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Evaluation of Asphalt Mixtures Containing Renewable Binder Technologies

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Abstract: Recently, the use of bio-oil as a replacement to petroleum-based asphalt binder has been proposed. The objective of this study was to conduct a comprehensive laboratory evaluation of asphalt mixtures containing green asphalt technology. To achieve this objective, a suite of laboratory tests was conducted to capture the mechanistic behavior of the mixtures against major distresses. Laboratory testing evaluated the rutting performance, moisture resistance, and fracture resistance of the produced mixtures using the Hamburg loaded-wheel tester, the modified Lottman test, and the semi-circular bending (SCB) test. Results of the experimental program showed mixtures modified with bio-binder had similar or improved rutting performance when compared to the conventional mixes. With respect to moisture susceptibility, all mixtures, except the mixes prepared with PG 64-22, exceeded the 80% tensile strength ratio. However, when an anti-stripping agent was added, the tensile strength ratio of the mix with 50% bio-binder exceeded 80%. With respect to fracture resistance at intermediate temperatures, the mixes containing bio-binder exhibited reduced fracture resistance as compared to conventional mixes.

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Key words*: Bio-binder; HMA; Sustainability; WMA.*

Introduction

Conventional asphalt concrete mixtures are produced using binders derived from fossil fuel; specifically, crude petroleum. Increases in construction prices and heightened environmental stewardship have encouraged the use of renewable resources in asphalt pavements. These technologies include, however are not limited to, reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), mixtures containing waste from industrial processes, and bio-oil asphalt modifiers. The use of these technologies often qualifies the resulting mixture for being classified as "sustainable."

A sustainable pavement is safe, efficient, and environmentally friendly while meeting the needs of the present generation without affecting the ability of future generations to meet their needs [1]. Sustainable pavements minimize the use of natural resources, reduce energy consumption, reduce greenhouse gas emissions, limit pollution, improve health and safety, and ensure a high level of user comfort [1]. The economic impact of a pavement should also be considered when discussing sustainability. Engineers must consider new technologies and design methodologies to comply with current and future environmental and economic constraints. Bio-oils have distinct advantages when compared to fossil fuel oils. Bio-oils are renewable, environmentally-friendly, provide energy security, and can be an economic opportunity for the United States [2].

Recently, the use of bio-oil as a replacement to petroleum-based asphalt binder has been proposed. Bio-based materials include industrial products, co-products, and by-products made from agricultural or forestry feed stocks. These feed stocks could be wood, wood waste and residues, grasses, crops, and co-products of crops. In most cases, the feed stocks for bio-based materials do not compete with food or feed supplies [2]. Bio-oil blending is often accomplished in three proportions; direct replacement (100% replacement), extender (25%-75% replacement), or modifier (< 10% replacement) [3]. Research studies have evaluated the use of bio-binders in flexible pavement structures [3-7]. In many of these cases the bio-binder was evaluated in minimal proportions (< 10%). Much of the research to date has evaluated manure, oak tree, and switch grass feed stock. There is a need for a comprehensive laboratory evaluation of mixtures containing bio-binder from alternative feed stocks at higher blending proportions (up to 50% replacement). This study determined the viability of asphalt mixtures prepared with high bio-binder content from pine tree feed stock for use in transportation infrastructure.

In this study, the laboratory results of a conventional 19-mm HMA mixture was compared to three 19-mm asphalt concrete mixtures prepared with modified binder technologies. The modified asphalt binders were modified with elastomeric polymer as well as bio-binder technologies. Binders modified with up to 50% replacement were evaluated. As a requirement for this class of binder, the binders modified with bio-binder technology were produced at lower temperatures resulting in the production of warm mix asphalt (WMA).

Objective and Scope

The objective of this study was to conduct a comprehensive laboratory evaluation of asphalt mixtures containing green asphalt technology. To achieve this objective, a suite of laboratory tests were conducted to capture the mechanistic behavior of the mixtures against major distresses. Laboratory testing evaluated the rutting performance, moisture resistance, and fracture resistance of the produced mixtures using the Hamburg loaded-wheel tester, the modified Lottman test, and the semi-circular bending (SCB) test.

