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Estimation and assessment of high temperature mix performance grade for select bio-based WMA additives

Joseph Herbert Podolsky [a,*], R. Christopher Williams [b,1]

[a] Iowa State University, Department of Civil, Construction, and Environmental Engineering, 174 Town Engineering, Ames, IA, United States
[b] Iowa State University, Department of Civil, Construction, and Environmental Engineering, 490 Town Engineering, Ames, IA, United States

HIGHLIGHTS

- Method 2 was found to be the better alternative over that of method 1.
- Isosorbide Distillation Bottoms (IDB) can be used as a WMA additive.
- IDB is highly comparable to WMA without an additive and WMA with FP.
- Estimation of the mixture high temperature performance grade is possible.
- The Al-Khateeb model works, but not the Hirsch model.

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ABSTRACT

The Hirsch and Al-Khateeb models are commonly used to predict an asphalt mixture's dynamic modulus (E^*) at intermediate temperatures. However, G^*_b and the mix volumetrics are needed to make these predictions. The main objectives of this paper are to demonstrate how mix testing and binder results can be used to estimate the high temperature performance grade (PG) of warm mix asphalts (WMA) with and without bio-based additives and to compare dynamic modulus performance between different asphalt binders and select bio-based additives. The results indicate that prediction of high temperature performance grade for an asphalt mixture cannot be done using the Hirsch model, but is possible using the Al-Khateeb model and that the additives and non-modified binder were not found to be statistically different from one another overall as well as within each binder type.

1. Introduction

Warm mix asphalt technologies reduce binder viscosity as well as mixing and compaction temperatures by 20–55 °C during asphalt mix production and laydown. Reducing mixing temperatures provides the asphalt industry the ability to both lower their carbon footprint and save money due to reduced energy use in mixing plants. Due to the reduced binder viscosity, compaction temperatures in the field can be reduced which improves mix compactibility, extends the paving season, allows longer haul distances, and increases the potential for using more reclaimed asphalt pavement (RAP) in mixes. Reductions in both mixing and compacting temperatures also lessen the fumes workers are exposed to during the production and laydown process of an asphalt mix [1–12].

Isosorbide Distillation Bottoms (IDB) is a recently bio-derived co-product from corn that has surfactant properties. IDB is produced from the conversion of sorbitol to isosorbide by using sorbitan to perform a dehydration reaction twice. Sorbitol is produced by hydrogenating the glucose from the corn biomass [13]. In the past the cost for producing a bio-based WMA additive such as IDB would not have been viable due to the lower cost of petrochemical based additives [13]. With the increasing number and growth of emerging markets around the globe as well as increasing demand for bio-based renewable products, a bio-based WMA additive such as IDB becomes viable from an economic and environmental perspective. However, a bio-based material must be also viable in terms of performance as compared to the material it is intended to replace [13]. A recently derived chemical additive from the forest products industry called forest product (FP) will also be used for binder modification in this study [14]. FP is a water-free

* Corresponding author. Tel.: +1 515 294 4419; fax: +1 515 294 4975.
E-mail addresses: podolsky@iastate.edu (J.H. Podolsky), rwilliam@iastate.edu (R. Christopher Williams).
[1] Tel.: +1 515 294 4419; fax: +1 515 294 4975.

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chemical additive that displays surfactant properties. When asphalt binder with FP is added to aggregates, the aggregate-binder interface friction is reduced due to the surfactant properties of FP. This reduction makes it possible to lower mixing and compaction temperatures [15,16]. In the literature it is recommended that the FP optimum dosage level is 0.5% by weight of the total binder, and in recently completed binder studies it was found that the optimum dosage level for IDB addition is 0.5% by weight of the total binder. Therefore, 0.5% addition level was used in this study [5].

Currently there is a procedure for determining the performance grade of asphalt binders unmodified and modified with WMA additives. This procedure is done by following the steps in AASHTO R 29-08 in conjunction with ASTM D7173 and verifying the performance grade of the binder through the use of AASHTO M 320-10 [17–19]. However, there is no standard or clear method for determining the high temperature performance for an asphalt mixture let alone warm mix asphalt. The main objective of this paper is to illustrate how a warm mix asphalt mix's performance can be determined using both mix testing results (dynamic modulus test) with the Hirsch and Al-Khateeb models, and binder testing results (RTFO aged DSR results) [20,21]. The secondary objective is to compare the mix performance grade of WMA with 0.5% IDB by weight of the total binder against the mix performance grade of WMA with 0.5% FP by weight of the total binder and see if IDB is a viable warm mix asphalt technology.

2. Experimental materials

2.1. Materials

This research used one crude source of binder from Montana, which is similar to a Canadian crude. The Montana Crude was tested at its original grade of PG 64-22 (Binder I), and tested as a polymer modified binder (1.5% SBS), PG 70-22 (Binder II). The mix design that was used in the laboratory to construct dynamic modulus samples is an Iowa DOT approved mix with a 10 million ESAL design level. The aggregates, their gradation, and suppliers used for this mix design are shown in Table 1 and Fig. 1. The gradation for each aggregate was verified and checked with the mix gradation in the job mix formula from the Iowa Department of Transportation (DOT). One adjustment needed to be made in the laboratory gradation was to increase the fines in the blended gradation. This was done through the addition of commercially produced hydrated lime as 100% of this material passes the No. 200 sieve. Before the blended gradation was matched to the job formula, each aggregate was sieved in their appropriate proportions to create less variability between batches. With this addition of the hydrated lime the blended gradation was matched to the job mix formula.

