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Low-temperature rheological behavior of ultraviolet irradiation aged matrix asphalt and rubber asphalt binders

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HIGHLIGHTS

- Low-temperature rheological behavior of ultraviolet irradiation aged asphalt binders are compared with original and thermal-oxidative aged ones.
- Burgers model was utilized to describe the constitutive relationship quantitatively.
- Genetic algorithm was employed to optimize the nonlinear regression of viscoelastic parameters.
- Asphalt binder beams were shaped in an advanced mold.

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ABSTRACT

In order to investigate the influence of ultraviolet (UV) irradiation aging on the rheological properties of asphalt binders at low temperatures, this paper analyzes the low-temperature rheology characteristics (stiffness modulus S and tangent slope m) of matrix asphalt and rubber asphalt in the bending beam rheometer (BBR) test. The beam of asphalt binder was shaped in an advanced mold to receive more ultraviolet irradiation. The asphalt samples were subjected to different given UV-irradiation time (50 h, 100 h, 200 h, and 300 h) after thin film oven test (TFOT), with an indoor UV-irradiation aging simulation system. As comparative groups, corresponding original samples and thermal-oxidative aged samples from TFOT and pressurized aging vessel (PAV) test were also measured in BBR. Furthermore, based on the viscoelasticity theory, Burgers model was utilized to describe the constitutive relationship. In order to achieve a global solution, genetic algorithm (GA) was adopted for the nonlinear regression of viscoelasticity parameters (E_e, E_d, η_1, and η_2) under different aging conditions. The results show that TFOT-UV aging had a different influence on the matrix asphalt and rubber asphalt. The effect of TFOT-PAV aging to the (relative variation ratio of) viscoelastic parameters was equivalent to that of TFOT-UV aging during the irradiation time less than 100 h to the rubber asphalt. Along with the UV-irradiation time increasing, the S increased and m decreased, therefore, the low-temperature performance of asphalt binders became worse.

1. Introduction

Relevant research shows that the direct contribution rate of asphalt nature on the low-temperature performance of asphalt pavement was up to 80% [1,2]. The low-temperature rheology performance of asphalt binder is one of the important factors for the surface cracking [3]. Excessive hardening frequently results in embrittlement and cracking of the pavement's asphalt layer, particularly when it is exposed to low temperatures in the service life [4,5]. When the temperature is below 10 °C, the performance of asphalt mixture depends on the asphalt nature, which mainly means that the stress relaxation ability weakens, along with the asphalt becoming brittle and harden. Under traffic loads and complex environmental factors, the tensile stress of asphalt mixture will exceed the ultimate tensile strength and result in cracking damage.

At present stage, the common methods of low-temperature performance testing for asphalt binders are summarized in Table 1. Among them, all four of low-temperature penetration, ductility, breaking point and equivalent breaking point are empirical indicators. They can only correspond to several given fixed temperatures or deformations, but could not reflect the mechanical properties for the whole process with temperature change. Thus, they are hard to be the parameters for theoretical analysis and calculation [6,7]. Next, in the specifications of the strategic highway research program (SHRP), some tests such as the dynamic shearing rheology

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Table 1
Comparison of different methods for low-temperature performance testing of asphalt binders.

Method	Indicator	Common testing temperature/°C	Single sample mass/g	Equipment
Low-temperature penetration	Penetration	≥5	50 ~ 150	Low-temperature penetrometer
Low-temperature ductility	Ductility	5, 10, 15, 25	30	Ductility testing machine
Breaking point	Temperature	Measure	0.4	Fraass breaking point instrument
Equivalent breaking point	Temperature	15, 25, 30 (10, 20)	50 ~ 150	Penetrometer
DSR	Modulus, phase angle, et al.	≥5	0.1 ~ 0.5	DSR
BBR	*S*, *m*	0 ~ −36	15	BBR
DTT	Rupturestrain/stress	0 ~ −36	3	DTT
T-critical [10,11]	Critical temperature	Calculation	18	BBR and DTT
Loading test	Modulus	Set	Set	Universal testing system

(DSR) and bending beam rheometer (BBR) are used to measure the modulus of asphalt binder and evaluate the low-temperature performance. Two indicators are given in the BBR test: the flexural creep stiffness modulus (*S* for short) and the curve tangent slope in the double-logarithmic curve of stiffness modulus vs. loading time (*m* for short). As the supplementary of BBR, direct tensile test (DTT) is applied when *S* is from 300 MPa to 600 MPa and *m* is not less than 0.3 [8]. Many researchers believe that the viscoelasticity can reveal the low-temperature properties of asphalt materials in an even better fashion. In 1954, Van Der Pool's research showed that the stiffness modulus approached the elastic modulus under low-temperature or short-term loads, but it sharply declined along with the longer loading time or higher temperature. Test results of Pennsylvania road confirmed that the transverse cracks were strongly relevant with the stiffness modulus [9]. Therefore, BBR was chosen as the experimental method, considering it can quantitatively describe the properties in lower temperatures and has been recognized globally.

