Research on Viscoelastic Mechanical Model of High Modulus Asphalt Mixtures Under Repeated Shear Load

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***Abstract* — Uniaxial penetrating repeated shear test was conducted in this paper to simulate the shear rheological law of asphalt mixture. A "five-unit and five-parameter" shear rheological model was built based upon parameter inversion according to the acquired test data. The test results of Super-20 high modulus asphalt mixture were fitted in accordance with the built rheological model, with parameters obtained for the model. The research result shows: (1) there is a critical value for the repeated shear stress peak of asphalt mixture under the action of repeated shear load, and this critical value is a long-term shear strength value of asphalt mixture; (2) Test data fitting shows that the built "five-units and five-parameters" model can describe the permanent deformation rule of asphalt mixture under the action of repeated shear load relatively accurately; (3) The non-deformability of asphalt mixture is significantly enhanced due to an increase in the viscosity of asphalt mixture after the incorporation of rock asphalt; (4) At the same temperature and under the same stress, along with the incorporation of rock asphalt, viscosity coefficient η1 increases remarkably, suggesting that the high-temperature stability of high modulus asphalt mixture is significantly enhanced.**

Keywords - asphalt mixture; repeated shear load; rock asphalt; shearing rheology; five-unit and five-parameter

I. INTRODUCTION

Vehicle load is one of the major influencing factors for the service life of asphalt pavement. With the development of economy, overloading phenomenon has become increasingly prominent. Moreover, pavement temperature is high in summer, which results in such damages as rutting and slippage on a large scale, severely affecting running safety and comfort. To solve this problem, it is necessary to carry out an in-depth study from the perspective of the rheological law of asphalt mixture under the action of repeated shear load based on such theories as rheology and viscoelasticity, etc., to explore the deformation mechanism of asphalt mixture under the action of repeated shear load.

The rheological properties of asphalt mixture mainly refer to the deformation rule and constitutive relation of asphalt mixture under the action of dynamic and dead loads. The test methods that can be used for researching the rheological properties of asphalt mixture include small-scale reciprocating wheel rut test, large-scale ring road experiment, large-scale accelerated pavement testing and creep test, etc.[1] Creep test has been used more and more frequently in the research of asphalt mixture owing to its flexibility and convenience[2~4]. At present, for most studies on the viscoelasticity of asphalt mixture, what is adopted is static creep test[5~7], there are only a few literatures related to studies through repeated shear creep test. Therefore, the paper researches the rheological properties of asphalt mixture through repeated shear test and viscoelasticity theory, to provide reference for the design of asphalt pavement.

II. TEST PROCESS AND RESULT ANALYSIS

A. *Raw Material Performance and Mix Design*

The modified asphalt used for the test in the paper is Korean SK SBS modified asphalt, and high modulus asphalt is made of SBS modified asphalt and 5% rock asphalt through compound processing. The aggregate is the same as the aggregated rock used in Leijiajiao-Xifeng Highway, and the lithologic character is limestone. The mineral powder is made of the high-quality limestone selected manually, and the asphalt-aggregate ratio is 4.48%. The graded texture is shown in Fig.1.

B. *Equipment and Test Method*

The asphalt mixture test specimen is shaped with superpave gyratory gompactor (SGC). The test specimen's diameter is 150mm and height is 100mm. The equipment used for the repeated shear performance test is UTM-100 pneumatic servo tester. The diameter of the pressure head used for loading is 2.5 times as much as the nominal maximum size of aggregate, equal to 57mm. The test method is shown in Fig.2.

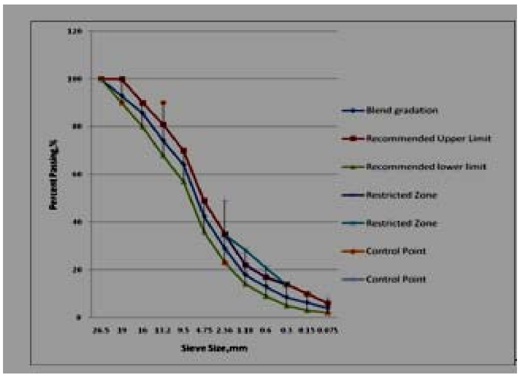

Figure 1. Superpave-20 gradation

Figure 2. Repeated shear rheological test

C. Result Analysis of Repeated Shear Creep Test

1) Load form and loading mode

Loading waveform is important to repeated shear creep test on asphalt mixture, and the loading form should simulate the loading state of real bituminous pavement as far as possible. When an automobile runs on pavement, the stress characteristic of bituminous pavement is similar to Haversine, as shown below:

