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Effect of bio-based and refined waste oil modifiers on low temperature performance of asphalt binders

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HIGHLIGHTS

- Stiffness master curve of oil modified asphalt is shifted to lower level.
- Oil can increase the fracture energy of asphalt significantly.
- T_g decreased after introducing oil into asphalt.
- Fracture temperature of oil modified asphalt mixture is much lower.

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ABSTRACT

Thermally induced cracking of asphalt pavement continues to be a serious issue in cold climate regions. As a modifier, oil can be used to improve the low temperature performance of asphalt binders because of lower stiffness and more rapid stress relaxation when added to asphalts. To investigate the oil effect on the low temperature performance of asphalt, different oils, including bio-based and refined waste oil are used in this study, and Bending Beam Rheometer (BBR) test, Single Edge Notched Beam (SENB) test and Modulated Differential Scanning Calorimetry (MDSC) test are employed to evaluate the effect of oil on low temperature performance of asphalt. It is found that the stiffness of asphalt decreased, *m*-value of asphalt increased, the fracture energy of asphalt increased and glass transition temperature (T_g) becomes lower after adding these oils. This means that these oils can improve the low temperature performance of asphalt. And in addition, Thermal Stress Restrained Specimen Test (TSRST) of asphalt mixture is used to verify the conclusion. The TSRST results show that the fracture temperature of oil modified asphalt mixture is much lower than neat asphalt mixture, which proves the conclusions of the advantages of oils used.

1. Introduction

To carry heavier loads, endure the extreme climate condition and reduce the traffic and climate damage of the pavement, more and more attention is focused on improving the performance of asphalt and mixture. To meet these requirements, numerous research works have been done, including studying the effect of polymeric additives, crumb rubber and some other additive factors on the binder [1–4]. Polymer modified asphalt and mixture have been used widely due to their good performance. Most modifiers used currently can improve the deformation resistance of binder significantly at high temperatures, but improve less on flexibility at low temperature.

Thermally induced cracking of asphalt pavement is a serious issue in cold climate regions. Therefore improving binder fracture and stiffness properties at low temperature continues to be a subject of particular concern. As it is known, asphalt molecular structures can be classified as oils, resins, and asphaltenes [5], some research also takes asphalt as the mixture of polar and nonpolar molecules [6]. Asphaltenes are responsible for the hardness and the resist deformation ability of binder; the flow characteristics are attributed to the oil-like molecules [7] and it is well known that the better flow characteristics always benefits low temperature properties. So one of possible methods to improve the low temperature properties of binder are that increasing the portion of oil in asphalt.

Some studies using oil as a kind of modifier in asphalt have been reported. Villanueva et al. [8] investigated the effect of lubricating oil on low temperature performance and found the low-temperature

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grade of the modified asphalt was not significantly improved due to failure of the Bending Beam Rheometer (BBR) test's *m* value; Yousefi et al. [9] studied the properties of polymer-modified asphalts after added used-tire-derived pyrolytic oil and found that asphalts modified with 10% pyrolytic oil (H18) obtained by vacuum pyrolysis of used tires showed improved low temperature properties; Seidel et al. [7] investigated the effect of soy fatty acids on the rheological properties on the binder and thought SFAs have potential application as a fluxing agent for binders that are stiff and hard to mix. Xiaoyang [10] evaluated the engineering properties of asphalt binder containing waste engine oil residues and found the inclusion of waste engine oil up to 5% significantly altered the infrared spectra and rheological properties of asphalt binder, which may lead to the improvement of low temperature performance. Simon et al. [11] studied the waste engine oil by XRF spectroscopy in asphalt and its effect on cracking in service. They thought waste engine oil residues may cause physical hardening and losses in strain tolerance which should account for low temperature performance.

From the literature review it can be found there are a few papers discussing about oil effect on binder and only few kinds of oil are studied. With the ever increasing range of new oil extenders and modifiers being introduced, studying the effect of these new oil modifiers or extenders on short and long term performance is necessary. In this paper, several different categories oil effect on the low temperature properties of binder will be investigated.

2. Materials and experiments

2.1. Materials used

One asphalt binder commonly used in the Mid-west region of the United States was selected in this study: Valero (VA) PG 64-22. Six types of oils were used as additives including bio-oil, petroleum based oil and refined waste oil, and details are shown in Table 1. Paraffinic oils 1 and 2 differed in the proportions of their chemical constituents.

2.2. Binder preparation

2.2.1. Mixing process

In order to investigate the effect of oil on asphalt performance and make the oil additives blended well with asphalt, high shear mixer, Ross 100L High Shear Laboratory Mixer, was employed in this study. The speed in this study was held constant at approximately 5000 rpm, the maximum possibility without material spillage. The blending time and temperature were controlled at 30 min and 150 ± 5 °C, respectively.

