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Effect of nano-zinc oxide and organic expanded vermiculite on rheological properties of different bitumens before and after aging

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HIGHLIGHTS

- Aging properties of different based bitumens with nano-ZnO and OEVMT were compared.
- The rheological properties of the binders were evaluated before and after TFOT, PAV, UV and NEA.
- The improvement effect in aging resistance of bitumen depends on the aging degree and nature of bitumen.

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ABSTRACT

A novel anti-aging modifier containing surface modified nano-zinc oxide (nano-ZnO) and organic expanded vermiculite (OEVMT) was used to improve the aging properties of different bitumens (denoted as 70#, 90# and 110#). These aging methods include thin film oven test (TFOT), pressure aging vessel (PAV), ultraviolet (UV) radiation and natural exposure aging (NEA). The aging properties of the binders after different aging methods were evaluated by dynamic shear rheometer (DSR) test and bending beam rheometer (BBR) test. The result shows that the rutting resistance of three types of bitumens before the above aging methods is enhanced with the introduction of anti-aging modifiers. As a result of TFOT, PAV, UV and NEA, compared with corresponding blank samples, these modified bitumens containing anti-aging modifier show the lower complex modulus and the higher phase angle, indicating their good thermal oxidation and photo oxidation aging resistance. Moreover, the improvement effect of anti-aging modifier is not only bound up with the aging degree of these bitumens, but also depends on the bitumen nature. Besides, the BBR test result manifests that the anti-aging modifier can improve the low-temperature rheological performance of 90# bitumen after PAV aging, and has little influence on that of 70# bitumen and 110# bitumen after PAV aging.

1. Introduction

Bituminous materials are vulnerable to aging in the process of construction and service time of pavement, which will seriously affect the service performance and service life of bitumen pavement [1,2]. Based on the different stages during construction and usage of asphalt pavement, the aging is divided into short-term aging and long-term aging. The short-term aging happens in the process of mixing, transportation, paving and compaction of bituminous mixture, which is also called for short-term thermal oxidation aging [3]. The short-term aging is usually simulated by TFOT or rolling thin film oven test (RTFOT). In addition, the long-term aging happens during the service time of pavement. On the basis of different causes of bitumen aging, the long-term aging is further classified into long-term thermal oxidation aging and long-term photo oxidation aging [4–6]. The PAV is used to simulate the long-term thermal oxidation aging, while the UV radiation is utilized to simulate the long-term photo oxidation aging.

In order to enhance the aging resistance of bitumen, many studies have been conducted. Generally, adding anti-aging modifiers to bitumen for enhancing the aging resistance is the main method. The anti-aging modifiers mainly include antioxidant [7–9], UV absorber [9–12], layered silicates [12–15] and inorganic nanoparticles [16–20].

In terms of antioxidant and UV absorber, Martin et al. [7] found that though some antioxidants (eg. phenols, amine and aminophenol) could improve the anti-aging property of lubricating oil, resin, rubber and so on, they had no pronounced effect on the anti-aging property of bitumen. What's worse, these antioxidants in

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improving the anti-aging property of bitumen had a larger selectivity, sometimes even accelerated the aging of bitumen. Cong et al. [9] studied the influence of two UV absorbers (octabenzone and bumetrizole) and two antioxidants (zinc dialkyldithio phosphate and carbon black) on aging resistance of bitumen. The results showed that the single UV absorbers or antioxidants could not enhance simultaneously the photo and thermal aging resistance of bitumen. Moreover, the bumetrizole sometimes showed the opposite influence on thermal-oxidative aging or UV aging of bitumen. Feng et al. [11] found that two UV absorbers (octabenzone and bumetrizole) could remarkably improve the photo aging resistance of SK-70 bitumen, whereas they had a little effect on the thermal aging resistance of SK-70 bitumen. Furthermore, different UV absorbers had different influence on aging resistance of different bitumens. That was to say that an UV absorber could enhance the aging resistance of some bitumens, but it had reversed effect on aging resistance of else bitumens.

With respect to layered silicates and inorganic nano-particles, Yu et al. [12] studied the effect of organo-montmorillonite (OMMT) on aging properties of bitumen, and found that OMMT could improve the physical and rheological properties of bitumen after thermal-oxidative aging. Lamya et al. [13] also found that OMMT could enhance the short-term thermal oxidation aging resistance of bitumen. Zhang et al. [14] drew a conclusion that expanded vermiculite (EVMT) and organic expanded vermiculite (OEVMT) could improve the thermal-oxidative aging resistance of bitumen, while they had no obvious effect on the photo-oxidative aging resistance of bitumen. Zhang et al. [15] further investigated the effect of different organic layered silicates (eg. OMMT, organic rectorite (OREC) and OEVMT) on aging properties of bitumen, and found that OEVMT had more significant improvements effect in aging resistance of bitumen in comparison with OREC and OMMT. Additionally, Zhang et al. [16] also found that the softening point increment and viscosity aging index of bitumen after UV aging were decreased significantly with the introduction of different inorganic nanoparticles (nano-SiO_2, nano-TiO_2 and nano-ZnO). Moreover, nano-ZnO showed the better improvement effect in UV aging resistance of bitumen in comparison with nano-SiO_2 and nano-TiO_2. Ellie et al. [17] utilized dynamic shear rheometer and infrared spectrometer to investigate the effect of nano-SiO_2 on aging performance of bitumen. The results showed that the rheological aging index and carbonyl aging index of nano-SiO_2 modified bitumen were lower than those of blank sample, which indicated that the anti-aging properties of bitumen were improved. Zhang et al. [18] arrived at a result that nano-ZnO could remarkably enhance the UV aging resistance of bitumen, whereas it had no evident effect on the thermal-oxidative aging resistance of bitumen. However, the effect of OEVMT on aging resistance of bitumen was just the reversed.

