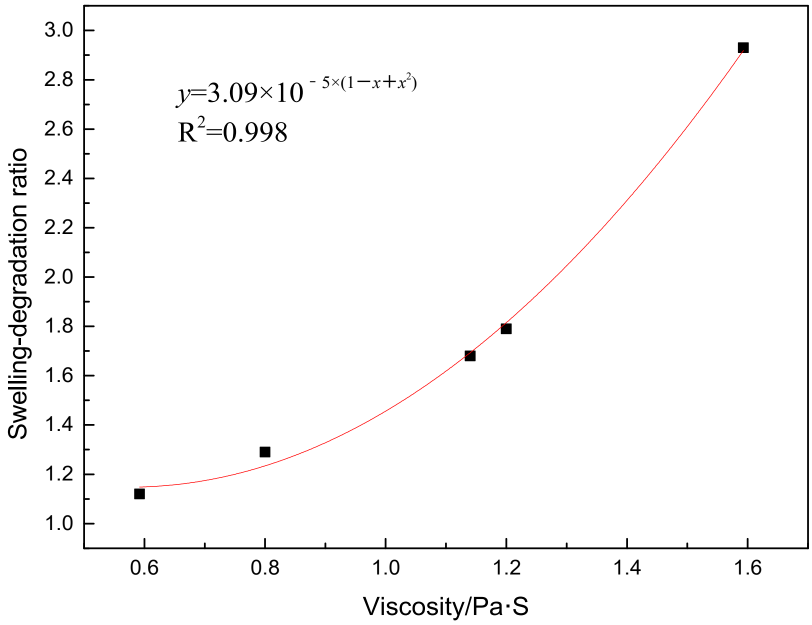


Figure 8. Correlation between φ and viscosity at different preparation temperatures.

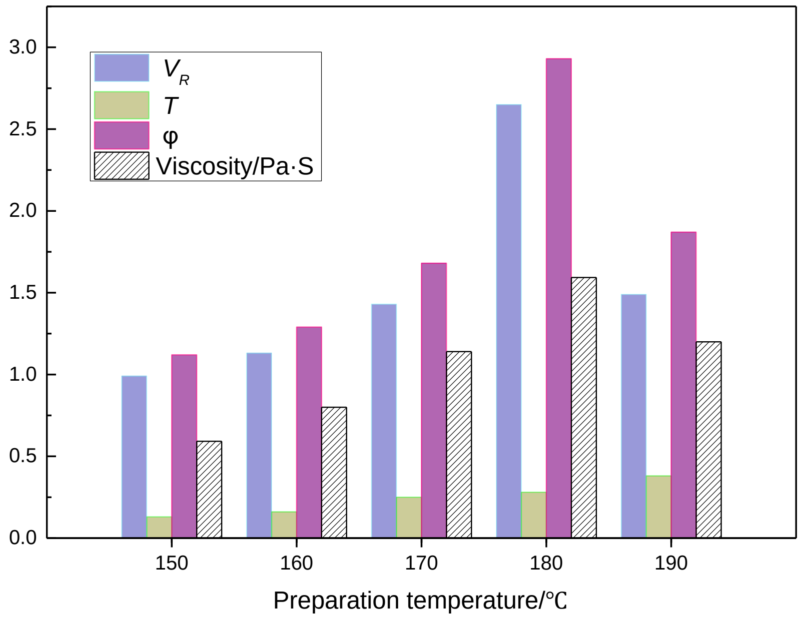


Figure 9. Comparison of viscosity and interaction parameters at different reaction temperatures.

At temperatures below 180 °C, both the swelling rate and degradation rate of the rubber powder increase with rising temperature. This phenomenon can be attributed to the poor flowability of asphalt at lower temperatures. On the one hand, the movement of rubber particles is impeded, and the time required for their uniform dispersion increases compared to higher temperature conditions, consequently reducing the time for the swelling of the rubber particles. On the other hand, the ability of the lighter components in asphalt to infiltrate decreases, and lower temperatures adversely affect the reactivity of rubber particles, resulting in a reduced capacity to absorb lighter components. When subjected to external forces, the intrinsic movement behaviors of the rubber particles are notably influenced by temperature, with higher temperatures intensifying the extent of their motion and augmenting the interaction forces when they collide with other rubber particles. As a result, individual rubber particles are more likely to generate the forces that differ from the movement direction of asphalt, thereby increasing their chances of contacting the light components within the asphalt [33]. As the temperature rises, the capacity of rubber particles to absorb lighter components steadily expands, yet concurrently, the extent of degradation increases. When the temperature surpasses 180 °C, the swelling rate of the rubber powder experiences a dramatic reduction. This phenomenon signifies an excessive level of degradation of the rubber powder, enhancing its capability to absorb lightweight components, ultimately leading to a reduction in the volume of the rubber particles. Therefore, the degradation of the rubber powders enhances the swelling, while leading to a decrease in the swelling rate. Consequently, achieving optimal interface interactions at lower temperatures necessitates the extension of the mixing duration, while temperatures exceeding 180 °C call for a reduction in the mixing time.

