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Rheological properties and anti-aging performance of asphalt binder modified with wood lignin

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HIGHLIGHTS

- Evaluate the potential use of lignin as partial substitute and performance modifier in asphalt binder.
- Lignin increases rutting resistance significantly but negatively affects fatigue cracking of asphalt.
- Lignin has little adverse effect on low temperature cracking of asphalt.
- Lignin can reduce formation of carbonyl groups in asphalt binder after aging.

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ABSTRACT

This study evaluated the potential use of wood lignin as partial substitute and performance modifier in asphalt binder. The rolling thin film oven (RTFO) and pressure aging vessel (PAV) methods were performed on asphalt samples to simulate different aging conditions. The Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests were utilized to explore the influence of adding lignin on the rheological properties of asphalt binder. The Fourier Transform Infrared Spectroscopy (FTIR) was used to evaluate the anti-aging performance of lignin on asphalt binder. The rutting resistance of lignin modified asphalt binder at the high temperature was evaluated using Multi Stress Creep and Recovery (MSCR) test, while the fatigue life of asphalt binder was characterized using Linear Amplitude Sweep (LAS) test. The viscosity test results showed that the addition of wood lignin into asphalt binder caused stiffening effect. The DSR and BBR test results implied that adding lignin positively affected high-temperature rutting performance without adversely influencing low-temperature. The MSCR results indicated that the lignin improved the elastic recovery and reduced non-recoverable deformation of asphalt binder. The FTIR results indicates that the presence of lignin can help resist the formation of carbonyl structure in the aging process, and thus improved aging resistance of asphalt binder. The LAS test results showed that fatigue resistance of asphalt was negatively affected by lignin. The study results suggest that wood lignin is a promising modifier for asphalt materials with economic savings and environmental benefits.

1. Introduction

The global demand for asphalt is forecast to increase for application in roadway. The intensive growth of asphalt consumption is largely driven by construction of asphalt pavement and pavement maintenance and repair. Asphalt binder used in pavement is mainly a by-product from crude oil refining process. The recent development of new technology in the refinery has degraded the quantity of asphalt, and thus resulted in an increased price of asphalt material [1]. On the other hand, pavement consumes large energy and releases greenhouse gases (GHG) considering fuel energy used in production, transportation, and application processes of asphalt binder [2]. Therefore, the rising cost of asphalt binder and the environmental concern encourage the use of alternative binders to replace petroleum-based asphalt binder or performance modifier to enhance the quality of asphalt binder.

A number of researches have been conducted to develop new binder materials and performance modifiers from sustainable resources. Shell Oil Company has used vegetable oil-based binder on field sections and found that the vegetable oil-based asphalt was less susceptible to temperature and it was produced with

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fewer emissions [3]. Ecopave Australia has used sugar and molasses to produce bio-asphalt product that showed the improved mechanical and rheological properties [4]. Recent study in French has proved the feasibility of developing alternative binder from microalgae. The advantage of using microalgae is that it grows fast and can be artificially cultivated [5]. Recently, several researchers have investigated the possibility of using bio-binder produced from animal waste [6], agricultural waste [7], wood waste [8], cedar wood [9] to partially replace the traditional asphalt binder. Waste cooking oil was also reported as potential substitute of asphalt and it can improve low temperature performance of asphalt binder [10].

In recent studies, lignin has attracted considerable attention as partial substitute or performance modifier for asphalt. Lignin is a hydrocarbon and consists of benzene rings with randomly attached methoxyl and hydroxyl, carbonyl, and aliphatic double bonds. The chemical structure of lignin is highly aromatic and contains a large amount of unsaturated aromatic rings connected by alkyl chains [11]. Lignin is the commonly abundant biological polymer on earth and it can be found in co-products of biofuel production [12]. Lignin is also a major by-product of paper making industry and the traditional use of lignin containing by-product is limited to fuel [13]. It will be beneficial to find alternative usage of lignin to improve the economic competence of biofuel or paper industry.

Lignin was found to act as reinforcement in asphalt binder and the viscosity of lignin-modified asphalt binder increased proportionally with the higher lignin content [14,15]. This indicates that the addition of lignin increases the rutting resistance of asphalt binder at high temperatures. The improvement of high-temperature performance of asphalt blended with lignin was reported using dynamic shear rheometer (DSR) tests based on Superpave specifications [16]. In that study, the lignin-containing co-product from ethanol production was used. Overall, the addition of lignin has been proved to widen the performance grade range of asphalt. However, the effect of lignin on fatigue cracking potential of asphalt binder has not been well studied.