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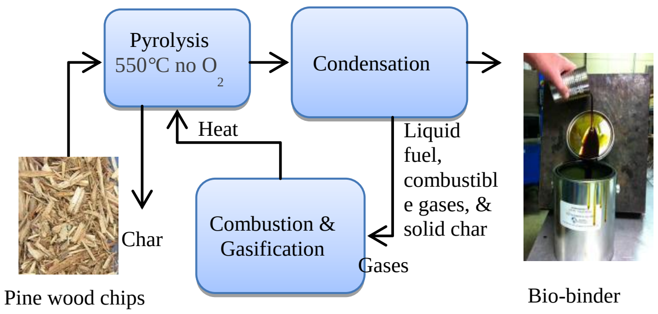


Fig. 1. Biomass Pyrolysis.

Background

Bio-Binder

Bio-binder is a co-product from the conversion of bio-mass into bio-oil. Bio-mass offers renewable source of bio-oil production. Bio-oils can substitute for fuel oils and a variety of other chemical applications [4]. Bio-oil is produced through either biochemical conversion or thermochemical conversion. [5]. Thermochemical, such as pyrolysis, allow for a more compact facility as well as a faster conversion time when compared to biochemical conversion [6].

The bio-binder considered in this study is produced by fast pyrolysis of biomass. During fast pyrolysis, biomass is heated rapidly in a high temperature environment (Fig. 1). The resulting product consists of a combination of liquid fuel (bio-oil), combustible gases, and solid char [4]. The binding property of the bio-oil material is desirable for use in asphalt pavements.

Bio-Binder is an alternative asphalt binder made from non-petroleum-based renewable resources. Typically, bio-binders are a combination of petroleum asphalt cement and bio-oils. Bio-binders are used to reduce the demand for petroleum-based bituminous binder in three ways: direct replacement (100% replacement), an extender (25%-75% replacement), or a modifier (<10% replacement). Applications of bio-binder range from asphalt paving to roofing shingles and sealants [2].

Bio-Binder Research

Bio-Binder research to date has been mostly directed at the rheological properties of binder modified with 10% or less bio oil [3-4, 7-9]. Characterization of mixtures modified with binders modified with higher percentages of bio-oil is needed. This study evaluates the performance of mixtures prepared with petroleum-based binder replaced with up to 50% bio-oil from pine wood biomass.

Test Materials

Bio-Binder

Tall oil derived from pine trees is subjected to distillation and/or oxidation under carefully controlled conditions. The resulting oxidized resin may be combined in various proportions with petroleum asphalt binder ranging from 5% to over 70% petroleum6 binder and may be combined with most asphalt modifying agents including ground tire rubber, and polymer modification. The bio-binder used in this evaluation can be referenced as US Patent number 8,034,172 B2 issued on October 11, 2011 [10].

Asphalt Mixtures

Table 1 presents the four mixtures used in this study along with their binder blend composition and resulting performance grade (PG). The conventional mixture contained PG 64-22 unmodified petroleum-based binder. Mixture 7022PM contained elastomeric polymer (SBS) modified petroleum-based binder. Mixtures 6422GM and 7022GM contained green asphalt binders as shown in Table 1. It is noted that the binder blends evaluated in this study had a bio-binder replacement range from 20 to 50%.

