

Research Article

Using the Rheological Index to Quantitatively Evaluate the Mechanical Performance of High-Elasticity Modified Asphalt

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High-elasticity modified asphalt is widely used in OGFC and bridge deck paving due to its high viscosity and strong displacement recovery capacity. It can improve the high-temperature deformation resistance and elastic recovery ability of the pavement. Especially in bridge deck pavement, high-elastic modified asphalt can inhibit the formation of reflective cracks and extend the service life. In order to quantitatively evaluate properties of the high-elasticity modified asphalt, rheological properties are studied by using a dynamic shear rheometer (DSR) test. The parameters were fitted with the Burgers model, and the constitutive equation was established. The 3 s elastic recovery rate E_r was proposed to quantitatively evaluate the elastic recovery of high-elasticity modified asphalt. The experimental results show that the instantaneous modulus of elasticity G_0 and the delayed modulus of elasticity G_1 can be used to evaluate the elastic capacity. E_r can quantitatively evaluate the elastic resilience of high-elasticity modified asphalt. The correlation coefficient between the test results of high-elasticity modified asphalt and those of impact toughness evaluation reached 0.9966, and the 3 s elastic recovery rate E_r could be used to evaluate the elastic recovery ability of high-elasticity modified asphalt.

1. Introduction

Asphalt mixtures used for pavements tend to harden and become brittle after prolonged exposure to ultraviolet radiation. Low-temperature cracking and fatigue cracking can be a problem in such environment [1–4]. For some bridge pavement, tunnel road, or airport pavement engineering projects, it is necessary to use modified asphalt with high-elastic recovery ability to solve heavy traffic, cracking, rutting, and other problems [5, 6]. Asphalt mixture is composed of coarse aggregate, fine aggregate, mineral powder, and asphalt, and asphalt is the only deformable component and continuous phase in asphalt mixtures [7, 8]. In this sense, the performance of asphalt binder has a direct impact on the mastics and mixtures [9, 10]. SHRP research results in the United States show that asphalt contributes 29% to high-

temperature rut, 52% to fatigue, and 87% to temperature crack [11]. High-elastic asphalt (HEA), also known as high-elasticity modified asphalt, is a modified asphalt based on regular SBS asphalt using additional modifiers such as plasticizers and cross linkers [12, 13]. Compared with ordinary asphalt concrete, high-elasticity modified asphalt concrete performs well in low-temperature anticrack, absorption of diffusion, tensile stress, and good stress absorption capacity. Therefore, in recent years, it has been widely used in cement concrete pavement asphalt layer and cement concrete bridge pavement layer [14]. Hao [15] developed and applied high-elasticity modified asphalt to solve the fatigue cracking problem of asphalt mixture for steel bridge deck pavement. It has been proved by engineering practice that the fatigue life of steel bridge deck asphalt mixture is greatly improved by high-elasticity modified asphalt.

The excellent properties and practical value of high-elastic modified asphalt have also been widely verified in the laboratory. Dennyale [16] indicated through the test results of permeability, softening point, and elastic recovery of asphalt that the elastic properties and production material properties of high-elasticity modified asphalt were improved, which is suitable for application in highway construction. Luo [17] evaluated the rutting resistance, low-temperature performance, and wet-damage resistance of three different types of asphalt through dynamic stability test, three-point beam bending test, and tensile strength ratio test, respectively. It is verified that the HEA mixture containing Mafilon has better road performance and snowmelt performance than ordinary SBS, which also indicates the practical value of HEA. D'angelo [18] pointed out that in the multiple stress creep-recovery test (MSCR) data, there was an obvious relationship between the recovery rate of the creep part and the strain. According to the unrecovered strain at the end of the recovery part of the test divided by the initial stress applied by the creep part, the characteristic called unrecoverable compliance J_{nr} is defined. Much research expects to find new indices to evaluate the properties of modified asphalt. For instance, $(G^*/(1 - (1/\tan \delta \sin \delta)))$ proposed by Shenoy [19] is one of them, which is used to evaluate the high-temperature performance of polymer-modified asphalt. Qin [20] verified the high accuracy of the Burgers model in simulating the creep process of asphalt and evaluated the high-temperature performance of high-viscosity asphalt with multiple creep-recovery test. Pouria [21] used a generalized fractional viscoelastic model to study the creep and recovery properties of asphalt binders and evaluated the influence of modifier addition on non-linear viscoelastic parameters of asphalt binders. Indirect tensile tests conducted by Baladi et al. on several modified asphalt mixtures showed that SBS modified asphalt could improve the tensile strength and stiffness of asphalt mixtures [22, 23]. Zhang's study [24] explored the correlation between different rheological indices to better evaluate the properties of asphalt, including complex modulus (G^*) and phase angle (δ) master curves, rutting factor ($G^*/\sin \delta$), and zero shear viscosity (ZSV). SHRP also demonstrated a good correlation between the $G^* \times \sin \delta$ of asphalt and the fatigue performance of the mixture [25, 26]. Wang et al. [27] evaluated the antifatigue performance of asphalt and asphalt mixture, respectively, by using $G^* \times \sin \delta$ fatigue factor and four-point bending fatigue test. As a road material used in specific projects, high-elasticity modified asphalt needs more accurate and reliable performance evaluation methods to evaluate its elastic capacity, which is related to the fatigue life of the mixture. In order to guide the selection of materials in engineering, it is necessary to carry out in-depth research in this aspect.

