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Relationship between glass transition temperature and low temperature properties of oil modified binders

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HIGHLIGHTS

- T_g temperature affects T_g temperature of binder significantly.
- Good linear relationship between T_g temperature and stiffness of asphalt.
- T_g temperature affects both rheological and fracture properties of asphalt.

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ABSTRACT

Oils can be used as modifiers to improve low temperature performance of asphalt. However, the relationship between phase transition of oil modified asphalt and their low temperature properties still need more detailed research to reveal the effect of the transition on rheological properties. To investigate this, 9 different oils of bio-base and refined waste oils are used as modifiers in this study. During the study, Modulated Differential Scanning Calorimetry (MDSC) test is used to study the phase transition, and the Bending Beam Rheometer (BBR) test and Single Edge Notched Beam (SENB) test are used to evaluate the rheological and fracture properties of oil modified asphalts, respectively. It is found that the glass transition temperatures of oil modifiers are significantly different but are all much lower than the glass transition temperatures of asphalts. The results show that there is a good linear relationship between glass transition temperature and stiffness of asphalts, but no good correlation with the relaxation parameter (m) measured with the BBR. There is a much stronger correlation of the glass transition temperatures with the fracture properties of asphalts. Considering this strong relationship with the fracture properties, DSC test shows the potential possibility for quickly and accurately evaluating the low temperature fracture performance of asphalts. The combination of BBR and DCS can therefore be used to select the type and amount of oil modifier to meet a specific low temperature performance. The study was limited to one asphalt source and thus validation of the relationships for other asphalts is needed before generalizing the results.

1. Introduction

In China and United States, more than 90% of highways are surfaced with asphalt mixtures, which consists of aggregate particles bonded by asphalt binders. These asphalt binder is usually a residue obtained during the crude petroleum refining process. However, because of the increasing environmental awareness and the tougher environmental control laws, petroleum industry has made a lot of change to the refining process which can increase the fuel quantity but the quantity of asphalt residue is decreased, leading to increasing the cost of asphalt in recent years [1,2]. Due to the increased cost, the road paving industry has started considering sustainable asphalt production and introduced paving practices to replace or reduce the petroleum-based asphalt used in HMA, which can reduce carbon emissions and increase cost effectiveness [3–5].

Recycled oil is one of potential materials which can be used as the modifier of asphalt to improve the performance of binder or as the alternative materials to reduce the quantity of asphalt. Using waste oil as the modifier of asphalt also has environmental benefits, since the waste oil may cause irrecoverable damages to the environment if not disposed properly. Villanueva et al. [6] investigated the effect of lubricating oil on low temperature performance

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and found the low-temperature 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. [7] studied the properties of polymer-modified asphalts after adding 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; Xiaoyang [8] 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. Lei et al. [9] studied the effect of recycled oil on low temperature performance of asphalt mixture and found the fracture temperature of oil modified asphalt mixture was much lower than neat asphalt mixture.

From the literature review it can be concluded that most of studies show that oils can improve low temperature performance of asphalt. Some studies [10–12] have shown that phase transition (from viscoelastic state to elastic state) of asphalt has significant effect on low temperature performance of asphalt, and usually, the glass transition temperature (T_g) is chosen to represent the temperature range at which materials start showing the glassy behavior including lower contraction coefficient and increased rate of stiffening with temperature reduction [13]. However, the relationship between phase transition of oil modified asphalt and their low temperature properties are still in need of more detailed research to reveal the relationship between them. In this paper the relationship between glass transition temperature and low temperature performance including rheological and fracture properties of oil modified binders are investigated to offer better understanding and best methods to estimate the change in properties when oils are used for improving properties and replacing asphalt.

2. Materials and experiments

2.1. Materials used

In this study, one neat asphalt of PG 64-22 grade and 9 different types of oils were selected as modifiers to prepare the oil modified asphalt. The oils included bio-oils, petroleum based oils and refined waste oils. More information about the oils are shown in Table 1. It should be noted that PP-1, PP-2 and PP-3 differed in the proportions of their chemical constituents.

2.2. Binder preparation

2.2.1. Mixing process

In order to 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 methods

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 modifiers used in this study.

Category		ID
Bio Based Oils	Wood plant based oil	Bio-1
		Bio-2
	Refine Waste Oil	R-Bio
Petroleum Based Oils	Refine Waste Oil	R-Pe
	Aromatic based oil	PA
	Paraffinic based oil	PP-1
		PP-2
		PP-3
	Naphthenic based oil	PN-1

2.3. Performance tests

2.3.1. 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. Single Edge Notched Beam (SENB) test

To better evaluate low-temperature cracking resistance of asphalt materials, the material fracture properties should be measured. Hoare, Hesp, Chailleux, Moulle and Bahia [14–18] evaluated the fracture properties of asphalt with the Single Edge Notched Beam (SENB) test and found that the SENB test can distinguish low temperature cracking resistance of different asphalt effectively, and had a good correlation with the road performance in field.

In this study, all binders low temperature fracture performance were evaluated by SENB test at −12 °C. SENB test equipment used in this paper is developed by University of Wisconsin., Madison. 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 is as shown 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:

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

P is the fracture load. The meanings of a, b, w,and L are shown in Fig. 1.

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

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

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 follows:

$$G_f = \frac{W_f}{A_{lig}} \tag{3}$$

where $W_f = \int pdu$, A_{lig} is the area of the ligament, which can be calculated as follows:

$$A_{lig} = b \times (W - a) \tag{4}$$

2.3.3. Modulated Differential Scanning Calorimetry (MDSC) test

Glass transition temperature is the reversible transition in amorphous materials (or in amorphous regions within semi-crystalline materials) from a hard and relatively brittle state into a viscoelastic state. It is related to the flow characteristics of asphalt. T_g also indicates the susceptibility of asphalt to thermal or low temperature cracking. The results from round robin experiments for DSC conducted by the Rilem TC 231-NBM in which eight laboratories seven from Europe and one from USA participated have shown that the use of DSC is promising for the characterization of bituminous materials [19]. Modulated Differential Scanning Calorimetry (MDSC) is a thermal analysis method to determine the heat capacity of a tested material as a function of temperature change. Because of the complex structure and rheological curve of asphalt binders, much work in the last few years has been performed with MDSC to study the binder microstructure and its relation to

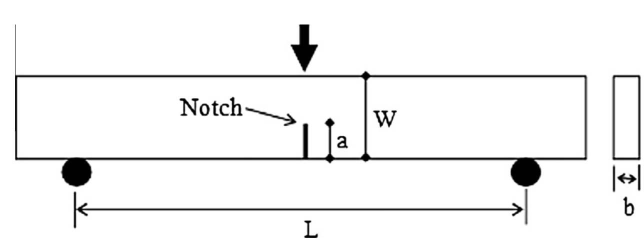

Fig. 1. Schematic diagram of single edge notched beam (SENB).