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Analysis of viscoelastic response and creep deformation mechanism of asphalt mixture

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HIGHLIGHTS

- Burgers viscoelastic parameters and the steady-state creep rate K were obtained.
- The effects on the viscoelastic parameters of asphalt mixture were analyzed.
- The stress index and creep activation energy of asphalt mixture were proposed.
- The creep mechanism of the asphalt mixture was discussed.

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ABSTRACT

Asphalt mixture is a typical viscoelastic material. Its mechanical response and deformation behavior depend on the role of time, temperature conditions and stress levels. Three kinds of asphalt mixture (i.e. AC-13, AC-16, AC-20) were used for the static creep test in different temperature conditions and stress levels. According to the creep curve, The Burgers viscoelastic parameters including E_1, η_1, E_2, η_2 and the steady-state creep rate K were obtained. The effects of test temperature, stress level and aggregate gradation on the viscoelastic parameters of asphalt mixture were analyzed. Based on the relationship between the steady-state creep rate and the experimental temperature & load stress, the stress index and creep activation energy of asphalt mixture were proposed. By analyzing the relationship between the creep activation energy and the rutting depth, the creep mechanism of the asphalt mixture was discussed. The results show that with the increase of temperature, the four parameters of E_1, η_1, E_2 and η_2 of the three kinds of asphalt mixtures generally decrease. But at different temperatures, the viscoelastic parameters of these three kinds of mixtures are not the same. The stress level has a significant effect on the viscoelastic properties of the asphalt mixture. The four viscoelastic parameters have the largest differences when the stress level is at the intermediate load level of 0.5 MPa, but the responses of the different gradation asphalt mixture to the stress level are different. With the increase of temperature and load stress, the steady-state creep rate increases gradually, but the stress indexes of these three kinds of asphalt mixtures stress index are not different. All of them are less than 3, and belong to the diffusion creep under the control of aggregate interface dislocation mechanism. The asphalt mixture that has larger creep activation energy has better stability under high temperature. AC-16 mixture has the highest creep activation energy. Nominal particle size is not a decisive factor for the performance in high temperature.

1. Introduction

Asphalt mixture is a material with typical viscoelasticity. Its mechanical behavior has time dependence and is related to temperature, load level and other external factors and their own material composition. Almost all viscoelastic materials (such as bitumen, latex, epoxy resin, etc.) have a creep mechanical behavior. Asphalt pavement rutting, cracking, fatigue damage and other pavement distresses are connected with the viscoelasticity of the mixture. The pavement distresses are the external manifestation of viscoelasticity of asphalt mixture out of its normal working condition. Therefore, the research on the viscoelasticity of asphalt mixture has been paid more and more attention by researchers both at home and abroad [1]. Researchers have done a lot of laboratory tests. Little et al. [2] analyzed the stress state and deformation behavior of asphalt mixture by the stress-strain relationship of asphalt concrete. Hafez [3] and Molenaar[4] used uniaxial

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unrestricted creep tests to study the performance of asphalt mixtures. Zhou et al. [5] studied the high-temperature stability of asphalt mixture under heavy load by the five-stage uniaxial compression creep test of asphalt mixture. The permanent deformation mechanism of asphalt mixture was analyzed from the perspective of energy. Seismic measurements and conventional cyclic loading were applied to a cylindrical asphalt concrete specimen to compare the complex modulus and complex Poisson's ratio [7]. Zheng et al. [8] discussed the viscoelastic damage characteristics of asphalt using creep test. Fan et al. [9] studied the static and dynamic responses of asphalt mixture by static and dynamic creep tests. However, few tests used a viscoelastic model to simulate the creep test of asphalt mixture. Chang et al. [10] compared the viscoelasticity of asphalt mixture by using the Maxwell, Kelvin and Burgers Model. They pointed out that the Burgers model can better simulate the mechanical properties of asphalt mixture. Hou et al. [11] used the Burgers viscoelastic model as a mathematical description of the viscoelastic behavior. The effect of temperature on the viscoelastic properties of asphalt mastic was studied by the static shear creep test of asphalt mastic. Schwartz et al. [12] performed the same creep test under the same loads, 25 °C–45 °C, and obtained a viscoelastic parameter. Masad et al. [13] proposed a multiple stress creep recovery (MSCR) to Characterize the asphalt binder resistance to permanent deformation. Wasage et al. [14] discussed the feasibility of replacing $|G^*|/\sin\delta$ with creep compliance J_{nr} obtained by MSCR Test and used the parameter to predict the high temperature resistance of the mixture. But White [15] found the creep compliance of asphalt binder was poorly correlated with asphalt mixture wheel track rutting and repeated shear flow test results. Zhou et al [16] deduced the viscoelastic parameters according to the dynamic creep test, and discussed the relationship between the model parameters and the dynamic stability of the rut. Pasetto et al. [17, 18] analyzed the mechanical response of asphalt concretes and discussed a visco-elastoplastic constitutive model to analyze the creep deformability of asphalt concretes. But the creep mechanism of the asphalt mixture and its relationship with the viscoelastic response lacked in-depth research. In this study, the parameters of the Burgers model and the steady-state creep rate were obtained through the creep test. The effects of temperature, stress level, gradation and aging on the viscoelastic response of asphalt mixture were analyzed. Based on the relationship between the steady-state creep rate and the experimental temperature and load stress, the stress index and creep activation energy of asphalt mixture were proposed, which further revealed the creep mechanism of asphalt mixture. The results can provide good references for the mechanical analysis of asphalt mixture, the asphalt pavement design and the pavement distress analysis.

