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Research on Fatigue Resistance Performance of Nano-Rubber Powder Modified Asphalt

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Abstract: Asphalt pavement has been used in road construction and many other applications for a long time. Because of the heavy loading and busy traffic, pavement distresses such as stripping, raveling, cracking, and moisture damage often occur during its serving life. The possibility of using nano-rubber as a modifier for asphalt was investigated in this research. Fatigue test according to the American Association of State Highway and Transportation Officials (AASHTO) T321-03 standard was conducted. Fatigue resistance performance of the original asphalt concrete and modified asphalt concrete was investigated by means of a four-point bending test with the phenomenological fatigue methodology at two temperatures. The results showed that rubber modified asphalt concretes have good basic physical performance. Also, the flexural stiffness modulus of modified asphalt-based composites had less influence on strain at 5°C, but at 15°C, the effect was obvious. The fatigue performance of nano-rubber modified asphalt-based composite was better than that of base asphalt and Styrene-Butadiene-Styrene (SBS) -modified asphalt. Strain (ε) of nano-rubber modified asphalt concrete was smaller, and its fatigue performance was better. Comparing the toughening effect of other ordinary modification powders, a little amount of nano-rubber powder could increase the toughness of modified asphalt concrete greatly and keep them in high tension and heat resistance. Nano-rubber powder modified asphalt has the advantage of aging-resistance, which could improve the service life of the modified asphalt and reduce the maintenance cost of pavement.

***Key words**: Fatigue resistance; Four-point bending test; Modified asphalt; Nano-rubber powder.*

Introduction

Application of nanometer technology on the modern industry has obtained many achievements due to its surface effect and volume effect as well as quantum size effect and macroscopical quantum tunnel effect of nanometer particles. It has been the most potential incremental portion in the industry and focused on by many countries in 21st century. The ultrafine powder full-vulcanized nitrile rubber has been used extensively in polymer-plastic materials in the past few years. Based on the toughness increment theory, the smaller the dispersion phase particle is, the easier the transition of brittlement-toughness of polymer-plastic mixture materials. Because distance between each particle was small and the length of base layer was thinner, the toughness could be increased effectively with utilization of ultrafine nano-material, and the general properties of materials could be improved with nanometer effect even some vagarious capabilities [1, 2].

Particle size of the ultrafine powdered full-vulcanized nitrile rubber can be controlled under 100*nm* with a bigger specific area and easier to disperse. Therefore the formation of network dispersion structure can be easily obtained. The particle size would not change after mixing with plastic; therefore, the nanometer effect can be performed effectively in polymer toughness increment modification and better mechanical properties can be achieved [3]. When it is used with a small amount of general polymer, synergism effect can be achieved. In addition, the strength and anti-thermal properties can be improved when the dispersion of nanometer polymers in plastic reach equilibrium state [4, 5]. Repeated loading will result in decreased strength because of the fatigue. Water can influence the adhesion between bitumen and the aggregate. All these influences can lead to early pavement failure [6-8].

Whether or not the nanometer technology can be applied on modification of asphalt has become interesting to pavement researchers. The application of nanometer technology into modified asphalt has been well recognized overseas. It is compound materials of polymer and nanometer modification. [9-11] However, the same technology in China is still not well recognized [12-14]. The ultrafine powdered full-vulcanized nitrile rubber and its application in the compounding toughening modification of bitumen are introduced in this paper. As compared with the toughening effect of base asphalt and ordinary powder Styrene-Butadiene-Styrene (SBS) -modified asphalt, a little amount of full-vulcanized nitrile rubber can increase the toughness of asphalt materials greatly and keep them in high tension and heat resistance.

Experimental Program

The asphalt binder tested was base asphalt and PG70-28 SBS-modified asphalt that was supplied by Shell Asphalt Co. Ltd. in Hubei province, China. Its specification is showed in Table 1. The ultrafine powdered full-vulcanized nitrile rubber was obtained from Chemical Industry of Beijing Institute and 3% weight content was

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Table 1. Specifications of Asphalt Binder.