$$\tau_t = \begin{cases} \tau_0 \sin \dfrac{\pi}{t_0} t & 0 \le t \le t_0, \\ 0 & t_0 \le t \le T, \end{cases} \quad (1)$$

where, τ_t denotes the shear stress at moment t; τ_0 denotes the maximum stress at the shear stress peak; t refers to time, and t_0 refers to the load duration within a period; T refers to the total cycle of load effect, and T= t_0+t_d; td refers to the intermittent loading time within a period.

The loading frequency is equal to 10Hz, roughly equivalent to that automobile's running speed is equal to 70Km/h. Owing to the viscoelastic behavior of asphalt mixture, certain intermittent time should be considered during repeated shear creep test. Bouldin et al.[8~10] argue that viscoelastic deformation can be fully corrected when intermittent load time gets close to 10 times of loading time. Therefore, loading time in test is set as 0.1s, and intermittent time as 0.9s. Load form is shown in Fig.3.

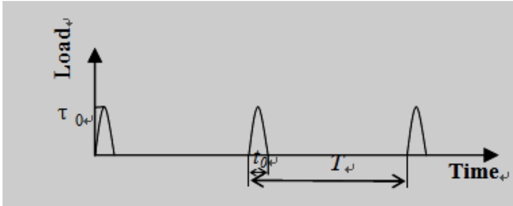

Figure 3. Repeated shear load form

2) Result analysis

Such two test temperatures as 40℃and 60℃,as well as such two stress peaks as 0.7MPa and 1.0MPa, were chosen for the test. 10,000 times of loading in test or over 5% of deformation was used as a termination condition. Two kinds of asphalts, SBS modified asphalt, and high modulus asphalt made of SBS modified asphalt and rock asphalt, were adopted. The test result is illustrated in Fig.4 and Fig.5.

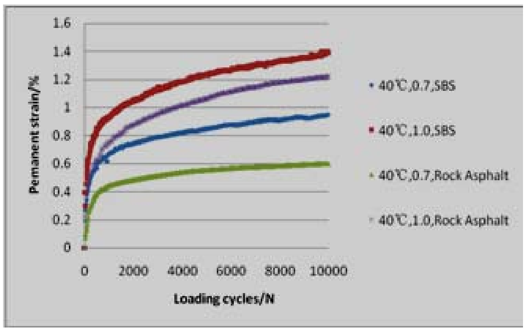

Figure 4. Repeated shear rheology(40℃)

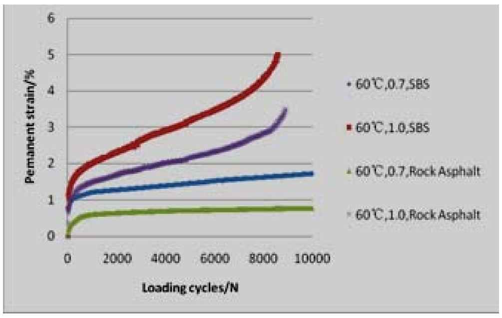

Figure 5. Repeated shear rheology(60℃)

A comparison between the deformation curves in Fig.4 and Fig.5 shows that the classic repeated shear rheological curve of asphalt mixture can fall into 3 stages: the first stage is the stage of decay creep. In this stage, the strain rate of asphalt mixture decreases rapidly with time to a non-zero stable value under the action of shear load; the second stage is the stage of uniform shear rheology of asphalt mixture. In this stage, the strain rate of asphalt mixture basically remains unchanged in a steady state under the action of shear load; the third stage is the stage of accelerated shear rheology of asphalt mixture. Only the first two stages of shear rheology of asphalt mixture are researched in the paper.