The objective of this research is to define an appropriate parameter to make the high-elasticity modified asphalt binder better distinguishable from other modified asphalt binder based on rheological properties and to compare the performance of different high-elasticity modified asphalt binders more rigorously. In our study, the creep-recovery curves of different asphalt samples were tested by dynamic

shear rheometer, and the Burgers model was selected to define the creep and creep-recovery of asphalt materials. Combining speed and safe distance, 3 s elastic recovery rate was defined to characterize the elastic recovery ability of high-elastic modified asphalt. Through this parameter, the branch of high-elasticity modified asphalt could be better distinguished from other functional modified asphalt binders. The reliability of this index was verified by the impact toughness test.

2. Materials and Test Methods

2.1. Experimental Materials. By adding various polymers, including polyethylene (PE), polypropylene (PP), and styrene-butadiene-styrene (SBS), asphalt can be modified to obtain better mechanical properties and road performance [28–30]. HEA is usually produced by adding a plasticizer and cross-linker to regular SBS modified asphalt. By changing the SBS block ratio, a new SBS modifier was developed and high-viscosity and high-elasticity modified asphalt was prepared. The shear temperature was 170°C, the shear rate was 4000 r/min, the shear time was 50 min, and the development time was 60 min. Five kinds of high-elasticity modified asphalt with different dosages were prepared. They were labeled as HEA1, HEA2, HEA3, HEA4, and HEA5, respectively, and their properties are shown in Table 1.

It can be seen from Table 1 that modified asphalt with different SBS modifier contents has different properties, among which the minimum value of elastic recovery test is 94% and the maximum value is 99%, both of which are far higher than the upper limit of SBS modification documented in “technical specification for construction of asphalt pavement,” namely, 75%. However, the elastic recovery ability of those five high-elasticity modified asphalt is not significantly different by using traditional indicators, so its performance cannot be well distinguished. Therefore, a highly discriminative index is urgently needed to evaluate the elastic recovery ability of high-elasticity modified asphalt.

2.2. Laboratory Testing

2.2.1. Repeat Creep Experiment. In order to compare the creep properties of different high-elasticity modified asphalt binders, five kinds of high-elasticity modified asphalt binders and two kinds of virgin asphalt binders were tested by rheometer under 40°C, 50°C, 60°C, and 70°C. Each cycle includes 1 s loading and 9 s unloading. In order to ensure that the asphalt binder was in the linear viscoelastic range, the stress of 300 Pa was used in the test. The creep-recovery curves under different loading times were obtained by preloading 200 cycles.

2.2.2. Model Selection. Asphalt is composed of hydrocarbons and their nonmetallic derivatives with extremely complex chemical constituents. Although the composition is extremely complex, asphalt still has the basic characteristics

TABLE 1: Performance of different modified asphalt binders with various modifier dosages.