Two additives will be used in this study – IDB and FP – both at addition rates of 0.5% by weight of the binder. As stated earlier, IDB is a recently bio-derived co-product from corn that has surfactant properties. FP is a WMA chemical additive derived from tall oil (tree oil) [14]. The research literature recommends that the FP optimum dosage level is 0.5% by weight of the total binder, and in recently completed binder studies at Iowa State University it was found that the optimum dosage level for IDB addition is 0.5% by weight of the total binder. Therefore, 0.5% addition level was used in this study to compare the two technologies [5].

2.2. Mix design, sample preparation, and testing

2.2.1. Dynamic shear rheometer binder sample experimental testing plan

Testing was done using a Dynamic Shear Rheometer (DSR) on multiple samples from each binder (Montana Crude – PG 64-22, and Polymer Modified Montana Crude – PG 70-22) that were not modified with any additives. The DSR was used to test the binders at multiple frequencies and at several temperatures [20]. Testing in a DSR at six temperatures (13 °C, 21 °C, 29 °C, 37 °C, 45 °C, and 54 °C) and ten frequencies (1 Hz, 1.59 Hz, 2.51 Hz, 3.98 Hz, 6.31 Hz, 10 Hz, 15.85 Hz, 25.12 Hz, 39.81 Hz, and 50 Hz), was done for creating a G^*_b master curve using binder samples from the original PG 64-22 and original PG 70-22 binders [20].

2.2.2. Dynamic modulus asphalt mixture experimental testing plan

The dynamic modulus testing was performed on three groups of samples: no additive, 0.5% IDB, and 0.5% FP samples using two binder types; the Montana PG 64-22 binder, and the Polymer Modified Montana PG 70-22 binder. The dynamic modulus values and phase angles were calculated at several different frequency–temperature combinations for the mix combinations. The temperatures used in testing were 4 °C, 21 °C, and 37 °C while the test frequencies were 25 Hz, 20 Hz, 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz, 0.2 Hz, and 0.1 Hz.

For dynamic modulus testing, 2600 g aggregate samples were proportioned and mixed with an optimum binder content of 5.2% to produce test samples. Dynamic modulus sample weights were estimated to be 2670 for achieving 7 ± 1% air voids. The WMA mixtures used for the dynamic modulus test in this paper differed by binder type and additive choice, but were mixed and compacted at the same temperatures (mix temperature – 130 °C, and compaction temperature – 120 °C). Three replicate samples for each group were used in the development of this paper. Each sample tested was used with the Hirsch and the Al-Khateeb models to back-calculate individually to the G^*_b master curve. The three samples' back-calculated results for each group were averaged and are used to make comparisons in this paper.

3. Experimental methods

3.1. Estimated G^* binder master curve methods back calculated from measured E^* data

Two methods were used for back calculating the binder modulus master curves from predicted complex dynamic modulus master curves made using measured E^* data. The first method used was the Hirsch model, while the second method used was the Al-Khateeb model [22,23]. The purpose of using the Hirsch model is to use binder modulus (G^*_b) and volumetric composition (voids in mineral aggregate – VMA, and voids filled with asphalt – VFA) to estimate the modulus of asphalt concrete (E^*). In this paper, VMA, VFA, and E^* are known and are used to estimate the binder modulus. The Al-Khateeb model is used to estimate the asphalt concrete dynamic modulus using only two inputs: asphalt binder dynamic shear modulus (G^*_b), and voids in mineral aggregate (VMA). The Al-Khateeb model is a simpler form of the Hirsch model, but was constructed using more data than the former which enables it to estimate the asphalt dynamic modulus for a wider range of temperatures and frequencies.

3.1.1. Sigmoidal E^* master curves using measured data

The dynamic modulus test is a linear viscoelastic test used for asphalt mixtures where the complex dynamic modulus (E^*) is determined by relating stress to strain at multiple temperatures each under several repeated loading rates (frequencies). E^* is defined as the pavement stiffness and is a very important property because it is used to simulate a pavement's response under repeated traffic loading [24]. The stiffness of an asphalt mix also depends on the temperature at which it is being loaded. When the stiffness is high under an applied stress, the asphalt mix will have lower strain. At high temperatures, high stiffness mixes are more resistant to permanent deformation, but high stiffness mixes at low temperatures are generally more prone to cracking [24].

The dynamic modulus test is defined as an uniaxial compression test with cyclic loading. In this test, a cyclic load is applied vertically in a sinusoidal wave form on a cylindrical sample. The complex modulus is the ratio of stress amplitude to strain in a sinusoidal wave form:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 \times e^{i\omega t}}{\varepsilon_0 \times e^{i(\omega t - \delta)}} = \frac{\sigma_0 \times \sin(\omega t)}{\varepsilon_0 \times \sin(\omega t - \delta)} \quad (1)$$

where E^* = complex modulus, σ_0 = peak (maximum) stress, ε_0 = peak (maximum) strain, δ = phase angle (degrees), ω = angular velocity, t = time (seconds), e = exponential, i = imaginary component of the complex modulus [25]. Ultimately the dynamic modulus is defined as the absolute value of the complex modulus:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (2)$$

where σ_0 = maximum dynamic stress, and ε_0 = peak recoverable axial strain [25]. The complex modulus (E^*) is made up of the storage modulus (E'), and the loss modulus (E''). E' deals with the