2. Experiment material

2.1. Binders

The asphalt binder has significant influences over the responses of asphalt mixture. In order to evaluate the effects on viscoelastic dynamic response of asphalt mixture, three typical binders were adopted in this study. SK™ modified asphalt with Yanshan™ SBS 4303 agent (SK-SBS), Maoming™ asphalt (MM) and Zhonghai™ asphalt (ZH) were respectively added into mixtures of AC-13, AC-16 and AC-20. Their properties were tested and listed in Table 1.

2.2. Aggregate and gradations

In order to achieve precise control over the aggregate gradation, all aggregates were sifted into different sizes and then mixed into the specific gradation. Amphibolite rock was adopted as the coarse and fine aggregates. The specific gravity of aggregates with each sieve size is given in Tables 2 and 3. The ground limestone applied as filler had a density of 2.706 g/cm^3.

The AC-13, AC-16 and AC-20 gradations, namely the conventional continuously dense gradations defined in the *Chinese Technical Specification for Construction of Highway Asphalt Pavement* [25], were adopted in this paper. Their nominal-maximum-aggregate-sieves are 13, 16 and 19 mm respectively. The applied gradations are shown in Table 4. The optimum asphalt content of the asphalt mixture was obtained by the Marshall design method in this study. The optimum ratios between the asphalt and the aggregate are respectively 5.2%, 4.9% and 4.3%, and the designed air void ratios of these three asphalt mixtures mentioned above are all 4.0%.

Table 1
Properties of asphalt binders.

Test indicators		SK-SBS	MM	ZH	Test methods [19–24]
Density (15 °C)/(g/cm^3)		1.031	0.986	1.005	ASTM D70
Penetration (25 °C, 5 s, 100 g)/(1/10 mm)		69	74	86	ASTM D5
Softening Point (R&B)/°C		75.0	49	45.5	ASTM D36
Ductility (5°C, 5 cm/min)/cm		42(@5 °C)	154	>150(@15 °C)	ASTM D113
Flash point/°C		298	283	272	ASTM D92
Penetration index/		−0.032	−0.495	−0.991	ASTM D5
Film Heating Test (163 °C, 5 h)	Mass loss/%	0.08	−0.35	0.04	ASTM D1754
	Penetration ratio/%	65.0	68	76.3	ASTM D1754/D5
	Residual ductility (5 cm/min)/cm	23(@5 °C)	44.3	>150(@15 °C)	ASTM D1754/D113

Table 2
Coarse aggregate bulk specific gravity according to AASHTO T-85.

Sieve Size, mm	19.0	16.0	13.2	9.5	4.75
Bulk Specific Gravity, Gsb	2.806	2.748	2.714	2.709	2.682

Table 3
Fine aggregate bulk specific gravity according to AASHTO T-84.

Sieve Size, mm	2.36	1.18	0.6	0.3	0.15	0.075
Apparent Specific Gravity, Gsa	2.729	2.798	2.788	2.791	2.800	2.834