Test item	Unit	HEA1	HEA2	HEA3	HEA4	HEA5	
Penetration (25°C, 100 g, 5 s)	0.1 mm	61	59	58	55	60	
Penetration index	—	0.10	0.22	0.42	0.77	0.53	
Ductility (5°C, 5 cm/min)	cm	54	53	58	43	45	
Softening point (ring and ball method)	°C	> 90	> 90	> 90	> 90	> 90	
Flash point (opening)	°C	> 260	> 260	> 260	> 260	> 260	
Storage stability (softening point difference) (165°C, 48 hr)	°C	1.5	1.5	2.0	4.5	3.0	
Elastic recovery (25°C, 10 cm)	%	94	95	99	96	98	
Dynamic viscosity (60°C)	Pa·s	169403	430521	761774	440524	450535	
Kinematic viscosity (135°C)	Pa·s	2.3	2.5	3.1	3.8	4.0	
Residue of RTFOT (163°C, 75 min)	Elastic recovery (25°C, 10 cm)	%	80	85	88	87	86
	Penetration ratio (25°C)	%	95	95	98	98	95
	Ductility (5°C, 5 cm/min)	cm	28	30	35	35	30

of amorphous structures. In the macrosense, asphalt is a homogeneous viscoelastic material. In the range of linear viscoelastic behavior, the creep and creep recovery of the Burgers model are shown in Figure 1. The four-unit Burgers model is most widely used in the research of asphalt rheology, as shown in Figure 2.

As shown in Figure 2, the instantaneous deformation is the elastic response of the material, and time-dependent deformation is the viscous part of the material, including viscoelasticity, namely, delayed elastic deformation and viscous flow deformation. After removing the load, the instantaneous elastic deformation immediately recovers. Viscous deformation no longer develops, but it cannot be recovered. The delayed elastic deformation gradually recovers at a decreasing rate. Therefore, the elastic recovery capacity of the asphalt used in the stress-absorbing layer mixture is required to be relatively high, and the size of permanent deformation should be close to 0. The constitutive equation of the Burgers model is shown in the following equation:

$$\gamma = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1} \left(1 - e^{(-tG_1/\eta_1)}\right) + \frac{\tau_0}{\eta_0} t = \gamma_e + \gamma_{de} + \gamma_v, \quad (1)$$

where γ is the shear strain, τ_0 is constant shear stress (creep load), Pa, G_0 is elastic modulus in Maxwell model, Pa, G_1 is the modulus of elasticity in the Kelvin model, Pa, η_1 is the coefficient of viscosity in the Kelvin model (viscosity), Pa·s, η_0 is the viscosity coefficient in Maxwell model (viscosity), Pa·s; t is creep time (loading time).

It can be seen that the strain response of the Burgers model is divided into elastic parts γ_e , delayed elastic part γ_{de} , and the viscous part γ_v . Compliance is the strain equivalent to unit stress and reflects the deformation property of the material. Corresponding to formula (1), the creep compliance of asphalt consists of three parts: the elastic part J_0 , the delayed elastic part J_{de} , and the viscous part J_v :

$$J(t) = J_0 + J_{de} + J_v = \frac{1}{G_0} + \varphi(t) + \frac{t}{\eta_0}, \quad (2)$$

where $J(t)$ is the creep compliance, J_0 is instantaneous/glassy shear compliance, J_{de} is the delayed shear compliance, and J_v is the viscous creep compliance.

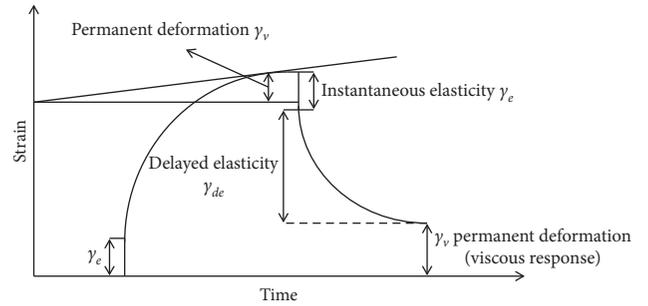


FIGURE 1: Creep-recovery response of binders.