Based on an exploration of the interface interactions of the rubber–asphalt system, while keeping other preparation conditions constant, this investigation demonstrates the mechanism behind the variation in the viscosity of rubber-modified asphalt by changing the preparation time. Rubber particles exhibit an increased volume of light component absorption, and as degradation progresses, the rubber–asphalt system gradually forms a three-dimensional network structure, leading to an increase in the viscosity of rubber-modified asphalt [34,35]. However, when the temperature exceeds 180 °C, with a preparation time of 90 min, rubber particles undergo further degradation, generating more small molecular substances. While this enhances the bonding capacity among rubber particles, it results in a reduced individual rubber particle elasticity and a decrease in the stability of the three-dimensional network structure, consequently leading to a decrease in the viscosity of rubber-modified asphalt. The physicochemical behavior of the rubber–asphalt system, which gradually enhances the stability of the three-dimensional network structure, is termed an effective interface interaction, and the corresponding degradation behavior is referred to as an effective degradation.

Furthermore, previous research has revealed that when the preparation temperature is excessively elevated, and the preparation time is unduly prolonged, the degrading rubber particles can undergo polymerization reactions or react with asphalt to form polar compounds [30]. Additionally, asphalt is susceptible to aging with higher temperatures, leading to an increase in its viscosity. These phenomena show that the viscosity reduction caused by excessive degradation is greater than the viscosity increase caused by the aging of asphalt.

As depicted in Figure 10, all other concentrations exhibit a prominent linear relationship between the swelling–degradation rate and viscosity, except for at a rubber content of 25%. When the rubber content increases to 25%, the total surface area for individual rubber particles to interact with light components decreases throughout the preparation process. Consequently, the interface interaction between rubber particles and asphalt weakens, and the interconnection among rubber particles is less robust. As a result, it becomes challenging to form a stable three-dimensional network structure within the rubber–asphalt system. However, the condition of a rubber content of 25% leads to the generation of a significant quantity of insufficiently swollen free rubber powder, augmenting the steric hindrance effect on rubber particles. Thus, the rubber-modified asphalt prepared with a rubber content of 25% exhibits the highest viscosity.

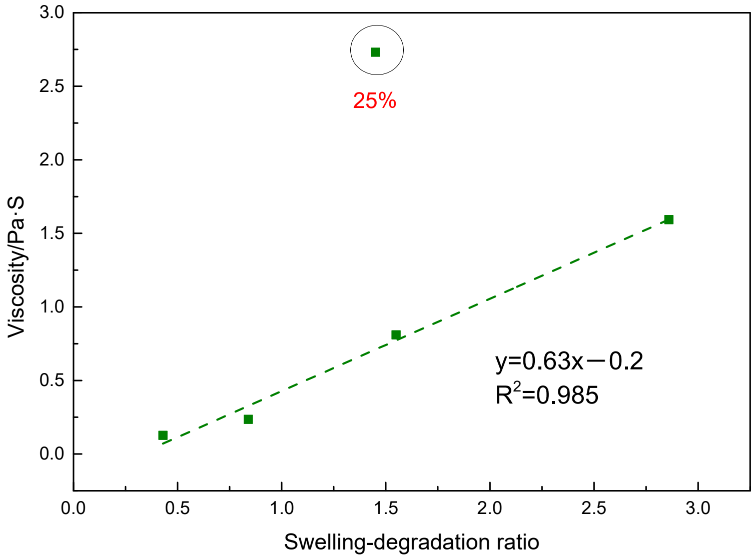


Figure 10. Correlation between φ and viscosity under different rubber contents.

As Figure 11 illustrates, the viscosity of rubber-modified asphalt rises with the increase in the degradation rate of swelling, except for at a rubber content of 25%. When the rubber content is relatively low, the probability of contact and collision between rubber particles diminishes. On the one hand, it hinders the capacity of individual rubber particles to interact further with other regions of the asphalt, once they have absorbed light components from the local asphalt region and undergone swelling and degradation. On the other hand, it allows individual rubber particles to be readily encapsulated by asphalt, effectively obstructing the passage for mass transfer between the rubber particles and asphalt, thereby diminishing the degree of interface interaction within the entire rubber–asphalt system. These factors collectively render the formation and stability of a three-dimensional network structure more challenging.