	Item	Results	Index
Base Asphalt	Penetration/0.1*mm*	64	60-80 (25°C)
	Softening Point/°C	48.5	44-54
	Ductility/*cm*	>100	≥ 100 (15°C)
SBS Modified Asphalt	Penetration/0.1*mm*	76	60-80 (25°C)
	Softening Point/°C	56.8	≥ 55
	Ductility/*cm*	27.4	≥ 20 (5°C)
Nano-Powder Modified Asphalt	Penetration/0.1*mm*	79	60-80 (25°C)
	Softening Point/°C	65	≥ 55
	Ductility/*cm*	36	≥ 20 (5°C)

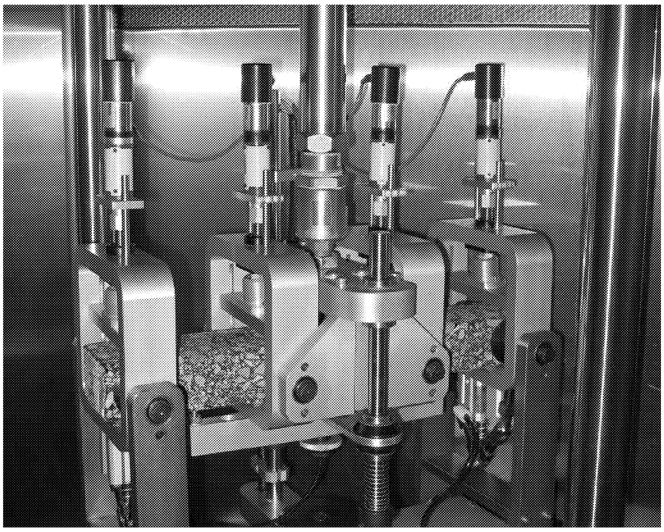

Fig. 1. Experiment Apparatus.

added into original asphalt. Gneiss coarse aggregates and fine aggregates (bulk specific gravity of 2.69 and 2.71, respectively) were used for the asphalt mixtures. Limestone was selected as mineral filler. The gradation type of AC 25 was selected for asphalt mixture. Mineral filler content is 2% by weight, and preliminary asphalt content is 4.0%.

The specimens were prepared by means of the wheel-roller method at 140°C and the dimension is 400 × 300 × 65*mm*. The density met the Marshall standard attacking samples 100 ± 1%. The rutting samples were placed aside for more than 12hrs and then were cut into beams, which had a length of 380 ± 2.0*mm*, and a width of 63.5 ± 2.0*mm*, and a height of 50 ± 2.0*mm*.

Universal Testing Machine UTM-25 was used to test the beam specimen according to the American Association of State Highway and Transportation Officials (AASHTO) Designing Standard T321-03 [15]. The experiment apparatus is shown in Fig. 1. Test condition is as follows: (1) Using strain control method, which keeps flexibility invariable; (2) Temperature was at 5 and 15°C; (3) Frequency is 10Hz; (4) Loading waveform was sine-wave, which is thought to be similar to the waveform of real road bearing; and (5) Bending stiffness modulus obtained after the 50th cycle of the test was the initial bending stiffness modulus and the broken condition was determined when the bending stiffness modulus was 50% of its initial.

Results and Discussion

Cycle load was applied to the specimen at a certain micro-strain and measured the maximum tension stress (σ_t) and strain (ε_t) in every cycle, then calculated bending stiffness, *S*, as shown in the Eqs. (1) to (3):

$$\sigma_t = \frac{0.375P}{bh^2} \tag{1}$$

$$\varepsilon_t = \frac{12\delta h}{3L^2 - 4a^2} \tag{2}$$

$$S = \frac{\sigma_t}{\varepsilon_t} \tag{3}$$

where,
P : sensor application load, *N*;
b : average breath of specimen, *m*;
h : average height of specimen, *m*;
δ : max shape change in the middle of beam, *m*;
a : distance between the middle two clips,0.357/3*m*, (0.119*m*); and
L : distance between the outer two clips, 0.357*m*.

Bending stiffness modulus, S_0, obtained after the 50th cycle of the experiment is the initial stiffness of specimen, and it is the reference when the specimen fails. Ten thousand cycles are the least requirement for the experiment, and when the bend stiffness decreases to 50% or less than 50% of the initial value, it indicates the specimen has broken.

The relationship between initial bending stiffness and strain at 5 and 15°C is showed in Figs. 2 to 4.

As seen in Figs. 2 to 4, the initial bending stiffness of all specimens increases with increasing strain standard regardless of the temperatures, at 5 or 15°C. Note that the initial bending stiffness modulus of material reflects the resistance capability of bending deformation.

Resistance capability of bending deformation at a low temperature is bigger than that at room temperature. As the strain standard increases, deformation resistance reduction of nano-rubber modified asphalt is shorter than that of the base asphalt. Meanwhile, the initial stiffness modulus of nano-rubber modified asphalt beam is obviously higher than that of base asphalt and SBS-modified asphalt beams.

Phenomenological fatigue methodology was applied to investigate fatigue performance of asphalt mixture. The fatigue life includes crack formation and extension periods. Furthermore, it is convenient to study the mechanism of crack formation and the relationship between strain-stress and fatigue life. Asphalt concrete fatigue is defined as the non-recoverable strength decaying accumulation appearance when repeated load on materials in phenomenological fatigue methodology. The cycled load, when fatigue damage of materials appears, is called fatigue strength; the corresponding cycle time is called fatigue life.