In addition, from the macro perspective, reasons for the low-temperature cracking of asphalt pavement mainly focus on: the tensile strength is not enough or the porosity is improper in most cases. Furthermore, aging can make the above two situations worse. Research shows that when the asphalt pavement is directly exposed to the sunlight, the ultraviolet (UV) irradiation, accounting for about 5% of the sunlight, will affect the part within the depth range of 0.1 mm from the pavement surface; and then the irradiation influence will expand to a depth of 1 mm because of the diffusion of asphalt molecules. Next, the irradiation influence will continue to expand to 10 mm depth owing to the air void or crack damage [12]. Without a doubt, since the thickness of asphalt film is generally in the range from 5 μm to 15 μm in the mixture, the UV irradiation affects the asphalt pavement inevitably [13].

In the studies of Ouyang and Durrieu, the aging process led to the decline of asphalt properties such as low-temperature cracking and shorter lifespan of asphalt pavement [14,15]. Oxidation existing in the aging has been considered to be the primary cause of hardening and embrittlement of asphalt binder in service [16,17]. UV-6 days aged of asphalt binders with various mass ratio of layer clay powder to asphalt were tested to investigate the low-temperature strength [18]. From the results of ductility and BBR test, UV aging reduced the low-temperature performance of rubber asphalt, and the result from pressurized aging vessel (PAV) test aged sample was equivalent to that of UV aging in 12–15 months [19,20]. With the increase of aging time, the low-temperature of rubber asphalt with the thickness of 1 mm was affected significantly [21]. The low-temperature parameters of warm mix rubber asphalt changed at an earlier stage of UV aging and then tended to steady [22]. For matrix asphalt in the DTT, that performance got to be worse under UV aging and the strain-energy density changed a little when the irradiation time exceeded 220 h [23].

Unfortunately, research on the low-temperature performance of UV aged asphalt is limited at this stage. That is because, there is no standard on the UV-aging test for asphalt materials, and the number of samples is scarce to meet the low-temperature test on account of the thin film. It's therefore not easy to carry out related studies. Moreover, the viscoelastic parameters of asphalt binders at low-temperature after UV-irradiation are not concerned enough and need further research.

In consideration of the fact, that the areas with heavy ultraviolet irradiation are widely distributed in China, it is necessary to study the UV-irradiation aging performance of asphalt materials since the asphalt pavement takes up more than 90% of the total pavements. In order to investigate the UV-irradiation influence, this paper analyzes the low-temperature rheology characteristics (stiffness modulus and tangent slope) of matrix asphalt and rubber asphalt in the BBR test. The samples include the original ones, different irradiated ones within an indoor UV aging simulation system and thermal-oxidative aged ones from the thin film oven test (TFOT) and PAV. Based on the viscoelasticity theory, Burgers model was used to describe the constitutive relationship, and genetic algorithm (GA) was adopted for the nonlinear regression of viscoelasticity parameters. The research process can be seen in Fig. 1. It is worth mentioning that: in view that the UV-irradiation aging and PAV aging are continued on the TFOT aged samples, TFOT-UV and TFOT-PAV represent the UV-irradiation aging and PAV aging in this paper, respectively.

2. Tests overview

In order to simulate and compare the low-temperature performance of asphalt materials with or without intense UV-irradiation aging, BBR tests are carried out on the original samples, TFOT, TFOT-UV and TFOT-PAV aged samples.

2.1. Raw materials

Two kinds of binders, matrix asphalt and rubber asphalt, were used in this research. The matrix asphalt is Shell 70#. According to our preliminary experiments [24], the preparation plan for rubber asphalt is as follows: (i) Shell 70# is as the base asphalt. (ii) The fineness of rubber powder is 60 mesh and its additive dosage is 25%. (iii) The mixing mode of high-speed shearing in 30 min and simple mixing in 90 min is adopted, and the mixing temperature is 185 °C. The asphalt binder tests followed the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) and the performance results are shown in Table 2.

2.2. Aging treatments

Due to the fact that the asphalt beams will generate deformation once out of forming mold, the beams should be in the molds during the aging test. In current specifications, the existing molds only allow the exposure of narrower side to the air, so a kind of advanced mold was employed [24]. The advanced mold can form