As is shown in Fig.4 and Fig.5, the strain rate decreases with the decrease of temperature and stress, and becomes lower after the incorporation of rock asphalt. So it can be seen that there is a critical value for asphalt mixture under the action of repeated shear load, and asphalt mixture will transit from the phase of decay rheology to the phase of stable rheology after stress reaches this critical value.

When rheological curve is in the stage of stable-state flow, after the incorporation of rock asphalt, non-deformability is significantly enhanced due to an increase in the viscosity of asphalt mixture. Compared to the asphalt not mixed with rock asphalt, the permanent deformation of the asphalt mixed with rock asphalt decreases by 15%～30% at 40℃,and decreases by 30%～50% at 60□,the permanent deformation of asphalt mixture increases rapidly, and the permanent deformation of the asphalt mixed with rock asphalt is 40%～60% lower than that of the asphalt not mixed with rock asphalt after temperature rises from 40□to 60□.So, the incorporation of rock asphalt can help significantly boost the non-deformability of asphalt mixture.

III. IDENTIFICATION OF REPEATED SHEAR LOADING RHEOLOGICAL MODEL

A. *Establishment of Repeated Shear Loading Rheological Model*

At present, the common rheological models include Maxwell Model, Kelvin Model, Standard Linear Model, Three-Mixing Amount Model, and Burgers Model[11]. The paper finally determined a shear rheological model for asphalt mixture by studying the above model and fitting the test data. Based on the above model, data fitting procedure was used to fit the test data at some level. The errors arising after fitting are illustrated in Tab.1.

TABLE I FITTING ERROR OF SHEAR RHEOLOGICAL MODEL

Model	Standard linear model	Three-mixing Amount Model	Double kelvin model	Burgers model
1	0.0395	0.0167	0.0130	0.0159
2	0.0373	0.0171	0.0124	0.0157
3	0.0402	0.0162	0.0135	0.0149
Average	0.039	0.0167	0.0130	0.0154

Note: Dual-Kelvin Model refers to a new model formed by two Kelvin Models in series

The fitting errors suggest that the average fitting error of Dual-Kelvin Model is equal to 0.0130, the minimum one among all fitting errors. Therefore, the final shear creep model was determined based on the base model Dual-Kelvin Mode. Since asphalt mixture is a typical viscoelastic material, a dashpot unit can be added to the repeated shear creep model of asphalt mixture based upon Dual-Kelvin Mode to build a new model, which is called “five-unit and five-parameter” model, as shown in Fig.6. Test data fitting on the strength of the newly built “five-unit and five-parameter” model indicates that the mean standard error is equal to 0.0079, which fully meets the experimental requirements.

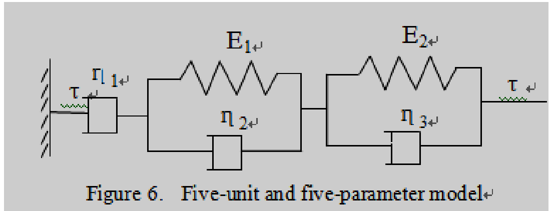

Figure 6. Five-unit and five-parameter model

“Five-unit and five-parameter” model is a linear viscoelastic model, and when constant load stress τ0 is exerted on the model, its creep compliance can be expressed as:

$$J(t)=\frac{\varepsilon(t)}{\tau_0}=\frac{t}{\eta_1}+\frac{1}{E_1}\left[1-\exp(-\frac{E_1}{\eta_2}t)\right]+\frac{1}{E_2}\left[1-\exp(-\frac{E_2}{\eta_3}t)\right] \quad (2)$$

where, J(t) refers to the shear creep compliance of asphalt mixture; t refers to the elapsed time; both E_2 and E_3 are viscoelastic shear moduli; both η_1 and η_2 are viscosity coefficients.

If first-order and second-order reciprocals of time t are evaluated respectively in Formula (2), then,

$$\dot{\varepsilon}=\frac{1}{\eta_1}+\frac{1}{\eta_2}\exp(-\frac{E_1}{\eta_2}t) \quad (3)$$

$$\ddot{\varepsilon}=-\frac{E_1}{\eta_2^2}\exp(-\frac{E_1}{\eta_2}t) \quad (4)$$

Formula (3) and (4) indicate that $\dot{\varepsilon}>0$ and $\ddot{\varepsilon}<0$. After τ_0 is exerted, the model will produce instantaneous elastic deformation, and with time passing, the creep rate will decrease gradually and reach a stable value finally, so this creep model can reflect steady state creep.