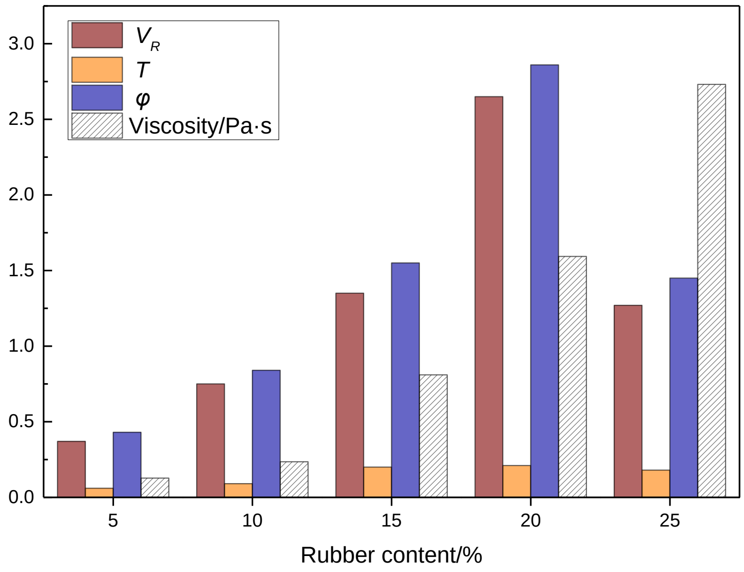


Figure 11. Comparison of viscosity and interaction parameters under different rubber contents.

However, under the combined influence of swelling and degradation, a gel-like film forms on the surface of the rubber particles, intensifying the adhesive effects between rubber and asphalt. As the content of rubber powder increases, this adhesive effect becomes more pronounced, thereby augmenting the steric hindrance effect on rubber particles, resulting in a higher viscosity of the rubber-modified asphalt. With the increasing rubber content, particles become less prone to immobilization by asphalt due to collision and friction, thereby increasing the probability of contact with lighter components from other regions and an enhancement in swelling and degradation capabilities. When the rubber content reaches 20%, both swelling and degradation rates peak. The swelling augments the volume of rubber particles, while degradation enhances the inter-particle connectivity, significantly improving the stability of the three-dimensional network structure. Moreover, it amplifies the contact area between the gel-like film and asphalt, resulting in an increase in the viscosity of rubber-modified asphalt.

6. Conclusions

This investigation conducted swelling tests and solvent elution tests to evaluate the swelling and degradation behaviors of rubber powder in asphalt under various preparation conditions. The swelling rate, degradation rate, and the combined swelling–degradation rate were proposed to characterize the interface interactions of the rubber–asphalt system. Furthermore, the influence mechanisms of interface interactions on the viscosity of rubber-modified asphalt were revealed. The main conclusions are as follows:

(1) The degradation of rubber powder is reliant on swelling, where swelling causes an increase in the volume of rubber particles, consequently enhancing the steric hindrance effect of individual particles, while degradation intensifies the connectivity among rubber particles. The interface interaction between rubber particles and asphalt facilitates the transfer of substances and promotes the formation of a three-dimensional network structure. The interface interactions within the rubber–asphalt system can be categorized into the following three stages: swelling, effective degradation, and excessive degradation.

(2) The stability of the three-dimensional network structure is a critical determinant of the viscosity of rubber-modified asphalt. The rubber size, the rubber content, and the preparation time and preparation temperature influence the inter-particle collision probability, individual particle activity, and the flow properties of asphalt, thereby impacting the interface interactions of the rubber–asphalt system. Stronger interface interactions lead to a higher viscosity in rubber-modified asphalt. The interface interactions of the

rubber–asphalt system are strongest under the optimal preparation conditions, all of which correlate with the highest viscosity of rubber-modified asphalt.

In the following research work, based on the interface interactions of the rubber–asphalt system, the contact slip test device independently developed will be adopted, taking into consideration aggregate factors, to explore the bonding/lubrication interface transition behavior of rubber-modified asphalt. This will provide a theoretical basis and new direction for determining the optimal mixing and compaction temperatures.

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Conflicts of Interest: The authors declare no conflicts of interest.

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