All the mixtures evaluated in this study consisted of the same mix design. A 19-mm Superpave mixture meeting LADOTD specifications (Ninitial = 8-, Ndesign = 100-, and Nfinal = 160-gyrations), was designed according to AASHTO TP 28, “Standard Practice for Designing Superpave HMA” and Section 502 of the 2006 Louisiana Standard Specifications for Roads and Bridges [11]. The optimum asphalt cement content was determined based on volumetric (VTM = 2.5 - 4.5%, VMA ≥ 12%, VFA = 68% -78%) and densification (%Gmm at Ninitial ≤ 89, %Gmm at Nfinal ≤ 98) requirements. Siliceous limestone aggregates and coarse natural sand were used in mix preparation. In addition, limestone aggregates were tested to verify their aggregate consensus properties. Consensus properties included coarse aggregate angularity (CAA), fine aggregate angularity (FAA), flat and elongated particles (F&E), and sand equivalency (SE). The bio-binder evaluated in this study allows for the reduction of mixing and compaction temperature. Therefore, the mixing temperature for the mixtures modified with green products was 143°C whereas the mixing temperature for the control mixtures was 163°C.

Experimental Program

An experimental factorial was developed in order to determine the mechanistic properties of the evaluated mixtures. Laboratory performance testing included evaluation of the rutting performance,

Table 1. Mixture Descriptions.

Mixture Designation	Binder Blend Composition	PG Grade
6422CO	Conventional Asphalt Cement Binder	64-22
7022PM	98-99% PG 67-22 + 1-2% SBS	70-22M*
6422GM	50% PG 58-28 + 50% bio-Binder	64-22
7022GM	79% PG 67-22 + 20% bio-Binder + 1% SBS	70-22M*

* M: denotes elastomeric polymer modified asphalt

Table 2. Test Factorial.

Mixture	Test Method		
	Rutting	Durability	Fracture
	LWT	Lottman	SCB
6422CO	2	6	9
6422GM	2	6	9
7022PM	2	6	9
7022GM	2	6	9

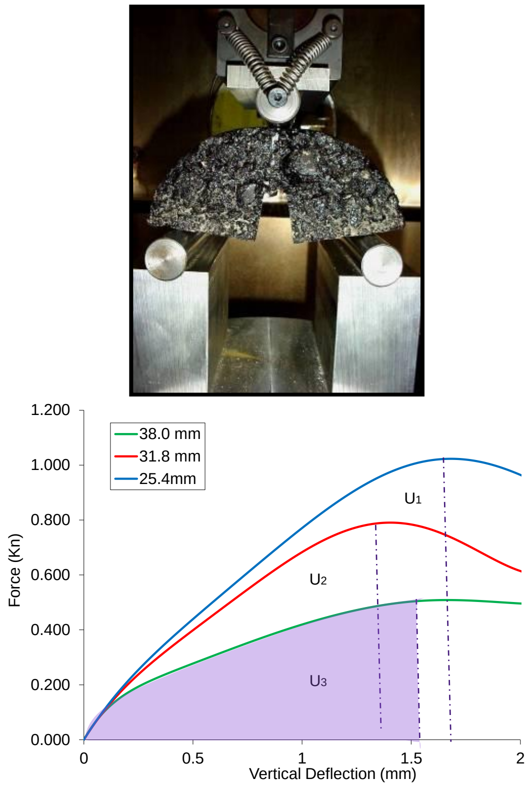


Fig. 2. The Semi-Circular Bending Test.

moisture resistance, and fracture resistance using the Hamburg LWT, modified Lottman test, and SCB test. Table 2 shows the test factorial evaluated in this study. Triplicate specimens were considered for each test, except for the LWT where two specimens were tested. All specimens were compacted to an air void level of 7% ± 0.50%. Results of the tests presented in Table 2 had a coefficient of variation (COV) of 20% or less. A brief description of each of the test methods considered in the experimental program is presented.

Laboratory Tests

A suite of laboratory tests was conducted to capture the laboratory performance of the mixtures. In addition, moisture susceptibility of the mixtures was evaluated. The following section describes the laboratory tests conducted to characterize the mixtures.