The aging or embrittlement of asphalt binder due to oxidation or volatile loss can cause pavement cracking at near-surface. Lignin has been showing high potential of anti-oxidation due to the polyphenolic structure in the lignin and free radical scavenging activity [17–19]. The potential use of lignin as an antioxidant in asphalt binder has been studied very limitedly [20]. Eight types of asphalt binder commonly used in Kansas and two types of lignin were selected and blended at different concentrations. The aging index of viscosity was used to study the effect of lignin as an antioxidant and it was found that the results were dependent on binder type. Therefore, the anti-aging effect of lignin should be studied using more accurate observation that is based on change of chemical structures of asphalt binder.

2. Objective and scope

The main objective of this study was to characterize rheological properties and performance of lignin modified asphalt binder using different laboratory tests. The rheological properties and performance indicators include viscosity measured by Rotational Viscometer (RV), permanent deformation resistance by Multiple Stress Creep Recovery (MSCR) test, thermal cracking resistance by Bending Beam Rheometer (BBR), and fatigue resistance by Linear Amplitude Sweep (LAS) test. The short-term and long-term aging processes of asphalt binder were simulated using rolling thin film oven (RTFO) and pressure aging vessel (PAV). The performance test results were compared between virgin asphalt binder and the modified asphalt binder with different lignin contents. In addition, changes in chemical composition of asphalt binder with addition of lignin were evaluated using Fourier transform infrared spectroscopy (FTIR). It is expected that the results can help better understand the potential benefit of wood lignin as performance modifier of asphalt binder.

3. Materials and experimental procedures

3.1. Material preparation

Two types of virgin asphalt binder were used in this study. The first one is PG 64-22 asphalt binder which is widely used in pavement constructions in the U.S. The second one is PG 76-22 asphalt binder which is styrene butadiene styrene (SBS) modified asphalt. The performance grades of asphalt binder were determined per Superpave specification. Actually, the continuous performance grades are 65.6 and −27 for PG 64-22, and 81.7 and −25 for PG 76-22, respectively. The wood lignin powder was obtained commercially from Sigma-Aldrich, which has average molecular weight of around 10,000 and 4% sulfur impurity. It is soluble in water and has pH value of 10.3 (3 wt%).

The lignin was used as an asphalt modifier as well as a partial substitute, which was added into the base binder at 5% and 10% by weight, respectively. The blending of lignin powder and asphalt was achieved by a regular shear mixing device at around 163 °C and a speed of 1500 rpm. It was observed that volumetric expansion was observed at the time of adding lignin into asphalt at the beginning of mixing stage, with air bubbles floating on the surface. The blending was continued for around 30 min until the bubbles disappeared and the lignin-asphalt blends were well-mixed.

3.2. Rheological testing

The rotational viscometer (RV) and dynamic shear rheometer (DSR) were used to determine the rheological properties of asphalt binder. The rotational viscosity of asphalt binder was measured at 135 °C, following the test procedures specified in AASHTO TP48. The rotational viscosity measures a fluid's ability to resist to flow. Different sized spindles were adopted for two types of asphalt binder.

The DSR was used to measure complex shear modulus (G^*) and phase angle (δ) of asphalt binder. By applying a sinusoidal stress on asphalt material, the shear modulus measures its total resistance to deformation, while the phase angle characterizes the time lag between stresses and strains. The 25-mm diameter plate with 1-mm testing gaps was selected because modulus measurements are performed at high temperatures, following test procedures specified in AASHTO TP5.

The BBR test evaluates asphalt binder's low temperature cracking potential in terms of creep stiffness and stress relaxation. During the BBR test, a creep load is applied to a small asphalt beam specimen that mimics the stress building up in pavement structure when temperature is coming down. Two parameters are measured by BBR test. One is creep stiffness that measures asphalt binder's ability to resist constant loading. The other is the m-value, which describes the changes of asphalt stiffness under applied load. The BBR test was performed per AASHTO TP1 specification.

Asphalt samples were then subjected to aging treatments. The rolling thin-film oven (RTFO) method, detailed in AASHTO T-240, was used to artificially simulate the short-term aging of asphalt binder. The pressure aging vessel (PAV) procedure, specified in AASHTO R-28, was aimed to mimics the situation of asphalt binder after around 10 years' service life in the field. The unaged asphalt samples were used for viscosity testing. The RTFO-aged asphalt samples were used for DSR tests and PAV treatment. The asphalt binder after PAV treatment was used for BBR tests.