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High temperature performance evaluation of bio-oil modified asphalt binders using the DSR and MSCR tests

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HIGHLIGHTS

- The high temperature performance of bio-oil modified asphalt were investigated.
- DSR test and MSCR test were utilized to characterize the high temperature performance.
- Three types of waste wood resourced bio-oils were used to modify asphalt.
- The effect of bio-oils on asphalt high temperature performance were evaluated.
- The results from the DSR test and MSCR test were compared.

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ABSTRACT

The high temperature performance of bio-oil modified asphalt binders were evaluated using dynamic shear rheometer (DSR) and multiple stress creep recovery (MSCR) tests. Three types of bio-oils generated from waste woods were investigated: untreated bio-oil (UTB), treated bio-oil (TB) and polymer modified bio-oil (PMB). The control asphalt binder (PG58-28) was blended with 5% and 10% bio-oils to prepare bio-oil modified asphalt binders. Dynamic shear modulus ($|G^*|$) and phase angle (δ) as well as high temperature stability index ($|G^*|/\sin\delta$) were evaluated through the DSR test, while non-recoverable creep compliance (J_{nr}) and percent recovery were investigated using the MSCR test. Both the DSR and MSCR test results showed that the addition of the bio-oils improved the high temperature stability of asphalt binder with respect to higher $|G^*|$, lower δ, lower J_{nr} and higher percent recovery. In detail, with the increase of bio-oil percentage, asphalt high temperature performance was improved. The statistical analysis showed that such improvement was statistically significant. In terms of the comparison among the three types of bio-oils, it was found that results from the DSR and MSCR tests were slightly different. In the DSR test, the UTB modified binders showed slightly weaker high temperature stability than the TB and PMB modified binders, which was mainly due to the high moisture content in the UTB. Whereas in the MSCR test, the PMB modified binder showed slightly weaker high temperature stability than the UTB and TB modified binders, which was attributed to the low fraction of polymer (only 0.4% by weight) in the PMB modified binder. The slight inconsistency between the DSR and MSCR test was likely due to different loading magnitude and loading mode of the two tests. The study also suggests that it is preferable to conduct both the DSR and MSCR tests to obtain a comprehensive understanding of asphalt high temperature performance.

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1. Introduction

1.1. Bio-oil

Bio-oils generated from biomass materials are regarded as potential alternative binders used in flexible pavement. Overall, bio-oils can be generated from a wide range of biomass materials, such as wood, algae, grass, cornstover, waste cooking oil, and animal waste. Some basic physical and chemical properties of bio-oils have been investigated in previous studies [1–4]. Several technologies have been developed to generate bio-oils. Fast pyrolysis has been proved to be a highly effective approach due to the high yield rate of bio-oils. Some mature fast pyrolysis equipment has been developed to produce bio-oils in the United States [4,5]. In fast pyrolysis, source materials are heated quickly to 400–500°C with the absence of air. During this process, the biomass is decomposed to vapor and chars. The vapor is cooled down quickly to obtain gas

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and liquid. The gas can go back as a heat source while the liquid is separated as bio-oil. Newly produced bio-oil usually contains some amount of moisture, which is from the source materials. Previous studies showed that the moisture content can be reduced by heating bio-oils at a temperature slightly higher than the boiling point of water [6].

Overall, bio-oil has similar components as petroleum asphalt binder. The components can be categorized into saturates, aromatics, polars and asphaltenes [7]. However, the elemental composition of bio-oil differs significantly from petroleum asphalt per the higher oxygen content in bio-oil [4,8,9]. Some other characteristics of bio-oil as compared to petroleum asphalt include lower pH and inhomogeneity [10]. In regard of the effect of bio-oils on asphalt binder performance, it was found that bio-oils from different resources can have various functions. Bio-oils derived from animal waste can improve asphalt low temperature performance [4,11,12]. Wen et al. [13] found that the bio-oil generated from waste cooking oils can also improve the low temperature performance of asphalt binder. Asli et al. [14] found that the addition of waste cooking oil can significantly reduce the softening point and viscosity of aged asphalt binder. On the other hand, it was found that bio-oils generated from wood resources can improve asphalt high temperature stability while compromise low temperature performance [3,15]. In addition, previous studies suggested that bio-oils are more susceptible to a high temperature aging as compared to the petroleum asphalt [11,15].