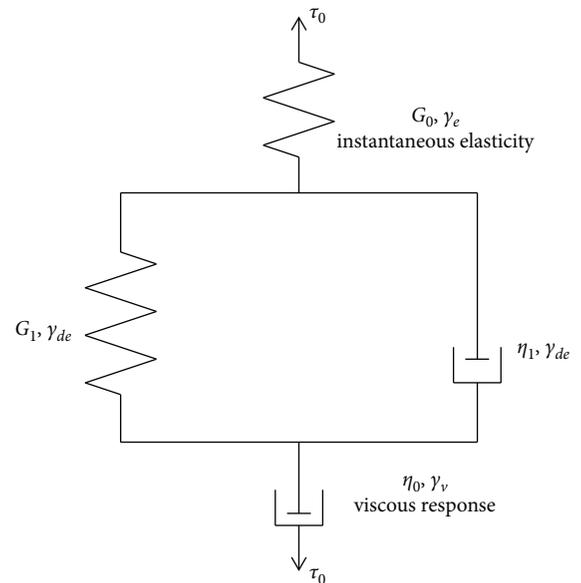


FIGURE 2: Burgers rheological model.

The Burgers model shows high accuracy in simulating asphalt's creep process [20]. Furthermore, the four-unit burgers model has good convergence. Therefore, this paper selected the Burgers model as the rheological model of fitting parameters.

2.2.3. Impact Toughness Test. The five kinds of high-elasticity modified asphalt mentioned above were used respectively, and the same gradation, aggregate, and mineral powder were selected to make the stress-absorbing layer mixture. According to the requirements of “Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering,” the 300 mm × 300 mm × 50 mm specimens were made by wheel-grind method.

The formed specimens were cut into prismatic specimens of 250 mm × 35 mm × 35 mm using the double-sided saw cutter made in Finland in the laboratory.

The test procedure is detailed as follows: the prepared asphalt concrete prism was placed in a constant temperature tank at the specified temperature for 2~4 h. The test specimen should be spaced, and the bottom of it should be padded, not less than 5 cm from the bottom of the container. The test was carried out after the water bath, and the loading rate was set at 500 mm/min. The test specimen should be removed from the constant temperature water bath for no more than 1 min at the end of the test, in order to avoid temperature changing of the trabecular beam after it is removed from the water bath.

3. Results and Discussion

3.1. Repeat Creep Experiment. As can be seen from Figure 3, the strain tends to be stable after loading more than 50 times, and the strain gradually becomes larger and larger with the increase of loading times, but the difference is not significant. Therefore, the number of subsequent tests is selected as 100 cycles, and the 50th cycle is taken for analysis [31].

3.2. Fitting Based on Burgers Model. By comparing the viscosity, elasticity, and delayed elasticity parameters of various bitumen, the following can be found:

- (1) The instantaneous elastic modulus of HEA3 is 833 times that of matrix asphalt and 14 times that of ordinary modified asphalt
- (2) The difference in delayed elastic properties of G_1 was also significant, among which the high-elasticity modified asphalt HEA3 was 19 times that of the matrix asphalt
- (3) In terms of creep stiffness of viscous component η_0 , HEA3 is 13 times that of matrix asphalt and 3 times that of ordinary modified asphalt, so highly elasticity modified asphalt has the strongest rutting resistance

The rheological properties of asphalt binders can be quantitatively evaluated with Table 2, but its elastic recovery ability cannot be well evaluated. ε_L is the total strain under creep load, ε_p is the residual strain after recovery stage, $\varepsilon_p/\varepsilon_L$ is used to characterize the elasticity of asphalt. This index can effectively distinguish general modified asphalt and virgin asphalt, mainly because of their different elastic recovery ability as shown in Figures 4 and 5.

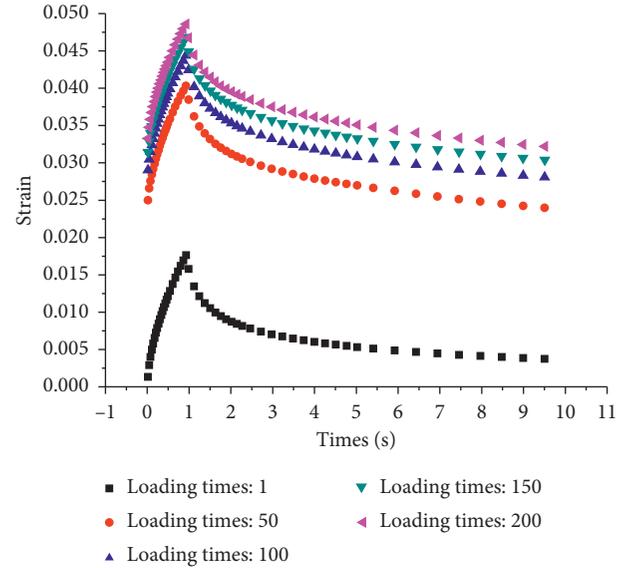


FIGURE 3: Creep-recovery response of binders.