If load duration is between 0 and t_0 in a load period, after the end of a period the total strain will be:

$$\varepsilon(T)=\int_0^{t_0}\frac{d\tau(t)}{dt}J((N-i+1)T-t)dt \quad (5)$$

According to Boltzmann superposition principle[12], after the end of *N* load periods the total strain will be:

$$\varepsilon(NT)=\sum_{i=1}^{N}\int_0^{t_0}\frac{d\tau(t)}{dt}J((N-i+1)T-t)dt \quad (6)$$

Under the action of repeated shear load, the total strain of asphalt mixture consists of elastic strain ε_e , viscoelastic strain and plastic strain ε_p . Since elastic strain will return instantaneously after stress is removed, and $\varepsilon_e=\frac{\tau(t)}{E_0}$, it is set aside for the time being in analysis, so model strain consists of viscous flow strain and viscoelastic strain, as shown below:

$$\varepsilon=\varepsilon_v+\varepsilon_{ve} \quad (7)$$

$$\dot{\varepsilon}_v=\frac{t}{\eta_1} \quad (8)$$

$$\varepsilon_{ve}=\sum_{i=1}^{N}\int_{0}^{t_0}\frac{d\tau(t)}{dt}\cdot\frac{1}{E_1}\cdot(1-\exp(-\frac{E_1}{\eta_2}((N-i+1)T-i)))dt+$$
$$\sum_{i=1}^{N}\int_{0}^{t_0}\frac{d\tau(t)}{dt}\cdot\frac{1}{E_2}\cdot(1-\exp(-\frac{E_2}{\eta_3}((N-i+1)T-i)))dt$$
$$+\sum_{i=1}^{N}\int_{0}^{t_0}\frac{d\tau(t)}{dt}\cdot\frac{(N-i+1)T-i}{\eta_1}dt \qquad (9)$$
$$=\frac{\tau_0 t_0\pi(1+\exp(\frac{E_1}{\eta_2}t_0))\exp(-\frac{E_1}{\eta_2}T)}{\eta_1(\frac{E_1^2}{\eta_2^2}t_0^2+\pi^2)(1-\exp(-\frac{E_1}{\eta_2}T))}\cdot(1-\exp(-\frac{E_1}{\eta_2}NT))+$$
$$\frac{\tau_0 t_0\pi(1+\exp(\frac{E_2}{\eta_3}t_0))\exp(-\frac{E_2}{\eta_3}T)}{\eta_1(\frac{E_2^2}{\eta_3^2}t_0^2+\pi^2)(1-\exp(-\frac{E_2}{\eta_3}T))}\cdot(1-\exp(-\frac{E_2}{\eta_3}NT))+\frac{2\tau_0 t_0}{\eta_0\pi}N$$

Let

$$\alpha=\frac{\tau_0 t_0\pi(1+\exp(\frac{E_1}{\eta_2}t_0))\exp(-\frac{E_1}{\eta_2}T)}{\eta_1(\frac{E_1^2}{\eta_2^2}t_0^2+\pi^2)(1-\exp(-\frac{E_1}{\eta_2}T))}$$

$$\beta=\frac{\tau_0 t_0\pi(1+\exp(\frac{E_2}{\eta_3}t_0))\exp(-\frac{E_2}{\eta_3}T)}{\eta_1(\frac{E_2^2}{\eta_3^2}t_0^2+\pi^2)(1-\exp(-\frac{E_2}{\eta_3}T))}$$

$$\gamma=\frac{2\tau_0 t_0}{\eta_0\pi}$$

Then, after half-sine intermittent load acts for N periods, the total strain can be expressed as:

$$\varepsilon(NT)=\varepsilon_{ve}+\varepsilon_v$$
$$=\alpha(1-\exp(-\frac{E_1}{\eta_2}NT))+ \qquad (10)$$
$$\beta(1-\exp(-\frac{E_2}{\eta_3}NT))+\gamma N$$

B. Determination and Validation of Repeated Shear Rheological Model Parameters

1) Parameter identification

Differential evolution algorithm[13] is adopted in Formula (10) for data fitting and parameter identification at different temperatures and under the action of different loads, with viscoelastic parameters obtained in the end, as shown in Tab.2.