Loaded Wheel Tracking (LWT) Test

Rutting performance of the mix was assessed using a Hamburg-type Loaded Wheel Tester (LWT), manufactured by PMW, Inc. of Salina, Kansas. This test was conducted in accordance with AASHTO T 324, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)." This test is considered a torture test that produces damage by rolling a 703 N (158 lb.) steel wheel across the surface of a slab that is submerged in 50℃ water for 20,000 passes at 56 passes a minute. A maximum allowable rut depth of 6 mm at 20,000 passes at 50℃ was used. The rut depth at 20,000 cycles was measured and used in the analysis [12].

Semi-Circular Bending (SCB) Test

Fracture resistance potential was assessed using the semi-circular bending (SCB) approach proposed by Wu et al. [13]. This test characterizes the fracture resistance of HMA mixtures based on fracture mechanics principals, the critical strain energy release rate, also called the critical value of J-integral, or J_c. Fig. 2 presents the three-point bend load configuration and typical test result outputs from the SCB test. To determine the critical value of J-integral (J_c), semi-circular specimens with at least two different notch depths need to be tested for each mixture. In this study, three notch depths of 25.4-mm, 31.8-mm and 38-mm were selected based on an a/rd ratio (the notch depth to the radius of the specimen) between 0.5 and 0.75. Test temperature was selected to be 25℃. The semi-circular specimen is loaded monotonically till fracture failure under a constant cross-head deformation rate of 0.5-mm/min in a three-point bending load configuration. The load and deformation are continuously recorded and the critical value of J-integral (J_c) is determined using the following equation [13]:

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2} \right) \frac{1}{a_2 - a_1} \quad (1)$$

where,
J_c = critical strain energy release rate (kJ/mm^2);
b_1, b_2 = sample thickness for specimen 1 and 2 (mm);
a_1, a_2 = the notch depth for specimen 1 and 2 (mm); and
U_1, U_2 = the strain energy to failure specimen 1 and 2 (N.mm).

Modified Lottman Test

The Modified Lottman test was used to evaluate the effect of saturation and accelerated water conditioning on compacted HMA samples utilizing freeze-thaw cycles. This test was conducted in accordance with AASHTO T 283, "Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage." Numerical values of retained indirect-tensile properties are obtained by comparing conditioned samples, samples subjected to vacuum saturation and freeze-thaw cycles, to unconditioned samples. "Unconditioned" samples are samples that are not saturated nor subjected to freeze-thaw cycles. For each mix used in the study, six – 150 x 95-mm diameter samples were compacted with a Superpave gyratory compactor (SGC). The average indirect tensile strength was determined for both conditioned and unconditioned samples. The tensile strength ratio (TSR) was determined and compared with specifications [14].

