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Effects of refined waste and bio-based oil modifiers on rheological properties of asphalt binders

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HIGHLIGHTS

- Oils have a positive impact on low temperature and fatigue performance.
- Oil modification is damaging to the high temperature performance.
- A simple method was provided to design oil modified asphalt.
- A practical oil ranking index Oil Modification Index (OMI) proposed.

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ABSTRACT

To better recycle the waste oil, it has been introduced into asphalt binder as a type of modifier. In this study, the effects of petroleum-based, re-refined, and bio-based oil modifiers on the rheological properties of asphalt binders at low, intermediate, and high service temperature ranges were evaluated. It is found that low temperature performance of asphalt can be improved significantly after adding oil modifiers, especially for re-refined oil modifier, through reducing the stiffness of binders at low temperatures. This effect was found to be oil-type dependent. The linear amplitude sweep test was deployed to evaluate fatigue resistance and damage tolerance of oil modified binders, especially with regards to the effect of aging. The Multiple Stress Creep and Recovery test was employed to evaluate the oil modifiers effect on rutting resistance as well as the possible nonlinearity implication of use of such oil modifiers in binders. Based on the observed trends, a prediction model for the effects of oil modifiers on rheological properties of asphalt was developed. A practical and efficient oil modification index (OMI) was proposed for classification of oil in terms of its effect on the binder performance grade.

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1. Backguound

If used oil is not disposed properly, it will threaten environment and health of human significantly. If these used oils were put into storm water drains or sewers, the waterways and coastal waters may be polluted. Also, risk exists that the used oil may pollute soil and surface water if it is sent to landfill, since the used oil can migrate gradually [1–3]. Meanwhile, due to the pressure of environment and laws, many changes have been made in petroleum industry for the refining process to improve the fuel output but reduce the asphalt residue quantity, which results in higher price of asphalt [4,5]. In addition, cracking caused by temperature (thermal) shrinkage is still the major distress for asphalt pavement in cold climate regions, and cracking can cause other pavement damage. Therefore, improving the low temperature performance of asphalt binder is one of most important focuses [6–8].

Under this condition, the oils are used in asphalt as a type of modifier to improve the low temperature performance of asphalt, decrease the cost of asphalt and reduce the risk of environmental pollution [9–11].

Study carried out by Villanueva et al. [12] showed the low temperature performance of lubricating oil modified asphalt was not as good as expected due to the failure of m-value measured by BBR test. Used-tire-derived pyrolytic oil was introduced into asphalt as a modifier by Yousefi, A.A. etc. [13] and he found this type of oil could improve the low temperature performance of asphalt binder. Study conducted by Xiaoyang [14] indicated that rheological properties of asphalt binder had been significantly changed after waste engine oil was introduced. The performance

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of oil modified asphalt was investigated by Lei et al. [15], and they found the rheological properties and fracture resistance at low temperature were improved after oil modifiers were introduced.

Studies on the effects of oil modifiers on performance of asphalt binder have been conducted, however, further efforts to confirm the trends observed and expand the knowledge on this subject are needed. In this paper, the effects of the addition of different types of oil modifiers, including recycled oil, on the binder properties were investigated and an index for classification of oil in terms of their effects on critical binder properties was proposed.

2. Materials and methods

2.1. Materials used

2.1.1. Asphalt

The base asphalt used in this study is one of common asphalts used in Wisconsin, and named VV in this paper.

2.1.2. Oil modifiers

Six types of oil modifiers were used in this study and the detailed information are summarized in Table 1.

2.2. Experimental procedures

2.2.1. Aging procedures

Short-term aging and long-term aging of the binders were prepared by the rolling thin-film oven (RTFO) and the Pressure Aging Vessel (PAV) procedure according to AASHTO T 240 and AASHTO R 28, respectively.

2.2.2. Rheological properties of binder

A Paar Physica MCR 301 Dynamic Shear Rheometer (DSR) was employed in this study to determine the rheological properties of the asphalt binders. The high temperature performance grade of binders were determined according to ASTM D6373 and AASHTO M 320.