1.2. Asphalt high temperature performance

Asphalt high temperature performance is related to rutting resistance of asphalt pavement. Several approaches have been developed to evaluate the high temperature performance of asphalt mixture, such as direct rutting resistance testing: asphalt pavement analyzer (APA) and Hamburg wheel-tracking test. Previous studies also revealed that flow number and dynamic modulus have a high correlation to rutting resistance of asphalt mixture [16–18]. Some approaches have also been developed to evaluate the high temperature performance of asphalt binder, such as penetration test, dynamic shear rheometer (DSR) test, and multiple stress creep recovery (MSCR) test. Penetration test estimates the high temperature performance based on asphalt stiffness. The detailed information of the test can be found in ASTM D5 [19]. Penetration test covers the typical service temperature of asphalt pavement. It is also quick and inexpensive. However, the limitation of penetration test is also obvious. It is an empirical method without taking account into the fundamental engineering properties of asphalt. DSR test can overcome this limitation as it measures asphalt rheological property in a wide range of temperature and frequency. It is a currently used approach by most agencies in the United States. DSR test has been used to characterize the high temperature performance of asphalt binders in many previous studies [20–24]. The detailed information of the test is specified in ASTM D7175 [25]. Superpave asphalt mixture design recommends the $|G^*|/\sin\delta$ at 1.59 Hz as the rutting potential index. The main shortage of the DSR test is that the strain level is low (about 10%), which may underestimate the performance of some modified asphalt binders because the modifiers are not fully activated at a low strain level [26]. In this regard, the MSCR was developed, as specified in ASTM D7405 [27]. According to the study by the Federal Highway Administration (FHWA) [26], non-recoverable creep compliance (J_{nr}) in MSCR test has a much higher correlation with asphalt pavement rutting performance as compared to the rutting index $|G^*|/\sin\delta$. Wasange et al. [28] also designed tests to correlate MSCR results to asphalt mix rutting. In addition, some parameters that can impact MSCR reliability were explored by Motamed and Bahia [29], such as geometry, temperature, stress level and loading duration. Recently, MSCR test has been widely used to evaluate asphalt high temperature performance [30,31].

2. Motivations and research objectives

Although some previous studies reported the effect of bio-oils on asphalt high temperature performances using DSR, they mainly focused on the rutting index ($|G^*|/\sin\delta$). The detailed effect of bio-oils on asphalt $|G^*|$ and δ was not well reported in previous studies [4,11,15]. Moreover, since it was found that the DSR test may be not capable to well reveal the high temperature performance of some modified asphalt binders [26], MSCR test was selected to determine if it can provide more reliable results for bio-oil modified asphalt. The comparison between DSR and MSCR tests on bio-oil modified asphalt may be a good case study for future researches to understand how DSR test results differ from MSCR test results.

The main objective of this study is to evaluate the high temperature performance of bio-oil modified asphalt binders using both DSR and MSCR test. The effects of bio-oil on asphalt $|G^*|$, δ, J_{nr} and percent recovery will be explored, respectively. Results from the DSR and MSCR tests were also compared to understand if the two approaches bring similar findings. In order to achieve the goal, three types of bio-oils generated from waste woods were investigated: the untreated bio-oil, treated bio-oil and polymer modified bio-oil. The petroleum asphalt binder was blended with 5% and 10% bio-oils to prepare bio-oil modified asphalt binders. The dynamic shear modulus ($|G^*|$) and phase angle (δ) as well as the high temperature stability index $|G^*|/\sin\delta$ were evaluated through the DSR test, while the J_{nr} and percent recovery were investigated using the MSCR test. Statistical analysis was conducted to understand if the effects are statistically significant.

3. Materials and preparation

The asphalt binder used in this study was the performance grade asphalt PG58-28, meaning the highest and lowest working temperatures are 58 and −28 °C, respectively. PG58-28 is a widely used asphalt in northern region of United States. The high temperature performance of the PG58-28 in this study has not been improved by other modifiers. The bio-oils used in this study were derived from waste woods collected in Upper Michigan through a fast pyrolysis. There is a moisture content of 15–30% by weight in the newly produced bio-oil, also named untreated bio-oil (UTB) in this study. A dewatered bio-oil with moisture content of 5–8% was obtained by heating the newly produced bio-oil at 110 °C, which was named as the treated bio-oil (TB) in this study. In addition, a polymer modified bio-oil (PMB) was prepared by adding 4% of polyethylene into the treated bio-oil. Previous studies showed that polyethylene can improve asphalt high temperature performance [32–35]. Specifically, Punith and Veeraragavan [33] stated that a 5% content of polyethylene is adequate to enhance asphalt binder performance. To produce bio-oil modified asphalt binder, the UTB, TB and PMB were added into the control asphalt by 5% and 10%, respectively. Thus, a total of seven asphalt binders were investigated in this study: the control asphalt binder, and the 5% UTB, 10% UTB, 5% TB, 10% TB, 5% PMB and 10% PMB modified asphalt binders. The mixing process was conducted with a high shear mixer. Some elemental and chemical compositions of the untreated bio-oil is shown in Table 1.

4. Experimental plan

4.1. DSR test

As previously mentioned, the DSR test was developed to characterize the viscoelastic property of asphalt binders in a wide range of temperature and frequency. In this study, the DSR test was conducted by a rheometer model Bohlin CVO 120. The water bath was used to control the temperature. A sinusoidal shear load was applied on the binder specimen to obtain the dynamic shear modulus ($|G^*|$) and the phase angle (δ). The maximum shear strain level was controlled as 10%. The effect of the bio-oils on the $|G^*|$ and δ was also investigated. The rutting potential index $|G^*|/\sin\delta$ at 1.59 Hz was then calculated to evaluate the high temperature performance. The testing temperatures were selected as 58, 64 and 70 °C considering this study aims to investigate the high temperature performance. The testing frequencies were 0.1, 1, 5, 10 and 25 Hz to covers a wide range. All the samples had been subjected to the standard RTFO test to gain a short term aging before the

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