2.2.2. Aging levels

Three stages in the life of the asphalt are considered in current asphalt binder specifications: (a) un-aged, which represents the asphalt stored in the tank before mixing with aggregates; (b) short term aging, occurring during the mixing and compaction process; and (c) long term aging, taking place over the course of many years of service life in the pavement. In this study the Rolling Thin Film Oven (RTFO), following ASTM D 2872 and AASHTO T 240, was used to simulate short term aging; long term aging was simulated by using the Pressure Aging Vessel (PAV), following ASTM D 6521and AASHTO R 28.

Table 1
Oil modification used in this study.

Category		ID
Bio-oil	Wood plant liquid	BO-1
		BO-2
Petroleum based oils	Paraffinic oil 1	PP-1
	Paraffinic oil 2	PP-2
	Aromatic oil	PR-3
Refine waste oil	Waste oil	RW

2.3. Performance tests

2.3.1. Low temperature creep test using the Bending Beam Rheometer (BBR) test

Thermo-mechanical properties of the plain and oil modified asphalt samples were measured using the Bending Beam Rheometer (BBR) to evaluate the low temperature properties of oil modification based on the ASTM D6648 and AASHTO T 313. Test were performed at temperatures of −12, −18 and −24 °C to cover a wide range of low temperatures conditions as well as attempting to target test temperatures below and above the binder glass transition temperature (T_g).

2.3.2. Low temperature fracture test using the Single Edge Notched Beam (SENB) test

The current asphalt cracking resistance evaluation methods (such as BBR test) are mostly based on linear viscoelastic mechanics under small strain to describe the low-temperature mechanical behavior of asphalt, it is difficult to use these methods to descript the low temperature cracking of asphalt material characteristics comprehensively. To better evaluate low-temperature cracking resistance of asphalt materials, the material fracture mechanics is employed. Hoare, Hesp, Chailleux, Mouillet and Bahia [12–16] evaluated the fracture properties of asphalt with Single Edge Notched Beam (SENB) test and found SENB test can distinguish low temperature cracking resistance of different asphalt effectively, and has a good correlation with the road performance in field.

In this study, all binders low temperature fracture were evaluated by SENB test at −12 °C. SENB test equipment used in this paper is developed by University of WI, Madison. This equipment is similar with BBR equipment, the difference of between both is that SENB equipment is controlled by displacement with step motor and another machine controled by load controlled by load sensor. During the SENB test, the loading rate is 0.01 mm/s and displacement and load are recorded with time, the acquisition rate is 8 Hz. Schematic diagram of Single Edge Notched Beam (SENB) test as shown in Fig. 1.

From this test, the fracture load, fracture deflection, fracture toughness (K_{IC}) and fracture energy (G_f) can be calculated. The K_{IC} parameter denotes mode I fracture in which crack formation occurs in tensile mode due to bending and can be calculated as:

$$K_{IC} = \frac{PL}{bW^{2/3}} f\left(\frac{a}{W}\right) \quad (1)$$

Where $f\left(\frac{a}{W}\right)$ is defined for SENB geometry and can be calculated as following:

$$f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right)\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}} \quad (2)$$

The fracture energy, G_f is calculated as the total area under the entire load–deflection curve, divided by the area of the ligament as shown:

$$G_f = \frac{W_f}{A_{lig}} \quad (3)$$

where $W_f = \int \text{pdu}$, A_{lig} is the area of the ligament.

2.3.3. Modulated Differential Scanning Calorimetry (MDSC) test

Modulated Differential Scanning Calorimetry (MDSC) is a thermal analysis method to determine the heat capacity of a tested material's as a function of temperature change. The results are used to quantify thermodynamic information about the material and in particular the phase transitions during heating. The heat flow into and out of a sample (compared to a reference state) is measured as that sample is subjected to a temperature change program. The heat flow measured by this test is a function of the heating rate and sample heat capacity. Because of the complex structure and rheological curve of asphalt binders, much work in last years has been performed with MDSC to study the binder microstructure and its relation to physical properties [17–19]. The modulated test is capable of locating T_g temperature and other thermal behavior of material and it provides greater sensitivity than regular DSC testing [19].

In this study, the glass transition of asphalt was investigated by Modulated Differential Scanning Calorimetry (MDSC) test, which were performed with a TA Q-100 instrument using 5–10 mg samples sealed in aluminum hermetic pans. An

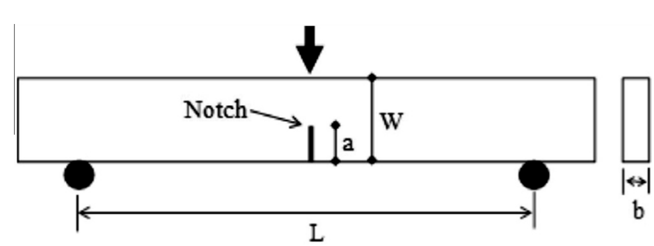

Fig. 1. Schematic diagram of Single Edge Notched Beam (SENB).