Results and Analysis

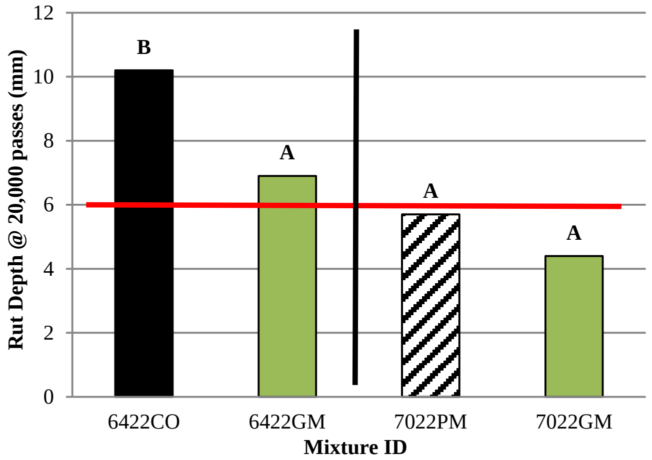
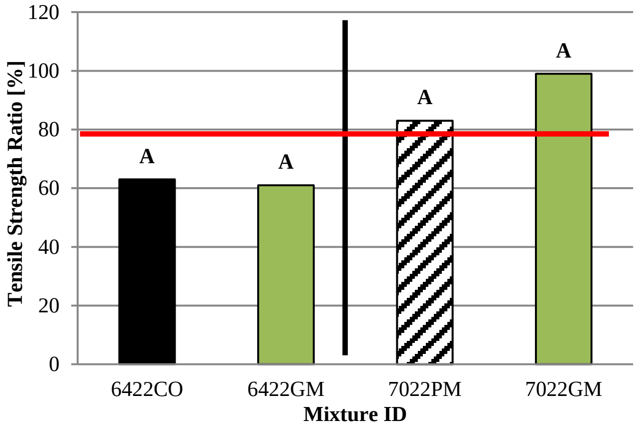
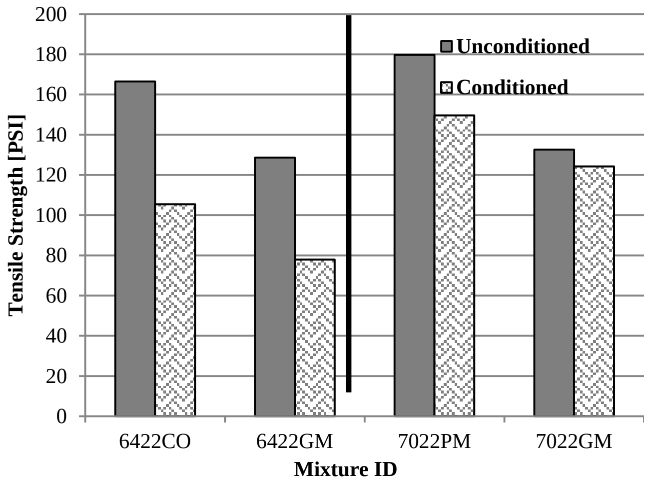


Fig. 3 Loaded Wheel Tester Results.



(a) Average Tensile Strength Ratio



(b) Average Tensile Strength

Fig. 4. Modified Lottman Results.

The following sections present the results and analysis of mixture testing conducted as part of the experimental factorial.

Rutting Performance

Fig. 3 presents the final rut depth for the evaluated mixtures, as measured by the Hamburg loaded wheel tracking test. As shown in the figure, all mixtures containing polymer modified binder passed the Louisiana rut depth specification of 6-mm at 20,000 passes. The 6422CO and 6422GM mixture failed to meet the specification. The modified mixtures where compared to their conventional counterpart mixture using a t-test with 95% confidence level (α=0.05). The letters displayed in the figure represent the statistical grouping associated with the rut depths. The letter A is assigned to the mixture with the best performing rut depth, while the letter B is assigned to a mixture if a significant difference exists between the means of the two mixtures. As shown in Fig. 3, the mean rut depths of the mixtures containing modified binder were significantly improved. It is noted, the mixtures did not experience tertiary flow indicating little moisture susceptibility

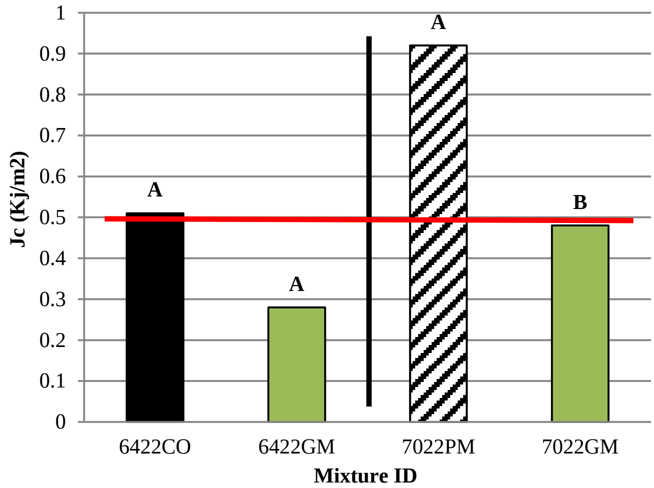


Fig. 5. SCB Test Results.