TABLE II SUMMARY TABLE OF PARAMETERS OF MECHANICAL MODEL

Temperature /□	Type	Peak stress /MPa	Parameters of mechanical model					
			η1 /(GPa.s)	E1 /MPa	η2 /(GPa.s)	E2 /MPa	η3 /(GPa.s)	Correlation coefficient /R^2
40	SBS	0.7	46.281	2.325	0.104	3.242	2.824	0.9979
		1.0	31.898	1.589	0.101	2.497	1.727	0.9985
	SBS+rock asphalt	0.7	65.734	3.811	0.188	2.802	1.347	0.9975
		1.0	34.222	1.974	0.163	2.302	1.293	0.9990
60	SBS	0.7	17.485	3.760	0.022	1.672	0.742	0.9990
		1.0	3.474	0.860	0.016	1.729	0.507	0.9995
	SBS+rock asphalt	0.7	19.912	11.361	0.084	12.279	0.749	0.9992
		1.0	5.685	1.363	0.036	1.737	0.394	0.9974

It can be seen from the fitting result that the correlation coefficient of fitting exceeds 99% at different temperatures and under different stresses, showing a high correlation, suggesting that the viscoelastic parameters obtained by fitting can well reflect the viscoelastic characteristics of asphalt mixture. At the same temperature and under the same stress, with the incorporation of rock asphalt, its viscous coefficient η1 increases significantly, and the high-temperature stability of high modulus asphalt is markedly enhanced. But the other parameters do not play a part independently in viscoelastic body, so they aren't analyzed separately, but should be considered as a whole.

2) Viscoelastic model and parameter verification

To verify the rationality of "five-unit and five-parameter" model and its parameters, we compared the theoretical result of the "five-unit and five-parameter" model with the test result, the result shown in Fig.7 and Fig.8.

It can be seen from Fig.7 and Fig.8 that the theoretical curve of "five-unit and five-parameter" model can fit well with the test points at different temperatures and in different stress states, suggesting that it is rational to simulate the first two stages of shear rheology of asphalt mixture by the use of the "five-unit and five-parameter".

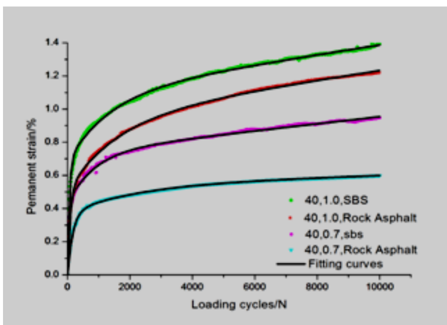

Figure 7. Viscoelastic strain at 40℃

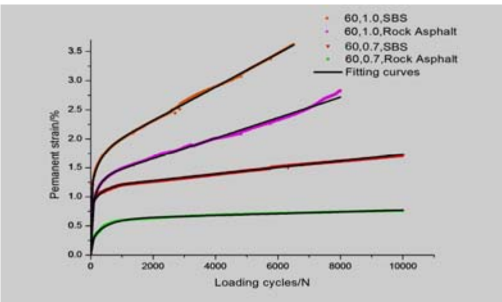

Figure 8. Viscoelastic strain at 60℃

IV. CONCLUSIONS

(1) There is a critical value for asphalt mixture under the action of repeated shear load, and asphalt mixture will transit from the phase of decay rheology to the phase of stable rheology after stress reaches this critical value.

(2) A "five-unit and five-parameter" model with a good fitting effect is built based upon parameter inversion in the paper, and then a creep equation is deduced for asphalt mixture under the action of repeated shear load.

(3) It can be seen from the test result that after the incorporation of rock asphalt, non-deformability is significantly enhanced due to an increase in the viscosity of asphalt mixture. At the same temperature and under the same stress, with the incorporation of rock asphalt, its viscous coefficient η_1 increases significantly, and the high-temperature stability of high modulus asphalt is markedly enhanced.

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