However, the method mentioned above is not suitable for high-elasticity modified asphalt because the high-elasticity asphalt almost completely recovers its deformation within 9 s. Figure 6 shows the 50th repeated creep-recovery curve of five kinds of high-elasticity asphalt.

As can be seen from Figure 6, although the trend is similar, the elastic recovery of the five kinds of high-elastic modified asphalt is not the same. After 1 s loading, the deformation of the five samples reached the maximum. The deformation of HEA2 was the largest and that of HEA3 was the smallest. Considering the difference of permanent strain, a universal index should be defined. Therefore, in order to better evaluate the flexibility of high-elasticity modified asphalt recovery ability, assume a highway vehicle traffic speed of 120 km/h and a distance of 100 m intervals; then, the car after the time of arrival in the leading position needs 3 s, and the ideal state is the best state road within 3 s. For this reason, we define elastic recovery rate at 3 s to evaluate the elastic recovery capacity. E_r is the percentage of the recovery strain ε_{3S} at the end of 3 s unloading to the total strain ε_L at the end of 1 s loading, as shown in formula (3). The index has a good differentiation as we can see from Figures 5 and 6.

$$E_r = \frac{\varepsilon_{3S}}{\varepsilon_L} \times 100\%, \quad (3)$$

where E_r is the elastic recovery rate at 3 s, ε_{3S} is recovery strain at the end of 3 s unloading, and ε_L is total strain at the end of 1 s loading.

The 3 s elastic recovery rate E_r of five kinds of high-elasticity modified asphalt and ordinary modified asphalt was calculated by formula (3), as shown in Table 3.

From Table 3, the elastic recovery rate E_r can clearly distinguish the elastic recovery capacity of different kinds of asphalt. HEA3 had the most outstanding elastic recovery ability, and the other high-elastic modified asphalt had

TABLE 2: Fitting parameters of the Burgers rheological model with different high-elasticity modified asphalt.

Parameters	Virgin asphalt	Ordinary modified asphalt	HEA1	HEA2	HEA3	HEA4	HEA5
G_0 (Pa)	$1.56E+03$	$9.32E+04$	$8.27E+05$	$8.11E+05$	$1.30E+06$	$9.37E+05$	$9.49E+05$
G_1 (Pa)	$9.45E+04$	$3.03E+05$	$1.03E+06$	$1.22E+06$	$1.81E+06$	$1.45E+06$	$1.72E+06$
η_1 (PaS)	$5.88E+05$	$2.63E+05$	$1.93E+05$	$2.23E+05$	$3.16E+05$	$2.65E+05$	$3.13E+05$
η_0 (PaS)	$8.62E+04$	$4.26E+05$	$6.80E+05$	$9.55E+05$	$1.14E+06$	$1.02E+06$	$1.18E+06$
J_0 (1/Pa)	$6.40E-04$	$1.07E-05$	$1.21E-06$	$1.23E-06$	$7.67E-07$	$1.07E-06$	$1.05E-06$
J_{de} (1/Pa)	$1.57E-06$	$2.25E-06$	$9.70E-07$	$8.15E-07$	$5.51E-07$	$6.87E-07$	$5.78E-07$
J_v (1/Pa)	$1.16E-05$	$2.35E-06$	$1.47E-06$	$1.05E-06$	$8.74E-07$	$9.77E-07$	$8.46E-07$
$J(60)$ (1/Pa)	$6.53E-04$	$1.53E-05$	$3.65E-06$	$3.10E-06$	$2.19E-06$	$2.73E-06$	$2.48E-06$