Moisture Sensitivity

Fig. 4 (a) and (b) presents the moisture-resistance of the mixtures based on the modified Lottman test. As shown in this figure, the addition of polymer and bio-binder has not adversely affected the moisture resistance of the mixtures. However, the reduction in tensile strength for the mixtures prepared with the bio-binder is noted. It was also observed that the tensile strengths for the unconditioned samples are all greater than 120 psi. For the PG 70-22 comparison, the moisture resistance was improved when bio-binder was used. Assuming an 80% minimum TSR, the 6422CO and 6422GR (without the anti-stripping agent), mixes would fail the performance requirement for this test. However, when an anti-strip additive was added to the 6422GR and 6422CO mixtures, the resulting percent TSR increased to 88% and 96.5%, respectively. Statistical comparisons show there are no statistical differences observed from the use of bio-binder.

Fracture Performance

Fig. 5 presents a comparison of the critical strain energy (J_c) data for the mixtures evaluated in this study. High J_c values are desirable for fracture-resistant mixtures. A threshold of a minimum J_c of 0.50 to 0.65 kJ/m^2 is typically used as a failure criterion for this test. As shown in this figure, bio-binder modified WMA mixtures possessed stiffer properties than that of the conventional mixture. Given that the cracking resistance is mainly controlled by the binder in the mixture, it is likely that the use of bio-binder increased the brittleness of the binder at intermediate temperature. Statistical comparisons show the PG 70-22 binder was significantly affected by the addition of the bio-binder. Additional research is underway to focus on the intermediate temperature properties of green asphalt mixtures.

Summary of the Results

The tests evaluated and presented in this paper were selected to capture the laboratory performance of the mixtures prepared with bio-binder technologies as compared to conventional mixes. Table 3 summarizes the ranking of the seven mixtures as predicted from the different test methods. A lower numerical number is indicative of better performance.

While polymer-modified mixtures performed satisfactorily, the need to reduce to consumption of natural resources (materials and energy) and to improve the economic competitiveness of asphalt paving construction drives the use of sustainable technologies such as bio-binder. Results presented in Table 3 indicate that the use of bio-binder enhanced the mixture rutting performance. The moisture sensitivity was not adversely affected by the addition of bio-binder. Fracture resistance tests showed that the mixtures containing binder modified with bio-binder possessed stiffer properties than that of conventional mixtures.

Summary and Conclusions

The mechanistic properties of asphalt mixtures containing green asphalt technologies were evaluated as compared to conventional asphalt mixtures. A suite of laboratory tests were conducted to capture the mechanical behavior of the mixtures against major distresses. Laboratory testing evaluated the rutting performance, moisture resistance, and fracture performance of the produced mixtures using the Hamburg loaded-wheel tester, the modified Lottman test, and the semi-circular bending test. Based on the results of the experimental program, the following findings and conclusions may be drawn:

- With respect to rutting performance, mixtures modified with green asphalt have shown similar or improved performance when compared to the conventional mixes. The mean rut depth of the mixture containing PG64-22 binder was significantly improved with the addition of bio-binder. In addition, all the mixtures did not experience tertiary flow or passed the stripping inflection point indicating moisture susceptibility.
- Both PG70-22 mixtures exceeded 80 percent tensile strength ratio. The 6422CO and 6422GR (without the anti-stripping agent) failed to meet the tensile strength ratio criteria. The anti-stripping agent was used for only one mixture comparison, 64-22. After the addition of the anti-stripping agent, the tensile strength ratio of both mix 6422GR and 6422CO exceeded 80 percent. There were no significant statistical differences associated with the addition of bio-binder.
- The mixes containing bio-binder exhibited reduced intermediate temperature fracture resistance as compared to conventional mixes. This may be due to the stiffening effects of bio-binder on the mix. The results for the PG70-22 comparison were significantly different.

Table 3. Summary of Test Results.

Mixture	Test		
	Rutting	Durability	Fracture
	LWT	Lottman	SCB
6422CO	4	3	3
6422GM	3	4	4
7022PM	2	2	1
7022GM	1	1	2

Acknowledgements

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