In strain control way, the fatigue broken standard is defined as the stiffness decreases to 50% of its initial. Fatigue life and bending strain relation of asphalt concrete, when it is strain-controlled, can be expressed in the classical fatigue function and is shown in Eq. (4):

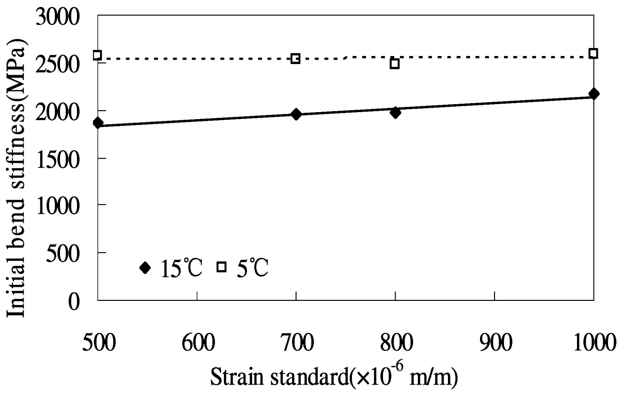

Fig. 2. Initial Bending Stiffness to Strain of Base Asphalt Beam.

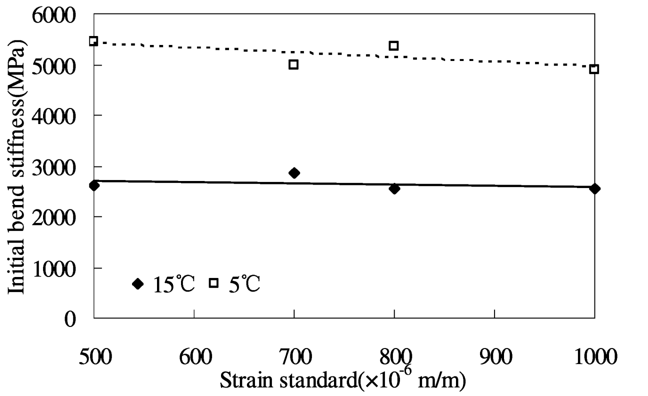

Fig. 3. Initial Bending Stiffness to Strain of SBS Modified Asphalt Beam.

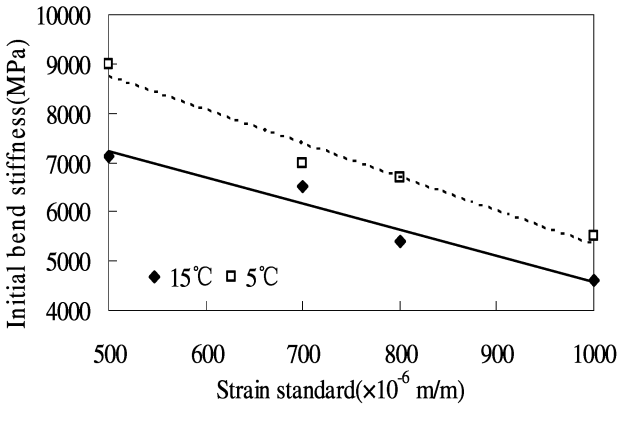

Fig. 4. Initial Bending Stiffness to Strain of Nano-Rubber Modified Asphalt Beam.

$$N_f = \left(\frac{\varepsilon_{\max}}{\varepsilon_0}\right)^n = \varepsilon_{\max}^n \left(\frac{1}{\varepsilon_0}\right)^n = K\left(\frac{1}{\varepsilon_0}\right)^n \quad (4)$$

where,

N_f : repeated load time when fatigue broken occurs in specimen,

ε_0 : bending strain,

$\varepsilon_{\max}$: maximum bending strain that specimen can bear in a cycle, that is limited bending strain, and

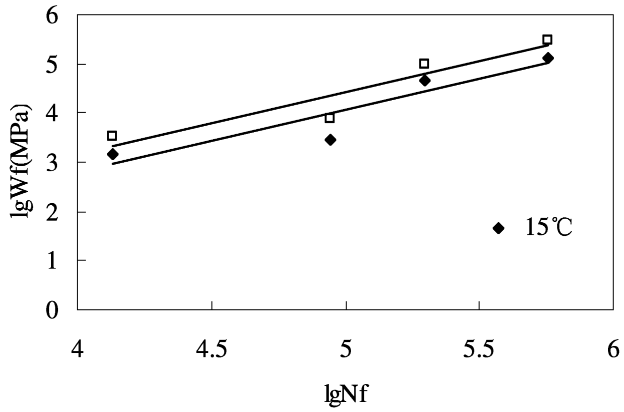

Fig. 5. Beam for Base Asphalt Cycle Time-Strain in Double-Log Coordinate.