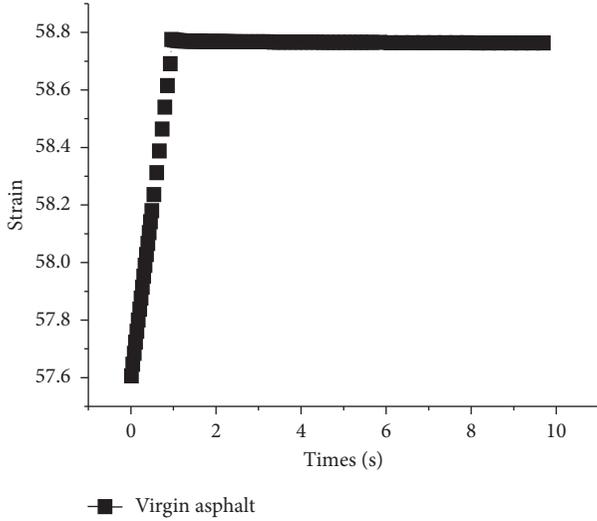


FIGURE 4: Creep-recovery response of virgin asphalt.

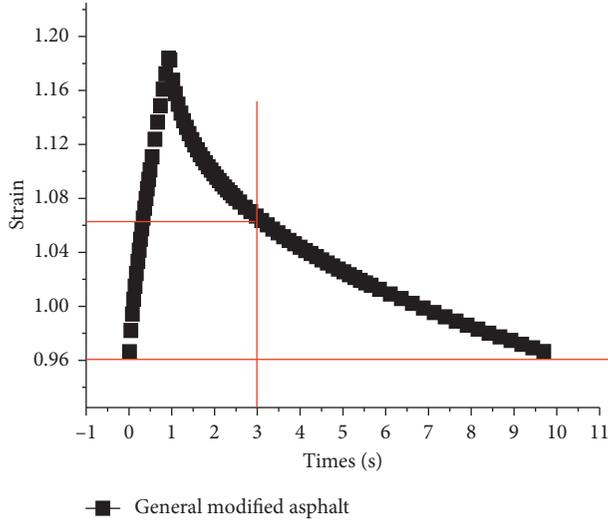


FIGURE 5: Creep-recovery response of general modified asphalt.

similar properties. Their elastic recovery ability was better than that of ordinary modified asphalt.

3.3. Performance Verification Based on Impact Toughness Test. The experimental results of impact toughness of five kinds of high-elasticity modified asphalt are shown in Figure 7.

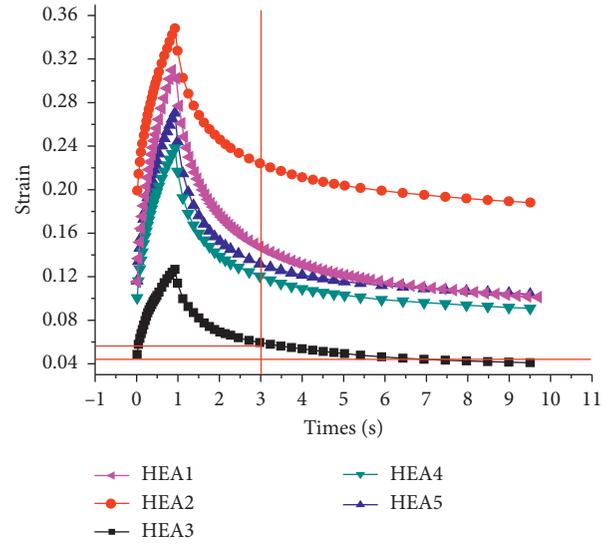


FIGURE 6: Creep-recovery response of five-type high-elasticity modified asphalt.

It can be seen from Figure 7 that the stress absorption layer produced by different kinds of high-elasticity asphalt has different impact toughness. The impact toughness can be calculated according to the area enclosed by the vertical line when the specimen was broken. When the failure displacement of each specimen was similar, the load applied to HEA3 was the maximum. The five kinds of modified asphalt have obvious differentiation.

The impact toughness test results of stress-absorbing layer asphalt mixture and the elastic recovery test results of 3 s before aging are shown in Table 4.

As can be seen from Table 4, the elastic recovery rate at 3 s and impact toughness show a positive correlation. In order to analyze the test results more intuitively, the relationship between impact toughness and elastic recovery rate at 3 s E_r is drawn in the same diagram, as shown in Figure 8.