Since oil modifiers can soften the asphalt binders, the limiting factor for determination of the content of each oil modifier to be added is the decrease of high temperature performance grade due to the decrease in stiffness resulting from the introduction of the oil modifier. Therefore the optimum dosage of oil for the modified binder was targeted as $G^*/\sin\delta$ value of approximately 1.0 kPa at 58 °C for binder (one grade temperature lower than the base binder grade of 64 °C). During the experiment, 1.1 kPa was adopted instead of 1.0 kPa to allow the variability of the tests.

2.2.3. Multiple stress creep recovery (MSCR) test

MSCR test is utilized to determine the rutting resistance of asphalt binders. According to AASTO T350 the non-recoverable creep compliance J_{nr} is calculated as a measure of the binder's contribution to mixture permanent deformation behavior [16]. While the MSCR test is promising based on the results from recent studies [17] the MSCR test procedure was slightly modified by increasing the number of cycles at each stress level from 10 to 30 cycles to minimize the effect of non-steady state response in each stress step. Also a third stress level of 10 kPa which is believed to be more representative of binder stress state in the mixture was added after the standard 0.1 and 3.2 kPa stress levels used in the test

2.2.4. Bending beam rheometer (BBR) test

Low temperature performance of asphalt binders used in this study were evaluated at −12 °C, −18 °C and −24 °C by Bending Beam Rheometer (BBR) test according to the AASHTO T 313 and the stiffness (S) and relaxation rate (m) were measured.

2.2.5. Linear amplitude sweep (LAS) test

The current PG specification (AASHTO M320) for evaluating asphalt fatigue performance cannot characterize the real damage resistance of asphalt well [18,19]. To better characterize the asphalt fatigue performance the linear amplitude sweep (LAS) test was developed. In this study, PAV-aged materials were used for the LAS test in accordance to AASHTO TP 101-12. All tests were carried out at 25 °C, which is the intermediate temperature grade of the base binder, to evaluate the oil effect on the fatigue performance.

Experimental plan of this research is shown in Fig. 1.

3. Result and discussion

3.1. Oil modified binder performance grading results

The performance grading results for each of the oil modified binders at their target oil content is summarized in the Table 2.

The results show that for different oil modifiers, the optimum content differs based on the oil type. Moreover, it can be seen that the main effect of oil modifier is reducing stiffness at all temperatures, which can be beneficial at low service temperatures. This will be discussed in further detail in the following sections.

3.2. The effect of oils on MSCR results

In addition to the determination of $G^*/\sin\delta$, the MSCR test was also employed to investigate the rutting resistance of the asphalt binders at the optimum oil content at their corresponding high temperature grade. The summary of results is shown in Fig. 2.

The J_{nr} parameter indicates the resistance of binder to permanent deformation. A higher J_{nr} indicates larger permanent strain and overall higher susceptibility to rutting [20,21]. It can be concluded from Fig. 2 that all oils negatively affected the high temperature performance for VA base binder; the addition of PR-3 oil is shown to result in the most deterioration of the MSCR results. These results can be attributed to the decrease in stiffness due to the addition of oil modification. It can also be found from Fig. 2 that RW modified binder has a better resistance to permanent deformation compared with other modified asphalt binders.

Furthermore, to evaluate the oil modifiers effects on stress sensitivity of the asphalt binder, J_{nrdiff} was calculated for each binder based on the procedure outlined in AASHTO T350. The parameter aims to evaluate the degree of nonlinearity of binder's response at high temperatures. The results are summarized in Fig. 3. Results show that the stress sensitivity of the material increases at higher stress levels, as the magnitude of $J_{nr\ diff}$ is higher between 3.2 and 10 kPa than that between 3.2 and 0.1 kPa. Furthermore it is clear that the oil modifiers did not significantly affect the degree of stress sensitivity. For the VV base asphalt there is no significant dif-

Table 1
Oils used in this study.

Category	Bio-oil Wood plant liquid		Petroleum Based Oils Paraffinic oil 1	Paraffinic oil 2	Aromatic oil	Refine waste oil Motor oil
ID	BO-1	BO-2	PP-1	PP-2	PR-3	RW

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