From all above, although these anti-aging modifiers can improve the aging resistance of bitumen by a certain extent, they still show some obvious defects. Antioxidants and layered silicates can enhance the thermal oxidation aging resistance of bitumen, while they have no obvious effect on the photo oxidation aging resistance of bitumen. However, the improvement of UV absorbers and inorganic nano-particles on the aging resistance of bitumen is just opposite. In addition, the bitumens from different crude oil vary obviously in constituents and properties, which in turn make the improvement effect of some anti-aging modifiers (e.g. antioxidants and UV absorbers) have a larger selectivity. Therefore, it is of significant importance to seek suitable anti-aging modifiers, which not only can improve both thermal oxidation and photo oxidation aging resistance of bitumen simultaneously, but also adapt to the vast majority of bitumens. According to the above introduction about layered silicates and inorganic nanoparticles, OEVMT and nano-ZnO can be compounded to develop a novel anti-aging modifier, which can utilize both the effect of OEVMT on hindering the penetration of the oxygen molecules and the shield and absorption effect of nano-ZnO on UV radiation [19,21]. Thus it can be promising modifiers to improve both thermal oxidation aging and photo oxidation aging resistance of the bulk of bitumens simultaneously.

In this paper, the anti-aging modifiers containing nano-ZnO and OEVMT were used to modify three types of bitumens from different origins. The binders were aged according to TFOT, PAV, UV and NEA, respectively. TFOT and PAV were used to simulate thermal oxidation process of bitumen, and UV and NEA were utilized to simulate photo oxidation of bitumen. The effects of the anti-aging modifier on the rheological properties of these bitumens before and after aging were investigated.

2. Experimental

2.1. Materials

Three types of base bitumens (70#, 90# and 110#) from different crude oil were used in this research. 70#, 90# and 110# bitumen are 60/80, 80/100 and 100/120 penetration grade bitumen, respectively. The 70# bitumen was supplied by China National Petroleum Corp., China. The 90# bitumen was manufactured by SK Energy Co. Ltd., South Korea. The 110# bitumen was obtained by Jiangsu Baoli Asphalt Co. Ltd., China. The physical properties and chemical compositions of these base bitumens are listed in Table 1.

Expanded vermiculite (EVMT) was procured from Shijiazhuang kinley mining Co., Ltd. To prepare organic expanded vermiculite (OEVMT, 300 mesh), cetyltrimethyl ammonium bromide (CTAB) was used to modify EVMT, supported by Shanghai Zhanyun Chemical Co., Ltd., Shanghai, China. Surface modified nano-zinc oxide (Nano-ZnO) with c-(2,3-epoxypropoxy) propyltrimethoxysilane was supplied by Zhoushan tomorrow nano materials Co., Ltd, and the average particle size is 20 nm.

2.2. Preparation of modified bitumens containing nano-ZnO and OEVMT

The liquated base bitumen (70#, 90# or 110# bitumen) was poured into an oil-bath heating container, the work temperature was controlled at 150 ± 5 °C. Then the anti-aging modifier containing 1% Nano-ZnO + 3% OEVMT by mass of base bitumen was added into the bitumen. Firstly the mixture was sheared by a high shear mixer at 4000 rpm for 60 min. Next it was stirred by a paddle agitator at a rotation speed of 2000 rpm for about 90 min, the control temperature was maintained at 150 ± 5 °C. The processed mixture was modified bitumen containing nano-ZnO and OEVMT. The same process was also conducted in the base bitumen in order to obtain blank sample.

2.3. Rheological properties test

Dynamic shear rheometer (DSR) was used to test the dynamic shear rheological properties of bitumens according to ASTM D 7175 [22], such as complex modulus (G^*) and phase angle (δ). The range of sweeping temperature was 40–90 °C with 0.5 °C intervals. Bending Beam Rheometer (BBR) was utilized to test the low temperature rheological performance of bitumens after PAV aging according to ASTM D 6648 [23], such as stiffness modulus (S) and stiffness change rate (m-value). The test temperatures were −6 °C and −12 °C, the S and m-value at 60 s were identified as the test result.