It can be seen from Figure 8 that impact toughness has a good correlation with 3 s elastic recovery rate E_r , and the correlation coefficient reaches 0.9966. Impact toughness refers to the ability of the material to absorb plastic deformation work and fracture work under impact load. From this, we can infer that the stronger the ability of the asphalt mixture to absorb plastic deformation work is, the more deformation can be recovered after the action of load. This also explains the good positive correlation between elastic recovery and impact

TABLE 3: Elastic recovery rates of different asphalt binders.

Types of asphalt	Ordinary modified asphalt	HEA1	HEA2	HEA3	HEA4	HEA5
Elastic recovery rate E_r (%)	56.5	82.5	83	93.3	85.7	87.5

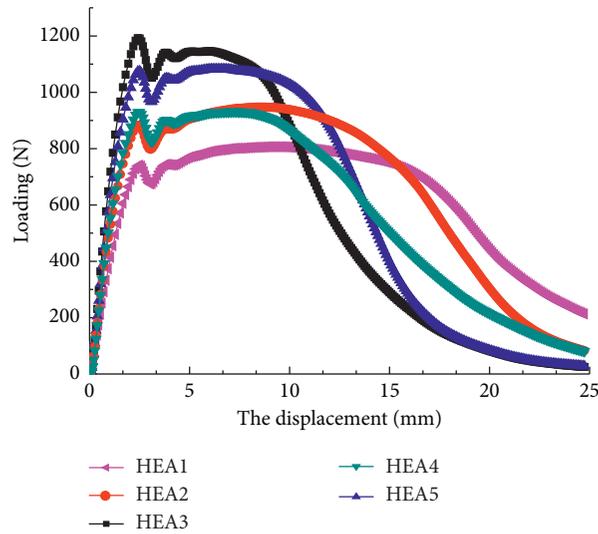


FIGURE 7: Impact toughness curve of asphalt with different asphalt binders.

TABLE 4: Elastic recovery and impact toughness OF high-elasticity modified asphalt.

High-elasticity asphalt species	Elastic recovery rate at 3 s E_r (%)	Impact toughness (N.m)
HEA3	93.3	1.95
HEA5	87.5	1.74
HEA4	85.7	1.51
HEA2	83	1.36
HEA1	82.5	1.26

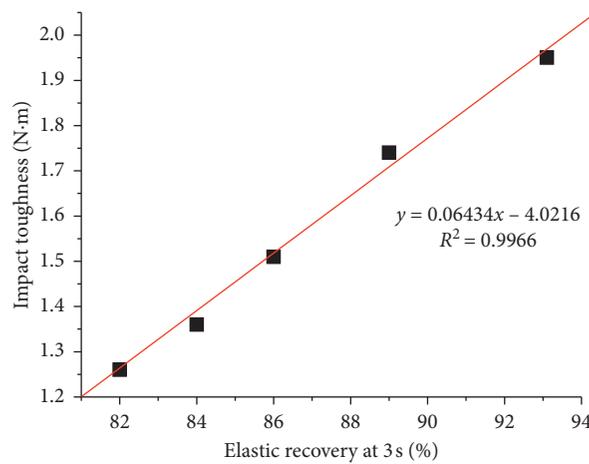


FIGURE 8: Correlation of impact toughness and elastic recovery at 3 s.

toughness. Experimental analysis shows that 3 s elastic recovery rate E_r is a good indicator to evaluate the anti-impact performance of the stress absorption layer, and because impact

toughness has a good correlation with fatigue life, the value of this indicator can indirectly reflect the antifatigue performance of the stress absorption layer [32, 33].

4. Conclusion

Through the rheological test, theoretical analysis, and impact performance verification of asphalt mixture, the main test conclusions are as follows:

- (1) Burgers model can be used to fit the rheological behavior of high-elastic modified asphalt. The performance of instantaneous elastic modulus G_0 and delayed elastic modulus G_1 can be used to evaluate its elastic capacity.
- (2) In combination with car following behavior on the highway, the percentage of 3 s recovery strain in the total strain at the end of 1 s loading was used to evaluate the elastic recovery ability of high-elasticity modified asphalt, which can be used to distinguish between ordinary modified asphalt and other high-elasticity modified asphalt.
- (3) The correlation coefficient between the test results of high-elasticity modified asphalt and the test results of impact toughness evaluation reached 0.9966. The 3 s elastic recovery rate E_r provides a means to predict the impact toughness of asphalt mixture.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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