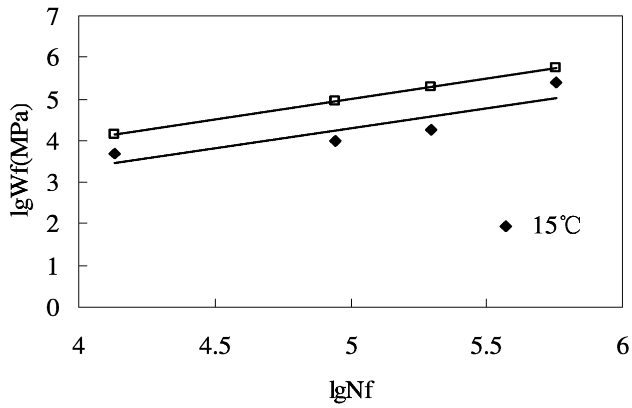

Fig. 6. Beam for SBS Modified Asphalt Cycle Time-Strain in Double-Log Coordinate.

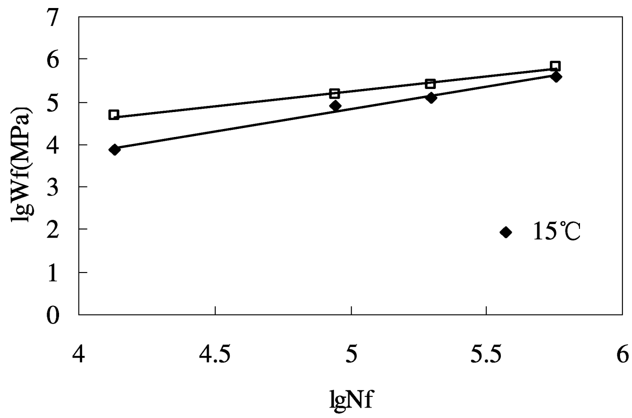

Fig. 7. Beam for Nano-Rubber Modified Asphalt Cycle Time-Strain in Double-Log Coordinate.

K and n : coefficients obtained from the experiment.

The bending beam fatigue curves are shown in Figs. 5 to 7. As seen from these figures, there is good linear relationship after logarithm transformation of strain and fatigue life at 5 and 15°C.

The linear relationships of fatigue life and strain standard in double logarithm reference frame for all specimens are given in Figs. 5 to 7. According to the figures, linear function can be regressed between fatigue life and strain standard after using logarithm reference frame and the calculation of K. The n, representing the

Table 2. Fatigue Life - Strain Equation at 5°C.

Material Categories		Fatigue Function	Regression Coefficient K	n	$\varepsilon_{max}(\times10^{-6})$
5°C	Base Asphalt	$N_f = 2.0\times10^{24}(\frac{1}{\varepsilon_0})^{7.0129}$	2.0×10^{24}	7.0129	3192
	SBS Modified Asphalt	$N_f = 7.0\times10^{20}(\frac{1}{\varepsilon_0})^{5.7594}$	7.0×10^{20}	5.7594	6335
	Nano-Rubber Modified Asphalt	$N_f = 2.0\times10^{20}(\frac{1}{\varepsilon_0})^{5.3949}$	2.0×10^{20}	5.3949	15958

Table 3. Fatigue Life - Strain Equation at 15°C.

Material Categories		Fatigue Function	Regression Coefficient K	n	$\varepsilon_{max}(\times10^{-6})$
15°C	Base Asphalt	$N_f = 2.0\times10^{24}(\frac{1}{\varepsilon_0})^{6.9351}$	2.0×10^{24}	6.9351	2919
	SBS Modified Asphalt	$N_f = 1.0\times10^{20}(\frac{1}{\varepsilon_0})^{5.2607}$	1.0×10^{20}	5.2607	4162
	Nano-Rubber Modified Asphalt	$N_f = 1.0\times10^{16}(\frac{1}{\varepsilon_0})^{3.8068}$	1.0×10^{16}	3.8068	5794

slope of the regressed linear function, in classical fatigue function can be calculated from *K*, the maximum strain that specimen can bear in a cycle and can be calculated, as seen in Tables 2 to 3.

Conclusions

The effect of nanometer rubber powder modified asphalt filler on the stiffness fatigue properties of beam was obviously better than those of SBS-modified asphalt and base asphalt. The results indicate that a proper amount of nano-rubber can lead to a bigger initial stiffness and longer fatigue life. So nanometer rubber powder has the potential in the application to the asphalt modification.

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